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UNIVERSITÉ DES
MASCAREIGNES

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ENGINEERING GEOLOGY

*with regional geology elements
of Indian Ocean islands*

Textbook, study guide for students of civil engineering, ecological and
natural sciences of higher education institutions

Kharkiv, Ukraine – Rose Hill, Mauritius
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The textbook contains the main sections of general and engineering geology: mineralogy, petrography, soil science, including classification and methods of soil research, engineering geodynamics, which considers both natural and man-made harmful processes, engineering surveys for construction in different natural conditions. Examples of geological processes, their impact on buildings and structures and the environment in general, as well as ways to protect against negative impacts using a modern database of regulations.

The textbook also contains important information on the geology and, especially, engineering and geological conditions of the island of Mauritius. Particular attention is paid to forecasting and georisk assessment in engineering geology. Several islands in the Indian Ocean are considered as example.

The textbook is intended for English-speaking students and graduate students in the fields of "Civil engineering" and "Ecology". It will also be useful for designers, builders, specialists in protection against hazardous processes.

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BOOK REVIEW

Textbook entitled “*ENGINEERING GEOLOGY with regional geology elements of the Indian Ocean Islands*” has been submitted for review in July 2021 by authors Dr. R. Goodary - Head of the Department of Civil Engineering, Université des Mascareignes, Mauritius; Professor V. Yu. Egupov and Associate Professor I. V. Khrapatova - Academics of the Department of Geotechnics, Underground and Hydraulic Structures, Kharkiv National University of Civil Engineering and Architecture (Ukraine).

The edition comprises five parts, namely: Element of General geology, Endogenous Processes, Exogenous Processes, Fundamentals of Soil Science and Engineering Geology of the Island of Mauritius and the region. Each part is split in chapters, bringing to about thirty-three carefully written chapters, in total. Special attempt has been made to enrich the book with simple language, lucid expressions, self-explanatory illustrations and make it available at affordable price. The quality and the originality of the illustrations, very often emanating from the authors' own collections, are highly commendable.

The book is an outgrowth of several decades of experience in teaching, research and consultancy in the field of Engineering Geology and Geotechnical Engineering and is being recommended as a textbook for undergraduate and graduate students in the field of Civil Engineering. It is also being extended to practicing Engineers and Lecturers.

Part 5 of the book is dedicated to the regional geology of the Mascarene Islands, in the Indian Ocean. Appreciable effort has been made to bring together all sparsely available information about the geo-engineering of the region, which again enhances the originality of the book, especially knowledge regarding the geology and geological processes occurring on territories of volcanic origin. Modern methods of forecasting, assessing geo-risks and the use of Sustainability Resource (SR) concept of these territories to hazardous external influences are derived from authors' own research work. The original figures and photos in all the chapters of Part 5, talk for themselves and are deemed highly valuable which expose the region as a real geological museum.

I believe that the book “*ENGINEERING GEOLOGY with elements of the regional geology of the Indian Ocean Islands*” meets the international requirements of a modern scientific and educational textbook and I recommend its publication.

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CONTENTS

FOREWORD	8
INTRODUCTION	11
PART I. THE ELEMENTS OF GENERAL GEOLOGY.....	15
Chapter 1.1. BASIC FACTS ABOUT THE EARTH	15
Chapter 1.2. MINERALS	29
Chapter 1.3. ROCKS.....	49
Chapter 1.4. STRATIGRAPHY AND GEOCHRONOLOGY.....	77
PART II. ENDOGENOUS PROCESSES.....	92
Chapter 2.1. TECTONIC MOVEMENTS AND ROCK DISLOCATIONS....	94
Chapter 2.2. MAGMATISM AND VOLCANOES	112
Chapter 2.3. SEISMIC PHENOMENA.....	136
PART III. EXOGENOUS PROCESSES AND ENGINEERING GEODYNAMICS	159
Chapter 3.1. SOIL SUFFUSION	161
Chapter 3.2. KARST	166
Chapter 3.3. SLOPES AND TYPES OF SLOPE PROCESSES.....	182
Chapter 3.4. LANDSLIDES	201
Chapter 3.5. MUDFLOWS, LAHARS AND AVALANCHES.....	216
Chapter 3.6. EROSION OF ROCKS AND SOILS. WIND EROSION AND DESERTIFICATION	234
Chapter 3.7. WATER EROSION. RAVINES.....	249
Chapter 3.8. RIVER EROSION	260
Chapter 3.9. ABRASION. PROCESSING OF THE COAST.....	271
Chapter 3.10. QUICKSAND. SOIL LIQUEFACTION	287
Chapter 3.11. UNDERMINING AREA	304
Chapter 3.12. FLOODING OF TERRITORIES BY GROUND WATERS ...	311
Chapter 3.13. FLOODING OF TERRITORIES BY SURFACE WATERS....	319
Chapter 3.14. PROCESSES RELATED TO WATER DRAINAGE AND WATER SUPPLY	334

PART IV. FUNDAMENTALS OF SOIL SCIENCE..... 338

Chapter 4.1. GENERAL CLASSIFICATION OF SOILS.....	339
Chapter 4.2. ROCKY SOILS AND THEIR ENGINEERING PROPERTIES.	344
4.2.1. Classification characteristics of rocky soils.....	346
4.2.2. Examples of determining the classification construction characteristics of rocky soils	352
Chapter 4.3. DISPERSED SOILS AND THEIR ENGINEERING PROPERTIES.....	357
4.3.1. Classification characteristics of dispersed soils	358
4.3.1.1. Subclass (group) of cohesionless or granular soils	359
4.3.1.1.1. Coarse soil. Origin and general engineering-geological characteristics	359
4.3.1.1.2. Classification characteristics of coarse soil.....	361
4.3.1.1.3. Sandy soil (sand). Origin and general engineering and geological characteristics	365
4.3.1.1.4. Classification characteristics of sandy soils	369
4.3.1.2. Subclass (group) of cohesive soils.....	373
4.3.1.2.1. Origin and general engineering-geological characteristics	373
4.3.1.2.2. Classification characteristics of cohesive soils	376
4.3.2. Examples of determining the classification construction characteristics of dispersed soils.....	383
Chapter 4.4. ARTIFICIAL SOILS AND TOPSOILS	395
4.4.1. Cultural layers, bulk and degraded soils.....	396
4.4.2. Washed soils.....	399
4.4.3. Topsoil.....	400
Chapter 4.5. SUBSIDING LOESS SOILS	403
Chapter 4.6. SWELLING AND SHRINKAGE PROPERTIES OF CLAY SOILS.....	418
Chapter 4.7. GROUND IMPROVEMENT TECHNIQUES	437
4.7.1. Technical reclamation of rocky soils	437
4.7.2. Technical reclamation of dispersed soils.....	438
4.7.2.1. The main methods of compaction of soils	438
4.7.2.2. The main types of soil consolidation.....	444

PART V. REGIONAL ENGINEERING GEOLOGY OF THE ISLAND OF MAURITIUS	448
Chapter 5.1. THE ISLAND OF MAURITIUS	448
Chapter 5.2. GENERAL GEOLOGICAL CHARACTERISTICS.....	450
5.2.1. Brief historical geology of the island	451
5.2.2. Geomorphology	454
5.2.3. Geology.....	460
Chapter 5.3 ENGINEERING GEODINAMICS OF MAURITIUS	469
5.3.1. Types of slope disasters in Mauritius	469
5.3.2. Cut Slope and Natural Slope Failures.....	474
5.3.3. Rock Falls.....	486
5.3.4. Debris Flow.....	492
Chapter 5.4. ENGINEERING PROPERTIES OF SOILS OCCURING ON THE ISLAND	499
5.4.1. Ground Investigation.....	499
5.4.2. Founding Materials encountered	508
5.4.3. Laboratory testing.....	512
5.4.4. In situ testing.....	513
Chapter 5.5. GEORISKS AND SUSTAINABILITY RESOURCE OF THE MASCARENE ISLANDS TERRITORIES TO EXTERNAL IMPACTS.....	518
5.5.1. Introduction	518
5.5.2. Multi-risk assessment approach.....	519
5.5.3. Assessment of Georisks and Resource of Stability for the Mascarene Islands.....	522
CONCLUSION	525
ACKNOWLEDGEMENT	526
REFERENCES.....	527

FOREWORD

Engineering Geology is one of the main basic disciplines in the curriculum of university students engaged in the knowledge field of "Natural Sciences" and "Architecture and Construction". The natural sciences include specialities like "Ecology" and "Earth Sciences" – including geology, hydrogeology and engineering geology, and in the architectural and construction industry – specialities like "Construction and Civil Engineering" and "Hydro-technical Construction, Water Engineering and Water Technology". This study guide is intended for students engaged in these areas using English as medium of study. The book will be particularly helpful to students from countries in Asia and Africa, and as such, authors tried to present the material as intelligibly and coherently as possible, paying special attention to practical issues. The manual will also serve as a good source of knowledge to English-speaking students from other countries.

The book contains the necessary materials in the field of Engineering Geology and meets the requirements of undergraduate programs. In addition, the materials presented may also be useful to masters and graduate students, as well as practicing professionals – builders, engineering geologists, hydrogeologists, hydraulic engineers, ecologists and urban specialists.

The basic theoretical provisions for courses in engineering geology, soil research with elements of soil mechanics, engineering surveys for construction – necessary for complete mastering of the course content with the necessary examples of calculations are given in this textbook, using modern scientific data.

One of the most important tasks of engineering geology is the interpretation of terrain features, geological structure and earth processes, required to identify potential geological and related technological hazards that can have a big impact on civil infrastructures and human life. Knowledge in the field of engineering geology gives construction specialists an understanding of how the "land" works, which is extremely important to minimize the dangers and risks associated with it. Building engineers receive special education and training in soil mechanics, rock mechanics, geotechnics, groundwater hydrology and civil engineering. These two aspects of knowledge and education provide geologists and builders with a unique ability to understand and mitigate the hazards associated with the interaction of construction and earth structures.

The reliability of buildings and structures, with appropriate cost effective foundations has always been and remains a predominating task. A rational decision largely depends on the ability to correctly assess the engineering and geological conditions of construction sites, the properties of foundation soils and the simultaneous action of these soils with the building structures. An important aspect of Engineering Geology also remains the assessment of the possibility of occurrence or intensification of hazardous engineering and geological processes: suffusion, karst, slope processes (landslides, rock falls), flooding of territories and seismic processes. For civil engineers, a clear knowledge of such processes and methods of protecting construction sites is a must.

Ultimately, materials presented in this volume will allow future specialists – civil engineers to carefully assess the geotechnical conditions of construction sites, design reliable buildings and structures, taking into consideration the rational use and protection of the environment in connection with construction activities, leading to a professional realization of construction works.

The manual was prepared as a result of an international cooperation project of the Kharkiv National University of Civil Engineering and Architecture (KNUCEA), Kharkiv, Ukraine and Université des Mascareignes, Mauritius. The creative team comprised:

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INTRODUCTION

Engineering geology forms part of the complex of geological sciences. According to the “Mountain Encyclopedia”, this is a science about the structure, properties and dynamics of the geological environment, its rational use and protection during engineering and economic activities. The main tasks of engineering geology: study of the current state and patterns of formation of engineering and geological conditions, predicting their changes in the process of construction and economic activity; engineering and geological substantiation of protective measures ensuring the rational development of territories, mineral resources and environmental protection.

Engineering geology is characterized by the application of geological methods to engineering research (surveys) in order to identify and take into account geological factors related to the location, design, construction, operation and maintenance of construction sites. To solve the problems of engineering geology, field observations, in-situ and laboratory investigations, modeling, analytical calculations, stationary observations and other general geological and special geotechnical methods are used.

As a result of the analysis of the performed surveys, geological engineers provide geological and geotechnical recommendations for design. The goal of a geological engineer is mainly to evaluate the interaction of building objects with soils and to study how engineering-geological processes affect human-made structures and human activities.

Brief History of Engineering Geology

Geology is one of the oldest areas of human activity and one of the first sciences. The study of rocks, minerals, ores of various metals has been conducted for many centuries. At the same time, the science and practice of engineering geology began to emerge as a separate discipline only in the late XIX and early XX centuries. The first book, *Engineering Geology*, was published by William Pen-ning in 1880. The first textbook on engineering geology in the United States was written in 1914 by Rhys and Watson.

At the beginning of the twentieth century, geologist Charles Burke became the first American engineer – a geologist. He worked on several New York City water supply projects, then worked on the design and construction of the Hoover Dam and many other construction projects.

The largest studies during the first half of the twentieth century in engineering geology were carried out in the USA – K. Terzaghi, R. Peck, J. Taylor, T. Lamb; in the UK – A. Skempton; in France – J. Talobre and in Austria – L. Muller. A particularly significant role in the formation of engineering geology as a science, was played by the Soviet scientist F.P. Savarensky.

With the intensive development of production and economic activities, including construction, man has become the largest geological force, and this, according to the definition of V. I. Vernadsky, has formed a new global geological phenomenon – the “noosphere”. On this scientific basis, engineering geology has been developing for many decades.

In 1979, Academician E. M. Sergeev defined engineering geology “as a science of the geological environment, its rational use and protection in connection with the possibility of occurrence of geological processes harmful to humans”. The three main sections of engineering geology that have developed are characterized by E. M. Sergeev as follows:

Engineering geodynamics is the science of modern geological processes, having its importance in the national economic and construction activities;

Soil science is a science that studies rocks and soils, as multicomponent dynamic systems that change in connection with human engineering activities;

Regional engineering geology is a scientific direction for understanding the laws governing the formation of engineering-geological conditions of large geological regions and the forecast of their change under the influence of human engineering activities.

At the same stage of development, such directions as engineering geology of cities, marine engineering geology, engineering geology of mineral deposits were formed.

A diagram of the composition of engineering geology, its main areas and relationships with other sciences is shown in Figure 1.

The main tasks facing engineering geology as a science are described quite fully in the five-volume collective monograph *Theoretical Foundations of Engineering Geology*. This monograph reflects the work of prominent scientists and specialists: E. M. Sergeev, V. G. Trofimov, G. S. Zolotarev, R. S. Ziangiroy, F. V. Kotlov, G. K. Bondarik and others.

Among the famous modern Ukrainian scientists, one can name M. G. Demchishin (regional engineering geology), G. I. Rudko (engineering geodynamics, monitoring of the geological environment, geoecology), E. A. Yakovlev (ecology),

V. M. Shestopalov (hydrogeology and ecogeology), G. G. Strizhelchik (engineering surveys), V. Proag (The geology and water resources of Mauritius), among others. The works of these scientists were used in the preparation of this manual.

At present, the main task of engineering geology as a science can be considered the creation of prerequisites for participation in the management of the development of the geological environment and harmonization of the "man – geological environment" system.

Engineering-geological surveys and studies can be performed for:

- residential, commercial and industrial buildings and structures;
 - state and military facilities;
 - public developments, such as power plants, wind turbines, power lines;
 - storm sewers, wastewater treatment plants, water treatment plants, pipelines (aqueducts, water pipes), tunnels;
 - hydraulic structures: canals, dams, reservoirs;
 - railways and roads, bridges, airports;
 - the development of a mine and quarry, reclamation of territories of worked mines;
 - wetland recovery programs;
 - government, commercial or industrial waste disposal sites;
 - coastal works: protection of sandy beaches, the stability of cliffs or sea cliffs, the construction of a harbor, pier and promenade;
 - offshore operations: drilling platforms and underwater pipelines, underwater cable;
- and as well as for other types of objects.

Engineering-geological studies can be carried out at the stages of long-term planning, analysis of environmental impact, general structural design, at the stages of detailed design and construction of public and private buildings and structures, as well as at the stages of reconstruction.

Works performed by geological engineers include: assessment of all types of geological hazards; determination of geotechnical properties of soils, including the possibility of their use as building materials; resistance of lands to landslides and other slope processes; to erosion of all kinds, floods, dehydration; seismic surveys.

Engineering and geological studies are carried out by an engineering geologist who is trained, has the qualifications and experience associated with the recognition and interpretation of natural processes, understanding how these

processes affect human-made structures (and vice versa), as well as knowledge of the methods by which we can prevent risks or mitigate the consequences arising from adverse natural or man-made incidents. The main task of an engineering geologist is to protect life and property from damage that can be caused by various geological processes and phenomena.

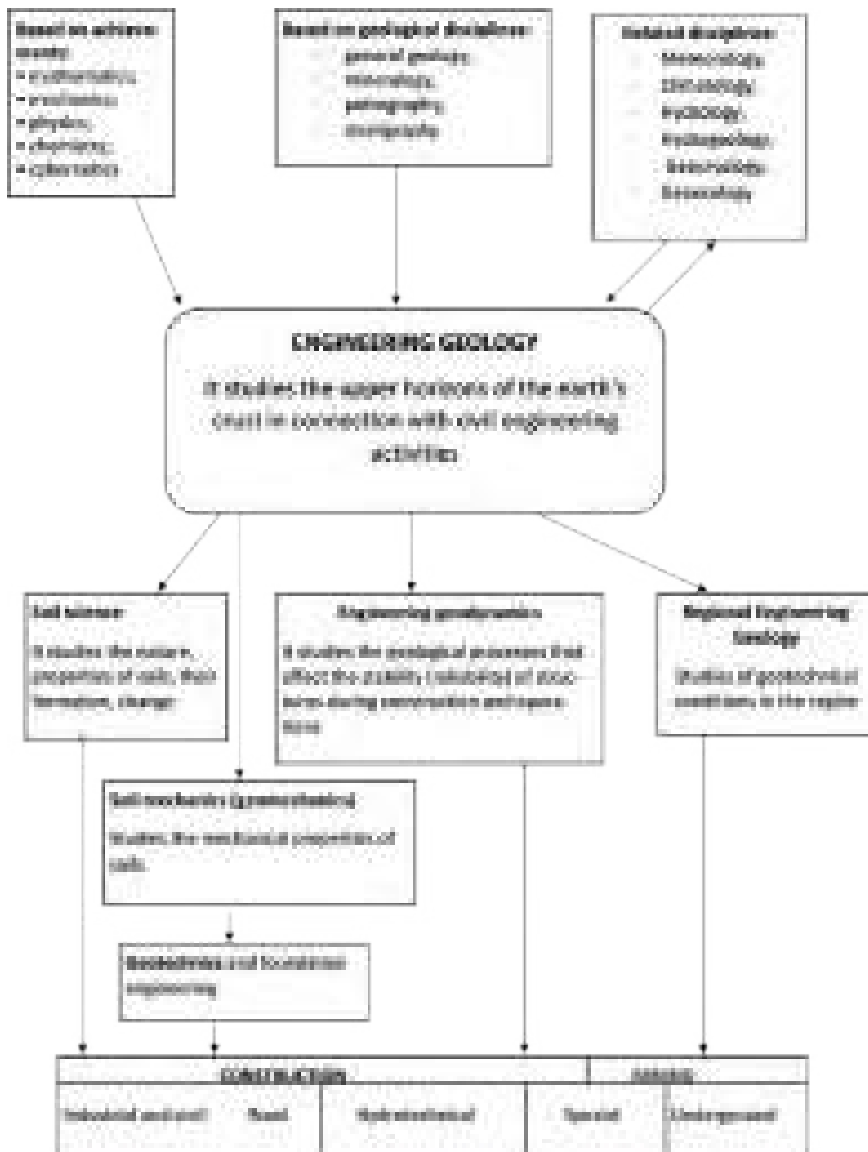


Fig. 1. The relationship of Engineering Geology with other disciplines Research practice

PART I.

THE ELEMENTS OF GENERAL GEOLOGY

Chapter 1.1. BASIC FACTS ABOUT THE EARTH

The shape, origin and structure of the Earth. The Lithosphere and tectonic plates. The types of the Earth's crust. The Hydrosphere. The Atmosphere. The Biosphere

The Earth is the third planet of the Solar System from the Sun. It is a part of a group of the planets that have hard, the stony surface along with Mercury, Venus, and Mars unlike the gas and ice giants like Jupiter, Saturn, Uranus, and Neptune. The Earth has the largest dimensions, mass, density, levels of the gravitational and magnetic fields among the planets of the “terrestrial group”.

The shape of the Earth. The shape of the Earth is similar to the spheroid that is a ball flattened at the poles. The distance from the centre of the Earth to the poles is 6,356.8 km, and it is 6378.1 km from the centre to the equator. Thus, the equatorial diameter of our planet is 43 km larger than the polar diameter. The centrifugal force stipulates the occurrence of deformation due to the rotation of the Earth. Thereby it is not the summit of the highest Mount Everest (8848 m above sea level) (Fig. 1.1.1), but the tops of Ecuador's Chimborazo volcano (Fig. 1.1.3) and Peru's Mount Huascarán (Fig. 1.1.4) that are the most remote points on the Earth's surface from its centre. The Mariana Trench (10,994 m below sea level) (Fig. 1.1.2) is the deepest point on the Earth. The unique shape of the planet was called *a geoid* taking into account all the elevations and depressions. It should be noted that the relief changes



Fig 1.1.1. Mount Everest (8848 m) – the highest peak of the planet

<https://fishki.net/50065-vershina-mira-jeverest-28-foto.html>



Fig 1.1.2. Mariana Trench
(10994 ± 40 m)

<https://www.haikudeck.com/copy-of-plate-tectonics-education-presentation-uDZEg6NoDI#slide14>

on the Earth's surface are less than 20 km, which is negligible in comparison with the radius of the planet (about 6360 km).

Mariana Trench or Marianas Trench is located in the western Pacific Ocean about 200 km east of the Mariana Islands, and has the deepest natural trench in the world. It is a crescent-shaped trough in the Earth's crust averaging about 2,550 km long and 69 km wide. The maximum known depth is 10994 m (± 40 m) at the southern end of a small slot-shaped valley in its floor known as the Challenger Deep. However, some unreported measurements place the deepest portion at 11,034 m. By

comparison: if Mount Everest was placed into the trench at this point, its peak would still be over two km underwater.

The origin of the Earth. The Earth was formed from a primary gaseous dust cloud along with the other planets of the Solar System 4.54 ± 0.04 billion years ago according to modern scientific ideas. The cloud gradually contracted under the influence of gravity; the particles collided, were attracted to the larger objects and the planets were formed within 10–20 million years. When the Earth was formed, the heavier chemical elements (iron, nickel) were concentrated closer to the centre while the lighter ones (silicon, carbon, oxygen) were concentrated closer to the outer part of the planet. There was a certain heating and melting of the matter inside the Earth due to the gravitational compression and a core was formed. It was surrounded by a series of concentric shells that were the mantle, the Earth's crust (the lithosphere). The hydrosphere and the atmosphere that was formed later (Fig. 1.1.5).



Fig. 1.1.3. Volcano Chimborazo, Ecuador (6267 m)

https://upload.wikimedia.org/wikipedia/commons/5/5b/EL_CHIMBORAZO.jpg



Fig. 1.1.4. Mount Huascaran, Peru (6768 m). On Mount Huascaran, the lowest value of the acceleration of free fall on Earth is recorded -9.7639 m/s^2

[https://ru.wikipedia.org/wiki/Уаскаран_\(гора\)](https://ru.wikipedia.org/wiki/Уаскаран_(гора))

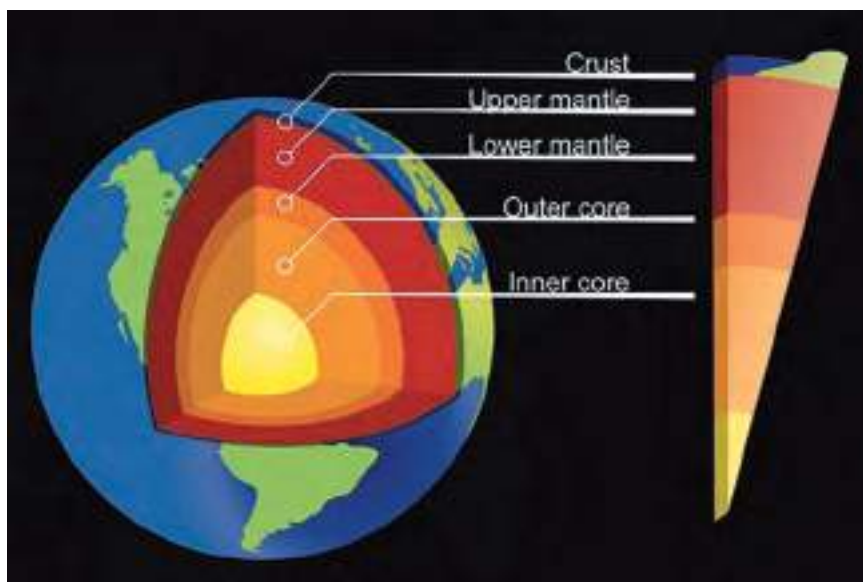
The structure of the Earth. There is a metal *core* in the centre of the Earth consisting mainly of iron ($\sim 80\%$) with the admixed silicon ($\sim 7\%$), nickel ($\sim 5\%$), sulphur ($\sim 2\%$) and other elements. The inner part of the core is a solid ball that is 2600 km in diameter. The outer part of the nucleus is liquid; its diameter is about 4400 km, the depth of cover from the Earth's surface is 2900 km. The temperature in the core reaches 5–6 thousand $^{\circ}\text{C}$ while the density can reach up to 13 t/m^3 . The presence of the Earth's magnetic field is connected with the core. The solar-wind particles are deflected to the poles due to the former, which makes it possible to exist on our planet.

The mantle is the next shell that is predominantly of silicate composition. It occupies the space between the Earth's crust (ending at the depth of 5–70 km) and the core (ending at the depth of 2900 km) containing the largest part of the terrestrial matter that is 67 % of the mass and 83 % of the volume of the globe. The Mohorovičić discontinuity, which was named after Serbian scientist who discovered the mantle at the beginning of the 20th century, separates the mantle from the Earth's crust. The velocity of seismic waves significantly increases below the surface, which indicates the increase in the density of the matter. The mantle substance mainly consists of silicon, iron, magnesium and oxygen. The state of the matter is solid due to a very high pressure. This is with the exception of the “asthenosphere” that is the layer lying at the depth of 100–700 km where the substance is almost in molten amorphous state.

The lithosphere and tectonic plates. The lithosphere is the Earth's solid shell. It includes the upper part of the mantle and the Earth's crust. Fault lines divide the lithosphere into separate blocks that are lithospheric (or tectonic) plates (Fig. 1.6). The eight largest lithospheric plates occupy more than 90 % of the Earth's surface: the Pacific Plate, the North American Plate, the Eurasian Plate, the African Plate, the Australian Plate, the Antarctic Plate, the South American Plate and the Indian Plate. Medium-sized plates include the Arabian Plate, The Nazca Plate, The Juan de Fuca Plate, The Cocos Plate and several others. There are also a lot of small plates. The plates move relative to each other at different rates: from 2 cm / year for the “slowest” Eurasian plate to 5.2–6.9 cm/year and 7.5 cm/year for the “fastest” Pacific and Cocos Plates. The outlines of the lithospheric plates are continuously changing; they can either split or unite. Sometimes they sink into the mantle and disappear from the Earth surface. Contemporary outlines of the continents and oceans arose due to the movement of the lithospheric plates. Hereby South America and Africa used to be a single continent, which

can be clearly seen from the outlines of the coastline of Brazil and the Gulf of Guinea.

The overall structure of the planet Earth



Depth, km	Layer	Density, g / cm ³
0–35	Earth's crust (in some places varies from 5 to 70 km)	2,2–2,9
35–60	Upper mantle	3,4–4,4
35–2900	Mantle	3,4–5,6
2900–5100	Outer core	9,9–12,2
5100–6370	Inner core	12,8–13,1

Fig. 1.1.5. Structure of the Earth

<https://www.google.com.ua/url?sa=i&source=images&cd=&cad=rja&uact=8&ved=0ahUKEwiBzoPR6t7kAhXoxcQBHWyyCFcQMwgsKAAwAA&url=http%3A%2F%2Fdaguaw.com%2Fnews%2Fd2F0ZXlgcmlvZmVzZWVhY2g%253D.html&psig=AOvVaw1KWSLpwddCLWgdU-0-HMsF&ust=1569049397654375&ictx=3&uact=3>



Fig. 1.1.6. Lithospheric tectonic plates
<http://blazegraphics.co/world-tectonic-plates-map/>

Then the Atlantic Ocean was formed through The Mid-Atlantic Ridge (MAR) due to the constant matter extrusion and it has been expanding even since (Fig. 1.7, 1.8). There are orogeny processes on the contacts of the tectonic plates and seismic activity is highly observed. There can be frequent earthquakes and volcanic eruptions.

The types of the Earth's crust. The upper part of the solid shell of our planet is called the Earth's crust. There are two fundamentally different types of crust. They are the continental crust, which is the older one, and the oceanic crust, which is no older than 200 million years. Some lithospheric plates are made exclusively of the oceanic crust, for example, the largest Pacific plate. The other plates are made of a block of the continental crust "soldered" into the oceanic crust. In addition, there are two main subtypes of the Earth's crust. They are the subcontinental and suboceanic types.

The thickness of *the continental crust* is 30–45 km within the limits of the plains and it is 60–70 km (the so-called "roots of the mountains") under the mountain areas. The maximum values of up to 75 km are revealed under

the highest mountain systems of the Himalayas and the Andes. Three layers usually participate in the building of the continental crust. The first layer is the “sedimentary layer” that is the upper discontinuous layer consisting of sedimentary and volcanic igneous rocks. The second layer is the “granite layer” that is situated below consisting of granites and gneisses. The third layer is the “basaltic layer” that is the most buried layer in which basalt, gabbro and metamorphic rocks predominate.

The oceanic crust is located under the oceans and its thickness is 5–10 km, which is much smaller than the one of the continental crust. There is a 1 km thick “sedimentary layer” above the crust. The “basaltic layer” is the next layer and it is 1–2,5 km thick. There is also a “lower oceanic” layer consisting of gabbro and pyroxenites with an average thickness of 5 km.

The subcontinental subtype of the Earth’s crust is structurally similar to the continental one. It is 20–30 km thick, which is smaller than the one of the latter. It is located under festoon islands (the Kuril Islands, etc.).

The sub-oceanic crust underlies the depressions of the inner and outer seas. They are the Mediterranean Sea, the Black Sea, The Sea of Okhotsk and some others. This subtype of the crust is characterized by a large thickness of 5–10 (sometimes up to 20) km of the sedimentary layer that lies on the 5–10 km thick “basaltic layer”. The total thickness of the sub-oceanic crust is 10–25 km.



Fig. 1.1.7. Relief of the bottom of the Atlantic Ocean
<https://mapdesign.icaci.org/map-examples/>

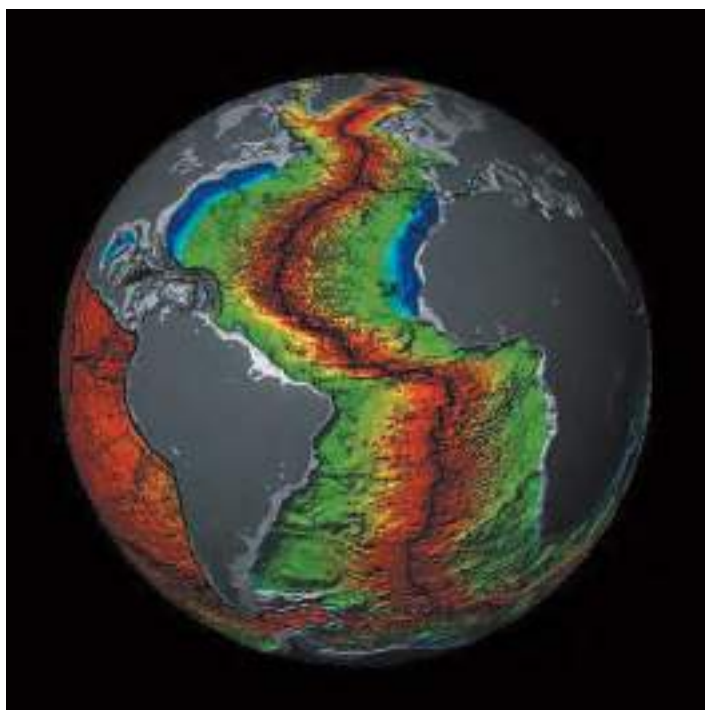


Fig. 1.1.8. Mid-Atlantic Ridge.

The youngest rocks of the oceanic crust are red, the oldest ones are purple

http://www.wikiwand.com/ru/Срединно-Атлантический_хребет

The Hydrosphere. The water shell of the Earth is called the hydrosphere. As of today, the presence of liquid water on the surface of our planet fundamentally distinguishes it from other well-known cosmic objects. The Earth looks like a blue planet, if observed from the space (Fig. 1.1.9, 1.1.10). The waters of the World Ocean cover 361 million km² (~ 71 %) of the earth's surface. The percentage of the water surface area to the land surface area significantly prevails in the southern hemisphere of the planet – 81 : 19, and in the northern hemisphere it is 61 : 39.

The total area of water bodies located on land (glaciers, lakes, swamps, reservoirs, rivers) is ~ 20 million km² or 15 % of its area. At the same time, 96 % of the land area occupied by water bodies falls on glaciers. Of this amount, the area of the Antarctic glaciers is 89.8%, Greenland – 9.7 %, the Arctic Islands – 0.3 %, and all high mountain glaciers occupy only 0.2 % of the land area.

The average depth of the oceans, in which 94 % of the water is concentrated, is 3.68 km. The total volume of the hydrosphere is only 0.13 % of the volume of

the globe. Thus, it can be said that water is a thin film on the surface of the Earth. The existence of earthly life is possible due to water. Most of the planet's water resources are salt waters. The average salinity of the ocean waters is 35 ‰ (35 g of salt per 1 kg of water). There are only 2.5 % of the fresh water on the Earth of total and ~ 69 % of the former is concentrated in frozen glaciers. The amount of water in different parts of the hydrosphere is given in Table 1.1.



Fig. 1.1.9. Photo of the Earth from space (by astronaut Alexander Gerst)
<https://super.abril.com.br/sociedade/enquanto-isso-2/>

As can be seen from the Table above, the rivers are one of the most important water-supply sources today. They are a very small part of the world's freshwater reserves.

The water, which forms the hydrosphere, is a powerful geological factor that influences the appearance of our planet. It promotes both rocks formation and their destruction.

The atmosphere. The gas shell that surrounds the planet Earth is called the atmosphere. The hydrosphere and the Earth's crust are the bottom interface of the atmosphere; the upper one is the altitude of 1300 km where it rotates with the Earth as a single whole. Its density is equalized with the density of the interplanetary space.

Table 1.1

Water reserves on the Earth (Belousova A. P., Gavich I. K., 2006)

Natural water location	Salt water volume, thousand km ³	Fresh water volume, thousand km ³	Average renewal period
Water on the Earth's surface (hydrosphere)			
World Ocean	1 338 000	-	2650 years
Glaciers	-	25 800	9700 years
Lakes	85	91	17 years
Swamps		11	5 years
Reservoirs	-	6	52 days
Rivers	-	2	19 days
Water in the lithosphere			
The groundwater	223 470	10 530	1400 years
Ground ice	-	300	10 000 years
Water in the atmosphere and biosphere			
Atmosphere couples		13	8 days
Water in living organisms	1,12		Several hours
Total water reserves			
Total water reserves	1561 609	36 700	

Nitrogen prevails in the chemical composition of the atmosphere. There are 78 % of nitrogen by volume, 21 % of oxygen, 0.93 % of argon and 0.04 % of carbon dioxide in the shell. The concentration of gases that form the atmosphere is virtually constant except for carbon dioxide and water vapour. The water content in the atmosphere varies from 0.2 % to 2.5 % by volume and it mainly depends on the latitude of the terrain.

A few layers are distinguished in the atmosphere differing in composition, density, temperature, etc.

The lowest layer of Earth's atmosphere, containing ~ 80% of its total mass and 99% of the total water vapour ($1.3\text{--}1.5 \times 10^{13}$ tons) is called *the troposphere* (Fig. 1.11). Its thickness is not the same and depends on the type of climate and some seasonal factors: it can reach 16–18 km in the tropical and equatorial regions, for example, up to 10–12 km in the temperate zone and it is about 8–10 km in the polar regions. Clouds form, cyclones and anticyclones move in the troposphere. The temperature decreases with an average height of 0.65 °C at the increase of every 100 m.



Fig. 1.1.10. Planet Morning

<http://nevseoboi.com.ua/wallpapers-collection/wallpaper-collections/page,2,12594-podborka-oboev-255-60-oboev.html>



Fig. 1.1.11. Troposphere (over the Pacific)

<https://fishki.net/mix/1673269-vid-na-tixij-ocean-iz-samoleta.html>

The stratosphere is the next layer and it is located at the altitude of 11–50 km. It contains about 20% of the mass of the atmosphere. A characteristic feature of the layer is a slight decrease of temperature to the altitude of 25 km (-56.5°C), and then its rise to $+0.8^{\circ}\text{C}$ to the altitude of 40 km; the temperature is constant (about 0°C) further to the altitude of 55 km.

The mesosphere extends from the height of 50 km to 80–90 km. It contains $\sim 0.3\%$ of the total atmospheric mass. The temperature drops by $0.25\text{--}0.3^{\circ}\text{C}$ for every 100 m and reaches the minimum of -100°C . Complex photochemical processes leading to the airglow are observed here.

There is a conventional boarder at the altitude of 100 km, beyond which there is no aeronautics. Therefore, it is a border with the space or *The Kármán line*. Orbital space flights occur at altitudes of 200–500 km.

The layer that is located up to the altitude of 800 km and contains less than 0.05% of the mass of the atmosphere is called *the thermosphere*. The temperature here is very heterogeneous at different levels and can quickly rise to + hundred degrees depending on the solar activity. The rise of temperature stops at the altitude of about 800 km because the gas weakly absorbs the solar radiation because of the sparseness. The thermosphere and the mesosphere form the ionosphere, in which polar auroras appear under the solar wind activity that ionizes molecules (Fig. 1.1.12).

The exosphere or the dispersion zone surrounds the exterior part of the thermosphere. The gas is very rarefied and its molecules leak into the interplanetary space here. The exosphere gradually passes into the interplanetary space. Individual hydrogen atoms, cosmic dust, cometary and meteoric matter particles encounter at the altitude of 2000–3500 km there.

The biosphere presents the parts of the Earth's shells (the uppermost part of the lithosphere, the entire hydrosphere virtually and the lowest part of the atmosphere), which is inhabited by living organisms that influence it. The biosphere began to form ~ 3.8 billion years ago when the first organisms appeared on our planet. There are several million species of plants, animals, fungi and microorganisms in the biosphere today. Living organisms constantly interact with the near-surface shells of the Earth and significantly affect their composition and habitus, that is, they are the most important geological factor.

Austrian geologist Suess singled out the biosphere, which is the Earth's shell where life is concentrated, in 1875 for the first time. However, Academician V. Vernadsky revealed its special significance for geological and geochemical

processes much later. The biosphere surrounds the Earth with a solid shell. The craters of active volcanoes, streams of unfrozen lava and some enclosed bodies of water with a particularly high concentration of salts and acids can be considered temporarily lifeless. The mass of the living organic matter on the Earth is 0.001% of the mass of the Earth's crust according to V. Vernadsky. Most of the mass is the plankton in the ocean. The geological significance of living organisms is enormous. They let through themselves and process a large amount of matter. Organisms let through themselves the amount of carbon that is 10 times greater than all its content in the Earth's crust within 13 years. V. Vernadsky considered all the oxygen in the atmosphere to be a product of the vital activity of organisms. The accumulations of coal, peat, oil, chalk, organogenic limestones, phosphorites, many iron and manganese ores are the result of the vital activity of organisms, as well as soils are the product of their interaction with rocks. About 20–22 chemical elements can be concentrated in significant quantities in organisms. These are Pb, Zn, Ni, Pt, Be, U, rare earths and other elements.



Fig. 1.1.12. Atmosphere Glow

<https://www.dailymail.co.uk/sciencetech/article-1305685/>

[Nasa-astronaut-tweets-spectacular-aurora-photos-taken-Space-Station-window.html](#)

Test questions to chapter 1.1. Earth Basics

1. What shape does the Earth have?
2. The origin of the Earth.
3. The internal structure and composition of our planet.
4. Lithosphere and tectonic plates.
5. Characterization of the continental crust.
6. Characteristics of the oceanic crust.
7. Characterization of the hydrosphere.
8. Layers of the atmosphere.
9. What is the biosphere?

Chapter 1.2. MINERALS

Definition of minerals. Physical and chemical properties.

The origin of minerals. Classification. Application

In the structure of the Earth there are several levels of organization of matter in which the objects of each next stage are formed by a regular combination of objects of the previous stage: mineral – rock – geological formation – geosphere – planet as a whole. The primary objects studied by geology are minerals. One of the main and probably the earliest branches of geology is the science of mineralogy, which studies the variety of minerals, their properties, and physicochemical characteristics. Note that in the middle Ages geology was represented only among the Earth sciences one mineralogy.

The mineral composition determines the physical and mechanical properties of rocks (soils) used as the foundations of buildings and structures or building materials, in this regard, it is of interest for engineering geology and construction.

Minerals are natural formations with a specific chemical composition, structure, and physical properties that are formed as a result of natural physicochemical processes. The bulk of the minerals formed in the bowels of the earth's crust, the smaller – near the earth's surface, some – in space. In addition, man has created a number of artificial minerals used in various fields.

Most minerals are solid inorganic crystalline formations; a much smaller part are in an amorphous, glassy state (for example, opal, flint, and also uranium-containing minerals); rare minerals in liquid state (native mercury).

Currently, the International Mineralogical Association (IMA)¹ has established about 4900 types of minerals. There are up to 7000 kinds of minerals. However, the composition of the earth's crust is dominated by ~ 100 of the most important minerals, which form the basis of rocks and are called rock-forming. The remaining minerals are accessory (sometimes making up to 5 % of the rock) and rare, cases of which are extremely scarce.

Note.

1 MMA (IMA) – The International Mineralogical Association, established April 8, 1958 with the aim of unifying the terms in the field of mineralogy. It unites associate members from 38 countries (as of 01/14/2011). It has, in particular, the Commission on New Minerals, Nomenclature and Classification (CNMNC), which decides which natural bodies can be considered minerals.

Physical and chemical properties of minerals. Each mineral has certain properties that depend on its composition and crystal structure. The main physical characteristics that are used to determine minerals are:

- appearance, form of minerals (crystals, aggregates or amorphous mass);
- optical properties (color, gloss, transparency, stroke color, discoloration);
- physical and mechanical properties (hardness, cleavage, kink, density);
- specific properties.

The shape of crystalline minerals is determined by the crystal lattice – a regular ordered arrangement of atoms, while in amorphous minerals – a random arrangement. The shape of the crystals is an important diagnostic feature for each specific mineral. It can be either simple (flat plates, tetrahedra, cubes), or complex, in the form of a combination of polyhedral prisms, pyramids, volumetric polyhedra (Fig. 1.2.1). It should be noted that minerals in the form of individual crystals are relatively rare, more often there are various intergrowths of two, several or a large number of crystals – mineral aggregates. The following main forms of mineral aggregates are distinguished: twins, brushes, druses, secretions (geodes), nodules, sap forms, granular and earthy masses (Fig. 1.2.2).

Optical properties.

The color of many minerals is strictly constant. For example, albite is white, malachite is green, azurite is blue, sulfur is yellow, cinnabar is raspberry red, etc. (Fig. 1.2.3). Depending on impurities or specific defects in the crystal structure, the color may change. So, quartz is usually white or transparent (rock crystal, Fig. 1.2.1 d), but it can be black (morion, Fig. 1.2.3 d), violet (amethyst, Fig. 1.2.2 c), yellow (citrine, Fig. 1.2.2 b), pink, red, etc. Some minerals, such as Labrador (Fig. 1.2.3 e), have a specific bright blue or green tint called irisation, which is an important diagnostic feature.

Shine is the ability of minerals to reflect light on their surface. There are two main types of gloss – metallic and non-metallic. Metallic luster is characteristic for minerals containing metals and it can be iron (hematite, Fig. 1.2.2 g), silver, golden (pyrite, native gold), lead (galena), dull (limonite), etc.

Varieties of non-metallic luster: – glass, which is characteristic of almost all varieties of quartz (Fig. 1.2.1 d, 1.2.2 b, c, d, 1.2.3 d), as well as for albite (Fig. 1.2.3 a) and other feldspars; – pearlescent (muscovite, Fig. 1.2.1 a); – bold (talc); – diamond (diamond), etc.

Transparency – the ability of minerals to transmit light. Three groups of minerals are distinguished by transparency: 1 – transparent (muscovite,

rock crystal, etc.); 2 – translucent (gypsum, chalcedony, halite, calcite, etc.); 3 – opaque (graphite, magnetite, hematite and other metal-containing minerals).



a



b



c



d



e

*Fig. 1.2.1. Various forms of crystals:
a – thin plates, sheets of muscovite (light mica);
b – cubic crystals of halite (rock salt);
c – is the combination of prisms and pyramids in native bismuth;
d – crystals of various forms (Vienna Museum of Nature);
e – hexagonal pyramid and prism near rock crystal (transparent quartz)*

a <https://ppv.k.me/c624930/v624930843/14138/zZLvnDIqaCg.jpg>

b <http://ok-t.ru/studopediaru/baza6/485137901270.files/image016.jpg>

c http://img1.liveinternet.ru/images/foto/c/9/apps/2/894/2894029_qt_4.jpg

d Photo by V. Novgorodov

e http://geo.web.ru/druza/m-Q_30-1.JPG



Fig 1.2.2. Mineral aggregates: **a** – staurolite doubles; **b** – hematite; **c** – druse of calcite in the amethyst geode; **d** – druse of actinolite; **e** – nodules of chalcedony; sinter forms; **f** – malachite

a http://geo.web.ru/druza/m-stavr_3_DSC00708.JPG;

b <https://catalogmineralov.ru/sample-all/gematit.html>;

c <http://media.snimka.bg/images/001879206-big.jpg>;

d http://geo.web.ru/druza/m-antim_5_Mu08_227_Moi.jpg;

e http://geo.web.ru/druza/m-chalc_0-1.JPG;

f http://img-fotki.yandex.ru/get/28/ilm.0/0_126f2_22f6b6a9_XL.jpg

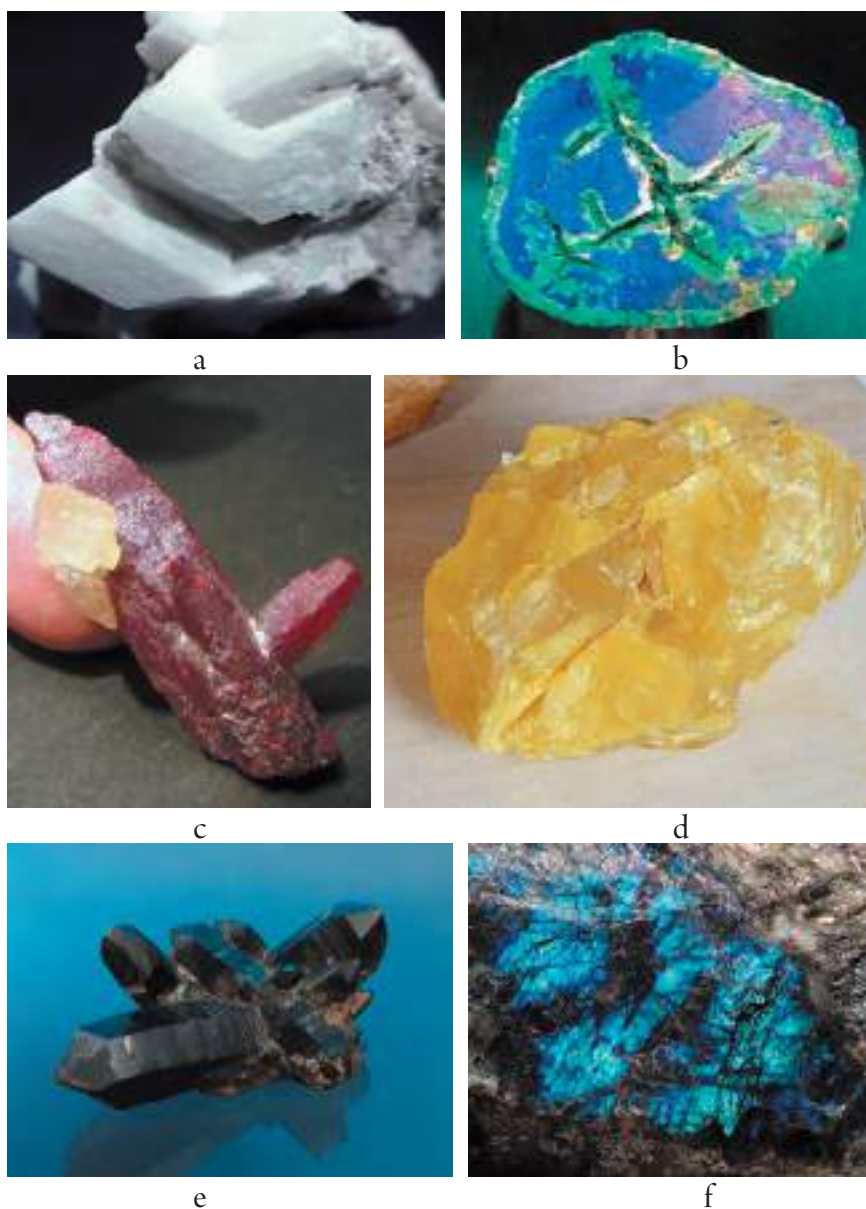


Fig. 1.2.3. Colors of minerals: **a** – white albite; **b** – blue azurite with green malachite; **c** – raspberry red cinnabar; **d** – is yellow native sulfur; **e** – is morion (black quartz); **f** – labrador irisation

a http://www.iu.edu/~geol105/images/gaia_chapter_5/rock_forming_minerals.htm

b http://geo.web.ru/druza/m-azu_14Kz_6004_mal.jpg

c http://geo.web.ru/druza/m-kinov_17_5511.jpg

d <http://cdn01.ru/files/users/images/1b/c1/1bc1e31d0ae3b0343868aa00e807a24e.jpg>

e <http://macroclub.ru/gallery/data/777/3593.jpg>

f http://hend-made.ru/wp-content/uploads/2013/11/98869138_large_ph05578.jpg

The color of the dash is the color of a fine mineral powder. Determined by drawing traits on a rough porcelain plate. The color of the mineral and the color of the stroke can vary significantly, in which case this is an important diagnostic feature. So, hematite (Fig. 1.2.2 g), has an almost black color, and its color is cherry red.

Degeneration is a thin, often multi-colored, film that forms on the surface of some minerals due to oxidation (decontamination on native bismuth, Fig. 1.2.1 c).

Physico-mechanical properties.

Hardness – the ability of minerals to withstand mechanical stress. This property is one of the main for the determination of minerals. As early as 1811, a 10-point scale was proposed by German natural scientist Friedrich Moos to evaluate hardness, which has been successfully used to date with indicative or field definitions. Hardness is determined by scratching the test sample with other minerals with known hardness or common objects (nail, glass, etc.). The Moos scale with some additional characteristics and images is given in table. 1.2.1, Fig. 1.2.4.

The first seven minerals, from talc to quartz, are rock-forming and widely distributed; and the eighth is the tenth: topaz, corundum and diamond are rare. It should be noted that Moos hardness, from one to ten, is only a relative value. The true hardness of minerals differs by tens and hundreds of times (Tab. 1.2.1).

Table 1.2.1

Minerals hardness scale according to F. Moos

Mineral reference; chemical composition	Relative hardness and (true hardness, MPa)	Simplified test; characteristic properties	Image and short description
1	2	3	4
Talc $Mg_3Si_4O_{10}(OH)_2$	1 (24)	Easy to scratch with a fingernail; greasy to the touch	 Fig. 1.2.4: a – talc aggregates and powder

PART I. THE ELEMENTS OF GENERAL GEOLOGY

Table continuation 1.2.1

1	2	3	4
Gypsum $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	2 (369)	Scratched with a fingernail; forms layered masses, forked crystals; soluble in water	 b – crystals of gypsum, Donbass, Ukraine
Calcite CaCO_3	3 (1090)	Scratched by a copper coin (soft metal); boils under the influence of acids	 c – sintered form of calcite, Uzbekistan
Fluorite CaF_2	4 (1890)	It is easily scratched with a nail (iron); color is white, violet, green; easy to melt	 d – fluorite vein, Transbaikalia
Apatite $\text{Ca}_5(\text{PO}_4)_3(\text{OH}, \text{Cl}, \text{F})$	5 (5360)	Scratched by a steel knife; forms blue-green crystals and earthy masses	 e – apatite crystal in the form of an irregular hexagonal prism and pyramid, Slyudyanka, Baikal

Table continuation 1.2.1

1	2	3	4
Orthoclase $KAlSi_3O_8$	6 (7950)	It is scratched by glass; a right angle between cleavage planes is characteristic	 f – pink orthoclase, England
Quartz SiO_2	7 (11 200)	Scratches glass; the most common of solid minerals	   g – types of quartz: transparent – rock crystal; milky white (most common); color: citrine, carnelian, agate, etc.
Topaz $Al_2SiO_4(OH, F)_2$	8 (14 270)	Resists diamond processing. The colors are warm hues: honey, reddish, less often – blue	 h – topaz, Volodarsk-Volynsky, Ukraine

PART I. THE ELEMENTS OF GENERAL GEOLOGY

Table continuation 1.2.1

1	2	3	4
Corundum Al_2O_3	9 (20 600)	Resists diamond processing. The hardest mineral after diamond	 i – red corundum – ruby, Malaysia
Diamond C	10 (100 600)	Not scratched by anything. Cuts glass; hardest natural mineral	 j – 'Shah' diamond, India

a <http://1.bp.blogspot.com/-WIrqTR5qbGY/TnyD-xRP73I/AAAAAAAAAqk/hj8eSWbo1e0/s1600/China+clay.jpg>

b Photo by V. Iegupov

c Photo by V. Iegupov

d <http://bizhu-blackcat.ru/up/article/img/spravohnic/fluorit.jpg>

e Photo by V. Iegupov

f <http://chinaneolithic.com/en/mineral/photos.asp?ID=260>

g <https://www.ezinekalidoscope.com/tag/clear-quartz/>

<http://www.oooarsenal.ru/post.php?id=19723>

<http://jacarebijoux.beepworld.it/files/agata.jpg>

h http://geo.web.ru/druza/m-topz_6_5938.JPG

i http://geo.web.ru/druza/m-corun_7_3280_Rai.JPG

j http://rutravel.net/uploads/posts/2015-03/1426610426_12793_original.jpg

Cleavage – the ability of minerals to crack in strictly defined directions, called cleavage planes. It depends only on the internal structure of the mineral and does not depend on the shape of its crystal. The following types of cleavage are:

- very perfect, possessing which the mineral is easily split into thin plates (minerals with a layered structure: mica (Fig. 1.2.1 a), graphite, etc.);
- perfect, in which the crystals break into thicker plates, parallelepipeds, cubes with smooth surfaces (calcite, galena (Fig. 1.2.5 a), orthoclase, microcline (Fig. 1.2.5 b));
- imperfect – the cleaved surface is uneven (apatite, nepheline,) and is difficult to detect;
- very imperfect – the mineral has practically no cleavage (quartz, magnetite).

Cleavage or cleaving planes can occur in one, two or more directions (prism, rhombohedron, cube, etc.)

A *kink* is a type of mineral fracture surface that is formed when it is not fractured along cleavage planes. The types of fractures found in various minerals are as follows: even, uneven, stepwise, conchoid (Fig. 1.2.5 c), splinous (Fig. 1.2.5 g), earthy, etc. The density of minerals varies widely from 0.917 g / cm^3 (the lightest mineral is ice) to 22.84 g / cm^3 (the heaviest mineral is platinum iridium). Density values of minerals can be divided into 4 groups (in g / cm^3):

1. Low (less than 3): sylvite – KCl (2.0); Halite – NaCl (2.1); gypsum – $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (2.3).
2. Medium (3–5): fluorite – CaF_2 (3.2); chalcocite – Cu_2S (4.2); Barite BaSO_4 (4.5).
3. High (5–10): galena – PbS (7.5); wolframite – $(\text{Fe, Mn}) [\text{WO}_4]$ – (7.4).
4. Very high (> 10): gold – Au (19.3), platinum – Pt (21.5).



a



b

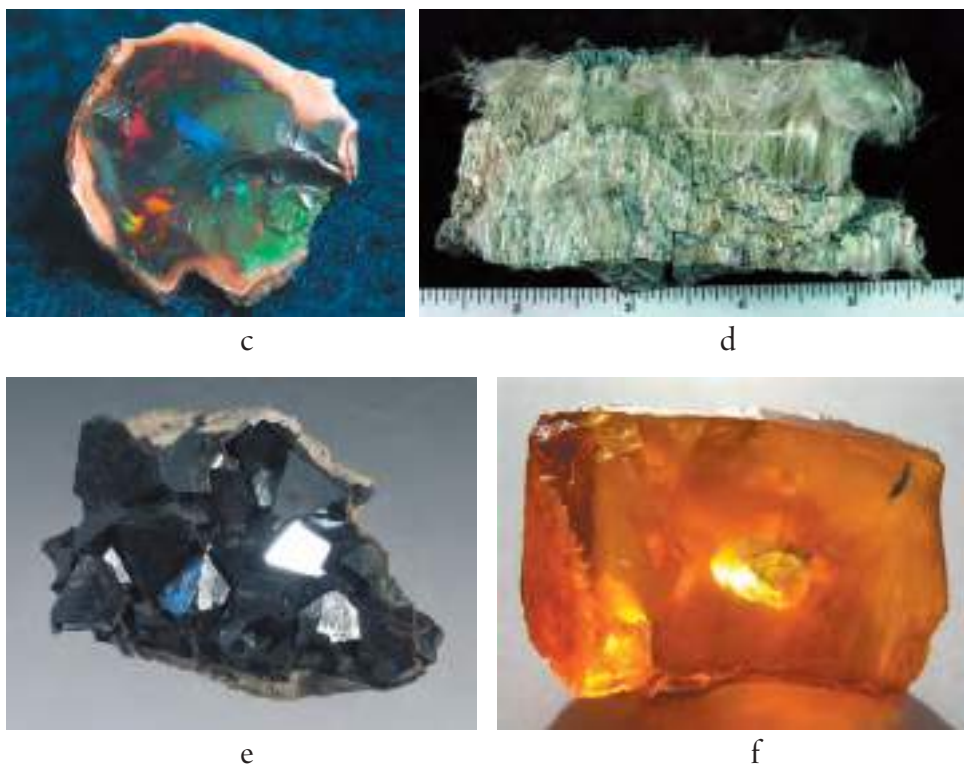


Fig. 1.2.5. Cleavage, fracture, density of minerals:

- a** – galena (perfect cleavage in a cube);
- b** – amazonite – a green variety of microcline (cleavage plane at an angle of 70°);
- c** – opal (a shell fracture is characteristic);
- d** – chrysotile-asbestos (needle-shaped fracture is characteristic);
- e** – magnetite (high-density mineral – $4.9\text{--}5.2\text{ g/cm}^3$);
- f** – amber (low-density mineral – $1.05\text{--}1.09\text{ g/cm}^3$)

a <http://svoystvakamney.ru/wp-content/uploads/2015/10/kamen-galenit1.jpg>

b http://geo.web.ru/druza/m-amaz_25-2.JPG;

c <http://i.imgur.com/xFRDwSn.jpg>

d <http://www.catalogmineralov.ru/collections/244-7.html>

e http://4.bp.blogspot.com/-MSKbVLTMuwY/VBDNWH-leFI/AAAAAAAABog/NSi4NkKaxGE/s1600/Magnetyt1,_Boliwia.jpg

f <http://mtdata.ru/u5/photo60A1/20892373710-0/original.jpg>

Some minerals have special properties by which they can be determined. These properties include:

- *fragility* – the ability to easily collapse upon impact (sulfur, apatite). Some very hard minerals can crack during abrupt mechanical stress, in particular diamond, i.e. be fragile;
- *malleability* – the ability to flatten during impacts. The most malleable mineral is gold, from which sheets up to 0.1 microns thick can be forged. Less malleable native copper, silver;
- *elasticity* – the ability to change shape under the influence of force and restore it after the termination of exposure. Elastic minerals – mica (biotite, muscovite, etc.);
- *specific optical properties*: irradiation of a labrador (Fig. 1.2.3 f); opal fluorescence (Fig. 1.2.5 c); birefringence in Icelandic spar (transparent calcite) (Fig. 1.2.6 a);
- *reaction with hydrochloric acid*. When a drop of HCl is applied to some minerals, carbon dioxide bubbles are released; in this way, minerals of the carbonate class – calcite and dolomite – react;
- *fusibility and combustibility*. Sulfur and amber easily melt and light up;
- *organoleptic properties*: fat content – determined by touch (talc, kaolinite have fat content); Odor: sulfur has a characteristic odor; garlic odor arises when striking minerals containing arsenic (beetroot, Fig. 1.2.6 b); taste: salty taste has halite; bitter – mirabilite (Fig. 1.2.6 c); burning, bitter-salty sylvite (Fig. 1.2.6 g);
- *magnetism*. This property is possessed by magnetite, native iron;
- *radioactivity*. Minerals containing isotopes of uranium, thorium, in particular uraninite, are radioactive (Fig. 1.2.6 e).

The origin of minerals. The main processes of the formation of minerals in nature are endogenous, exogenous and metamorphic.

The endogenous process (from the Greek. Endon – inside genesis – origin) occurs during slow solidification of magma in the bowels of the earth's crust. Magma (from the Greek. Magma – thick ointment) is a molten fire-liquid mass of predominantly silicate composition that forms in the earth's crust or upper mantle. It consists of compounds of a large number of chemical elements, among which Si, Al, Fe, Mg, Mn, Ca, Na, K, O, N, S, Cl, F predominate. Along with cations, anions are present in magma, most often represented by silicon compounds and oxygen in the so-called silicon oxygen tetrahedron SiO_4^{4-} .



a



b



c



d



e

Fig. 1.2.6. Specific properties of minerals:
a – Icelandic spar – a transparent variety of calcite has birefringence;
b – scorodite (when you hit it there is a strong smell of garlic);
c – sylvite has a pungent bitter-salty taste;
d – mirabilite (Glauber's salt) has a bitter taste;
e – uraninite has radioactivity.

a <https://pro-kamni.ru/islandskij-shpat>

b <https://shuwany.rs/2015/03/%D1%81%D0%BA%D0%BE%D1%80%D0%BE%D0%B4%D0%B8%D1%82/>

c <https://slide-share.ru/klassifikaciya-mineralov-150232>

d http://khrulev.ucoz.ru/_si/0/10904844.jpg

e <https://upload.wikimedia.org/wikipedia/commons/4/4e/Uraninite-39029.jpg>

Crystallization of magma begins when the melt cools to 900–800 ° C, and the bulk of the minerals are formed at temperatures of 800–600 ° C. This process is called pegmatite. The depth of mineral formation of pegmatite associations is ~ 6–15 km. At an early stage of the endogenous process, magnetite, pomegranate, spinel, olivine, anorthite are formed. In the main stage, pyroxenes, hornblende and some plagioclases crystallize; at the end – mica, orthoclase, quartz, albite. Gemstones (tourmaline, topaz, zircon, beryl), as well as ore minerals of rare elements – cesium, tantalum, niobium, are sometimes found in cavities inside pegmatite formations.

At the last stage of magma crystallization, the residual portions of the solidifying melt are carbonated fluid (according to A. E. Fersman). It has great mobility and is enriched in volatile (H_2O , HF , B_2O_3 , CO_2) and other components (Li, Be, etc.). The final stage of the endogenous process is the formation of minerals from hot aqueous mineralized (hydrothermal) solutions. The maximum depths of hydrothermal minerals are about 5 km, and the minimum are right up to the surface of the earth. The form of deposits most often takes the form of veins (filling cracks in the rocks). The crystallization temperature ranges from 500 to 50, and even 20 ° C. Gangue minerals are: quartz, calcite, dolomite, fluorite. Ores are often found in the veins – tungsten, sphalerite, galena, pyrite, gold, antimonite, cinnabar, etc.

Some minerals become solid directly from the gaseous state, for example, native sulfur, cassiterite (tin stone), and boron compounds.

Exogenous (from the Greek. Exo – outside, outside) are the processes of formation of minerals occurring on the surface of the Earth or near it. Various minerals and rocks that have fallen into surface conditions as a result of mountain building or other tectonic processes, under the new conditions, undergo weathering – destruction and changes in composition. As a result, the weathering crust forms on the surface, which is an accumulation of products of altered rocks and minerals. In particular, in the weathering crust due to changes in feldspar rocks (granites), aluminum and iron oxides and hydroxides are formed – bauxites; clay minerals (kaolinite, montmorillonite) appear in a similar way. Insoluble minerals remain in place or can be moved with the help of water currents, wind. In this way, various placers are formed, the typical minerals of which are quartz, gold, cassiterite, rutile, garnets, and others. Chemical compounds dissolved by surface water can move into the deep horizons of the weathering crust and precipitate there. So there are clusters of siderite, uranium ores, phosphates, copper sulfides. If

dissolved chemical compounds are carried away by rivers into water bodies, then they give rise to chemical sedimentary minerals (calcite, dolomite, etc.). Minerals arising from the evaporation of water in dry climates from high salinity basins are represented by gypsum, halite, and sylvin. Exogenous minerals also include minerals of biological origin, which are formed in the seas and other bodies of water due to the fossilized organic remains of organisms. Biogenic minerals are calcite and aragonite, formed from corals and shells of mollusks; opal composed of siliceous skeletons of microorganisms; amber, which is a petrified resin of coniferous trees, etc.

The metamorphic process takes place during tectonic transformations, covering large regions. Rocks and minerals, which were previously formed as a result of endogenous and exogenous processes, descend to great depths – in the region of high temperatures and pressures. Under such conditions, they become unstable and undergo changes – metamorphism. The processes of regional metamorphism occur at great depths (up to 20 km) and at high temperatures (500–900 °C), but without melting (!). The pressure of the overlying rocks can reach 10,000 atm. The main methods of mineral formation in regional metamorphism are the processes of dehydration (dehydration), recrystallization, and compaction. An increase in temperature helps to remove water from pre-existing minerals: for example, limonite ($\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$) is converted to hematite (Fe_2O_3); opal ($\text{SiO}_2 \cdot n\text{H}_2\text{O}$) – into quartz (SiO_2). Recrystallization leads to the conversion of coal to graphite, phosphorite to apatite. When compacted, low-density minerals are converted to high-density minerals: albite ($\text{NaAlSi}_3\text{O}_8$), $\rho = 2.7 \text{ g / cm}^3$ – into jadeite ($\text{NaAlSi}_2\text{O}_6$), $\rho = 3.3 \text{ g / cm}^3$; dolomite $\text{CaMg}(\text{CO}_3)_2$, $\rho = 2.8 \text{ g / cm}^3$ – into tremolite $\text{Ca}_2\text{Mg}_5[\text{Si}_8\text{O}_{22}](\text{OH})_2$, $\rho = 3.0 \text{ g / cm}^3$.

Classification of minerals. By the 30s of the twentieth century, a crystal chemical classification was developed, the basis of which is the chemical composition and structural (crystal chemical) features of minerals. Currently, the modern version of this classification recommended by the International Mineralogical Association (IMA) is generally accepted. According to it, 19 classes of minerals are distinguished, in addition, there are subclasses, families, and other systematic units. A simplified classification with examples of minerals is given in Table 1.2.2.

It should be emphasized that, as can be seen from Table 1.2.2, three quarters of the mass of the earth's crust are silicates, including feldspars more than half. More than 12 % of the mass of the earth's crust is quartz (SiO_2), which, according to some classifications, is also referred to as silicates. Thus, the stone shell of

the Earth consists mainly of silicon-oxygen compounds. The basis of the crystal lattice of silicates is the silicon-oxygen tetrahedron (SiO_4)⁺ (Fig. 1.2.7), to which, thanks to four free valence bonds, atoms Al, Fe, Ca, Ni, etc., as well as other tetrahedra can be attached. So, among the crystalline lattices of silicates, isolated structures (island and ring), chain and ribbon, layered (Fig. 1.2.8) and bulk framework (Fig. 1.2.9) are found.

Table 1.2.2

Mineral classification

Type of minerals	Class his IMA number; mass content of the earth's crust	Characteristic minerals; chemical formula
1	2	3
I. Single atom	1. Native elements 0.1 %	Native metals (gold Au, silver Ag, copper Cu, mercury Hg, platinum Pt, as well as Ru, Rh, Pd, Os, Ir, Fe, Ni); native metalloids (arsenic As, antimony Sb, bismuth Bi); non-metals (sulfur S, Se, Te, (diamond, graphite C).
II. Sulfides and similar compounds (arsenides, etc.); sulfosalts	2. Sulfides 0.3–0.4 % (together with sulfates). 3. Sulfosalts	Pyrite (sulfur or iron pyrites) FeS_2 , chalcopyrite, CuFeS_2 , galena PbS , sphalerite ZnS , cinnabar HgS .
III. Halide compounds (halides)	4. Halides (chlorides, fluorides, bromides, iodides); 0,5 %	Halite NaCl , fluorite CaF_2 sylvin KCl .
IV. Oxides and Hydroxides	5. Oxides. 6. Hydrooxides; About 17 %, including quartz 12.6 % (together with chalcedony and opal); iron oxides and hydroxides 3.6 %.	Quartz SiO_2 , corundum Al_2O_3 , hematite Fe_2O_3 , Opal $\text{SiO}_2 \cdot n\text{H}_2\text{O}$, limonite (brown iron) $\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$.
V. Arsenites and their analogues	7. Arsenites and their analogues (sulfites, antimonites, tellurites)	Auripigment As_2S_3 , antimonite Sb_2S_3
VI. Oxygen Salts (Oxisols)	8. Carbonates (1.7 %); 9. Nitrates 10. Borates 11. Sulfates 12. Chromates 13. Molybdates 14. Tungstates	dolomite $\text{CaMg}(\text{CO}_3)_2$, malachite $\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$. Nitronatrite (sodium nitrate) NaNO_3 . Tincal ("borax") $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$. Gypsum $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, anhydrite CaSO_4 , mirabilite $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$. Calcite CaCO_3 , magnesite MgCO_3 , Crocoite $\text{Pb}[\text{CrO}_4]$. Poellit CaMoO_4 .

PART I. THE ELEMENTS OF GENERAL GEOLOGY

Table continuation 1.2.2

1	2	3
	15. Phosphates (0.7%) 16. Arsenates 17. Vanadates 18. Silicates (~ 75 %, including feldspars 55 %): A. Island silicates. B. Ring silicates B chain silicates G. Tape silicates. D. Layered silicates. D. Frame silicates.	Wolframite is a group of minerals of the composition (Fe, Mn, Mg) WO_4 . Apatite $\text{Ca}_5(\text{F, Cl})(\text{PO}_4)_3$. Erythrin $\text{Cu}_2(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$, scorod Fe $(\text{AsO}_4) \cdot 2\text{H}_2\text{O}$. Vanadinite $\text{Pb}_6[\text{VO}_4]_3\text{Cl}$ Olivines, garnets, zircon, topaz, staurolite, orthite, rhodonite etc. Beryl (a variety of emerald), tourmaline; Pyroxenes (enstatitis, hypersten, diopside, augite, etc.) Amphiboles (actinolite, jadeite, hornblende, etc.); Talc, serpentine, chrysotile asbestos, mica (muscovite, phlogopite, biotite), hydromica (vermiculite, glauconite), chlorites, clay minerals (kaolinite, montmorillonite, etc.); Feldspars: potassium (microcline, orthoclase), calcium-sodium: (albite, anorthite, labrador); nepheline and others
VII. Organic compounds	19. Organic compounds	Amber, pearls, jet, ozokerite (mountain wax)

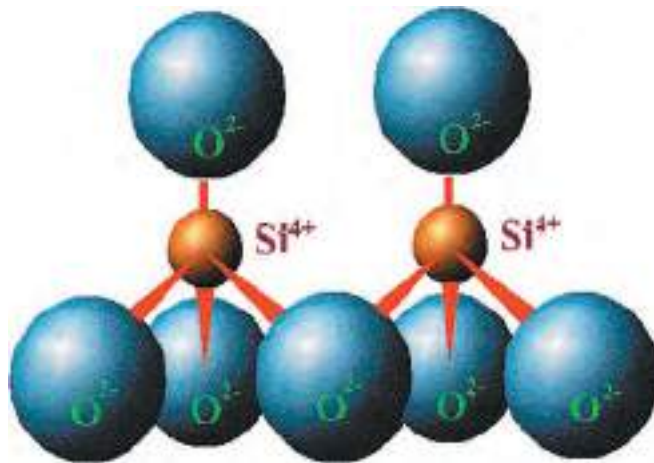


Fig 1.2.7. Silicon Oxygen Tetrahedra SiO_4^{4-}

<https://docplayer.biz.tr/45139826-T-c-gnonu-ungversgtesg-fen-bglgmrg-enstgtusu-kontrollu-polgmergzasyon-yontemgyle-organgk-anorgangk-polgmergk-kompozgt-malzemelergn.html>

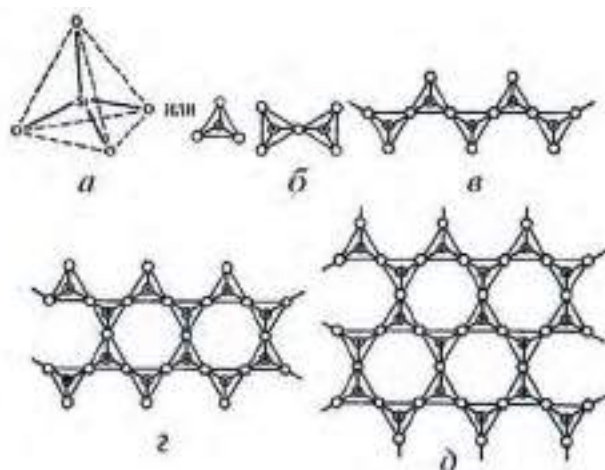


Fig. 1.2.8 Types of structures of silicates:
a, b – island, **c** – chain, **d** – tape (from rings), **d** – ayered
http://www.krugosvet.ru/images/1011871_1871_301.gif

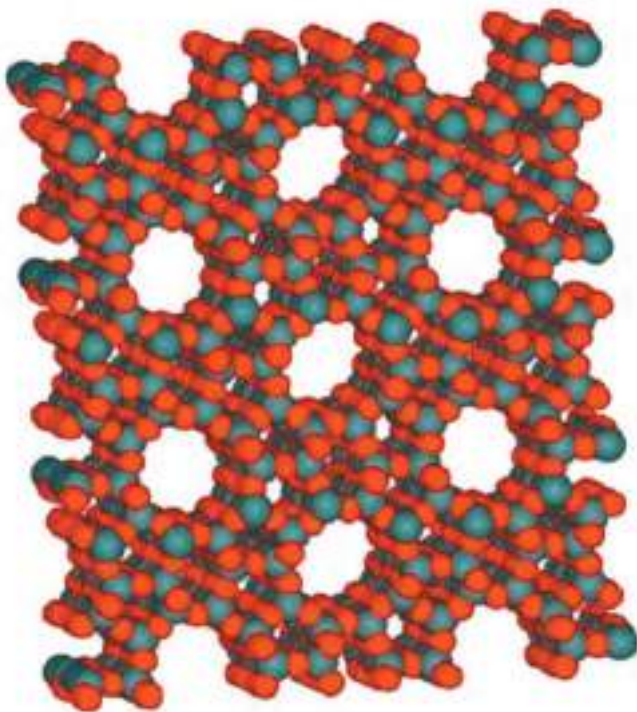


Fig. 1.2.9. Molecular model of the zeolite skeleton structure
http://bilder.afterbuy.de/images/NPNWRQ/00_40080_Zeolite.jpg

The use of minerals. Modern civilization on Earth is based on the use of minerals. Starting from the first primitive tools made of flint, producing fire using it, to the most advanced microcircuits, also made on a silicon basis (!). All metal products are made from ore minerals mined at different times from the earth's crust. All stone buildings and structures are built from building materials made from mineral raw materials. The basis of modern artificial materials is also made up of natural minerals and substances. Here we give only some of the most important and common examples of the use of natural minerals in construction and industry (Tab. 1.2.3).

Table 1.2.3

The use of major minerals

Minerals	Industrial applications
Quartz	The main component of sand is aggregate of cement and concrete mortars. Production of glass, porcelain, refractories. Metallurgy. Rhinestone – in optics and precision instruments; agate, chalcedony and other colored varieties – ornamental stones. Raw materials for pure silicon for microcircuits, semiconductors, especially durable SiC materials
Feldspars: albite, anorthite, microcline, orthoclase, labrador	A component of stone building materials: rubble stone, crushed stone, facing slabs; raw materials for the ceramic and glass industry. Labrador – valuable facing material
Nepheline, augite, hornblende	A component of stone building materials
Biotite, Muscovite	A component of stone building materials; manufacture of electrical insulation boards; heat resistant plates
Kaolinite	It is part of the clay. The main raw materials for ceramics, porcelain, faience. Refractory production. Paper and oil industry.
Montmorillonite	It is part of the clay. It swells heavily in water. Refining petroleum products and reducing water hardness. Production of waterproof concrete. Paper, rubber, perfumery industry.
Talc	Production of electrical insulation, acid and refractory materials. Paper, rubber, perfumery industry. The medicine.
Calcite	Production of lime and cement. In metallurgy as a flux. Icelandic Spar – in Optics
Dolomite	Building stone. Production of hydraulic lime and refractories.
Magnesite	Production of refractory bricks, grinding wheels, extra-strong plaster. Medicine (medicine magnesia)
Magnetite, limonite (brown iron), siderite, hematite	The main iron ore. Limonite is the raw material for the production of yellow ochre paint.
Pyrite (iron or sulfur pyrite)	Raw materials for the production of sulfuric acid. Harmful admixture in building materials, as when interacting with water forms H_2SO_4 , which destroys cement
Chalcopyrite	Basic copper ore
Galena	Ore for lead and silver. Production of white lead

Table continuation 1.2.3

Minerals	Industrial applications
Sphalerite	Ore for zinc. Production of zinc oxide
Cinnabar	The main ore for mercury. Making red paint
Wolframite	Raw materials for the extraction of tungsten for hard alloys, incandescent lamps, welding electrodes
Gypsum	It is widely used in construction as a part of putty, putty, stucco molding, drywall; molding material. The medicine. Paper and chemical industry. Fertilizer production
Barite	Chemical industry and medicine – obtaining barium preparations. Weighting of drilling fluids. Part of the plaster of X-ray rooms
Mirabilite (Glauber's salt)	Chemical, glass industry. The medicine
Halite (rock salt)	The main source of salt in the food industry and technology. Raw materials for the production of chlorine, soda and hydrochloric acid.
Sylvin	Chemical, glass industry. The medicine. Soap making.
Fluorite (fluorspar)	In metallurgy as a flux. In the chemical industry for fluorine and hydrofluoric acid. Making enamels and glazes.
Apatite	Production of phosphate fertilizers, matches, phosphorus, ceramics
Graphite	Production of pencils and paints; electrodes, melting crucibles, lubricants. Neutron moderator in nuclear reactors
Diamond	Stone industry. Metal and glass cutting. Drilling wells in extremely hard formations
Sulfur	Chemical, paper, rubber industry. Agriculture. The medicine

Test questions to chapter 1.2. Minerals

1. Definition of the term “mineral”.
2. The main physical characteristics that are used to determine minerals.
3. Forms of minerals.
4. Optical properties.
5. Mechanical properties.
6. The scale of the hardness of minerals according to F. Moos.
7. What is cleavage and fracture of minerals?
8. The density of minerals.
9. Characterization of the specific properties of minerals.
10. The main processes of the mineral formation in nature.
11. The endogenous process of mineral formation.
12. The exogenous process of mineral formation.
13. Metamorphic process of mineral formation.
14. The principles of classification of minerals.
15. The main classes of minerals.
16. Examples of the use of minerals.

Chapter 1.3. ROCKS

Definition, classification and origin of rocks. Igneous rocks. Sedimentary rocks. Metamorphic rocks. Use of rocks.

Rocks are natural associations of minerals that compose various geological formations and the earth's crust as a whole. Composition, physical properties of rocks, their origin and occurrence form are studied by the science of "petrology" (from the Greek πέτρος – stone). In Russian-speaking countries, the term "petrography" is more often used.

Currently, there are about 1000 different rocks in the earth's crust, which differ in the content of the main rock-forming minerals. *Polymineral* rocks consist of several minerals, for example, granite includes quartz, orthoclase, hornblende, biotite; basalt consists mainly of feldspars, augite, olivine. *Monomineral* rocks consist of one mineral, for example: limestone and chalk consist of calcite; rock salt – from halite.

The structure of the rocks is characterized by their structure and texture. The structure of the rock is determined by the internal structure and state of the mineral substance, which can be crystalline, amorphous, clastic, organogenic, as well as the size and shape of the mineral grains or fragments of the rock. The texture characterizes the appearance of the rock, and it is due to the location in space of minerals, crystalline grains or debris.

According to their genesis (origin), all rocks are divided into three main groups:

1. Magmatic (primary).
2. Sedimentary (secondary).
3. Metamorphic (transformed).

Igneous rocks make up 60–65% of the mass of the earth's crust, about 30% are metamorphic, the remaining 5–10% are sedimentary rocks, but the latter occupy up to 75% of the earth's surface. In the history of the Earth, igneous rocks began to appear first during the solidification of magma, sedimentary ones appeared as a result of the weathering (destruction) of primary igneous rocks; metamorphic rocks were formed from pre-existing igneous and sedimentary rocks as a result of their deep modification under the influence of high temperatures and pressures.

The cyclic processes of formation, destruction and alteration of rocks have been ongoing continuously since the advent of the Earth and are ongoing. A diagram illustrating these processes is shown in Figure 1.3.1.

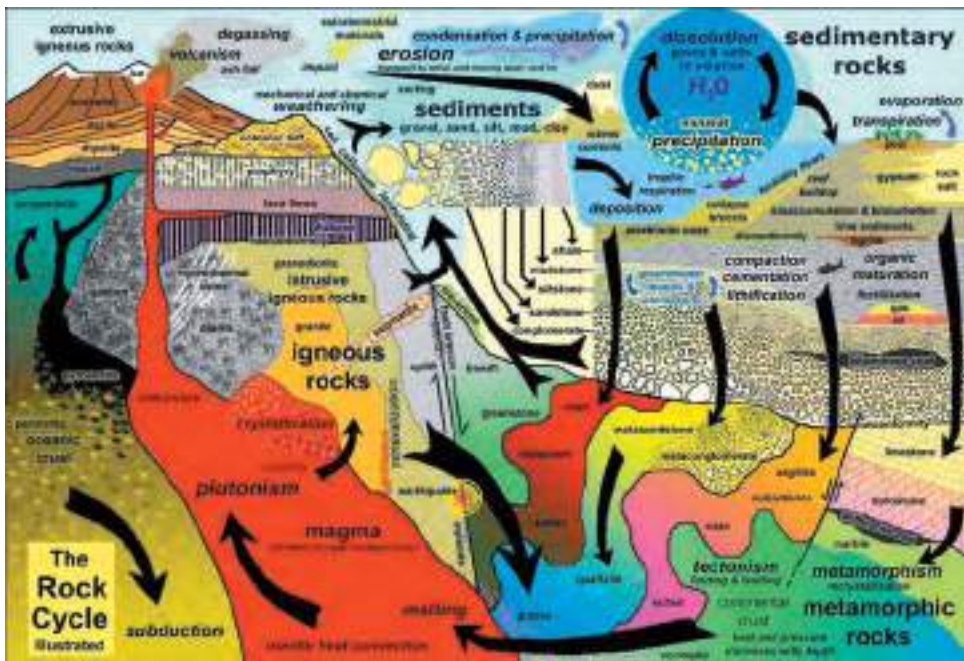


Fig. 1.3.1. The processes of formation, destruction and alteration of rocks

https://earth.usc.edu/~luska/Docs/GEOL115/LECTURES/5-Earth_Materials_rocks.pdf

Igneous rocks

Igneous rocks are formed as a result of solidification of magma – a fiery-liquid silicate melt, which begins when the temperature of magma drops below ~ 1000°C. In the deep parts of the earth's crust, magma cools slowly, stratifies, crystallizes well, and crystalline granular rocks are formed from it, which are called *intrusive* or deep, such rocks as various granites, as well as gabbro, syenite, diorite, etc. (Fig. 1.3.2). These rocks are characterized by granular (full crystalline) structures and homogeneous textures. Intrusive rocks occur in the earth's crust in the form of continuous massifs: batholiths, stocks, laccoliths, and other bodies.

Magma, poured onto the earth's surface in the form of lava of volcanoes, cools quickly (part of it does not have time to crystallize, but hardens in the form of volcanic glass), forming *effusive* or igneous rocks – basalt, andesite, trachyte, liparite, etc. (Fig. 1.3.3). The structures of these rocks are semi-crystalline or glassy, the textures are heterogeneous, banded, and slag. Volcanic tuffs and tuff breccias, which are cemented solid products of volcanic eruptions – ashes, lapilli (formations from solidified lava 1–5 cm in size), volcanic bombs (from a few centimeters to 7 m in size), also form at the same time. Effusive rocks often occur in the form lava flows and covers, make up volcanic cones.



Fig. 1.3.2. Igneous intrusive rocks: **a** – varieties of granite; **b** – gabbro; **c** – syenite; **d** – granodiorite; **e** – “foggy mountains” on the moon, consisting of anorthositis; **f** – a kind of anorthositis – labradorite

a <http://1-gc.ru/image/data/info/articles3/granit-porody.jpg>

b <http://www.stroyteh.ru/file/wiki/image/2/8k/Gabbro/original.jpeg?1>

c <http://0.tqn.com/d/create/1/S/V/K/2/-/DSC01218.JPG>

d http://geo.web.ru/druza/m-Mi_13_5329_graf.jpg

e http://investments.academic.ru/pictures/investments/img1983903_Tumannye_gornye_porodyi_na_Lune.jpg

f http://dic.academic.ru/pictures/wiki/files/65/Anorthosit_fin.jpg

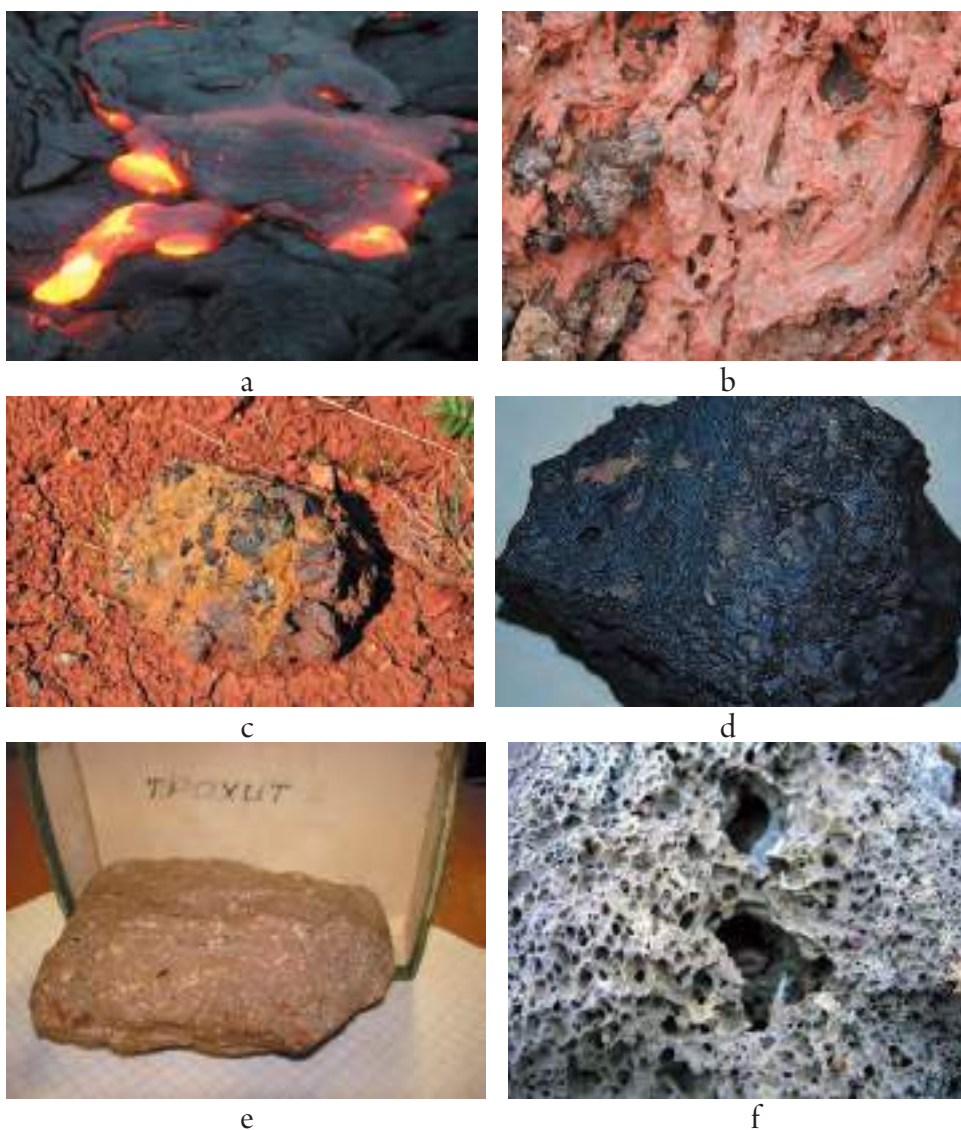


Fig. 1.3.3. Igneous effusive rocks and their formation: **a** – solidification of lava; **b** – solidified lava; **c** – volcanic breccia; **d** – basalt – the strongest rock in the upper part of the earth's crust; **e** – trachyte – acid-resistant building stone; **f** – volcanic tuff having a slag texture

a http://images.slideplayer.com.br/5/1587426/slides/slide_13.jpg

b Photo by A. Yegupov

c Photo by A. Yegupov

d <http://space1004.cafe24.com/bbs/data/photo/jigak28.jpg>

e http://investments.academic.ru/pictures/investments/img1984891_trahit.jpg

f http://investments.academic.ru/pictures/investments/img1983915_Vulkanicheskaya_poroda.jpg

The most characteristic substance in the composition of various magmas and igneous rocks is silica (SiO_2), the content of which varies from 25 to 85%. With an increase in SiO_2 content in rocks, their color usually changes from dark to light, and their density and viscosity decrease. The main rock-forming minerals of igneous rocks are feldspars, quartz, mica, etc., for effusive rocks a high content of amorphous volcanic glass is characteristic. According to the amount of silica in the composition of igneous rocks, they are divided into five groups: ultrabasic, basic, middle, acidic and ultra-acidic.

One of the modern classifications of igneous rocks by mineral composition and texture is shown in Fig. 1.3.4.

The classification of igneous rocks, the most important for construction is given in table 1.3.1.

Table 1.3.1

Classification of the main * (for construction) igneous rocks

Type of rocks by SiO_2 content, %	Intrusive (deep)	Effusive (erupted)	Mineralogical composition (characteristic of intrusive rocks); notes
Ultrabasic, $\text{SiO}_2 < 45\%$	Pyroxenites	Picrites	Augite
	Peridotites	Komatiitis	Augite, olivine, ore minerals
	Dunite		Olivine, ore minerals
Basic, $\text{SiO}_2 45-52\%$	Gabbro (varieties: norit, anorthositis, including labradorite)	Basalt, porphyrite (obsolete.), diabase (obsolete.) Synonym – dolerite (modern)	Plagioclase (often labradorite), pyroxene, sometimes olivine. Anorthosites are one of the main rocks that make up part of the surface of the moon – "lunar continents." On Earth, anorthosites, often together with rapakivi granites, make up large magmatic complexes in Finland, Ukraine, Canada
Intermediate, $\text{SiO}_2 52-66\%$	Diorite	Andesite, porphyry	Feldspars (often andesine), hornblende, biotite, pyroxene
	Syenite	Trachyte	Orthoclase, hornblende, biotite. Syenite practically does not contain quartz – it is easily processed.
Acidic, $\text{SiO}_2 > 66\%$	Granite, granodiorite, quartz porphyry	Liparite (synonym – rhyolite), dacite	Feldspar (usually orthoclase), quartz (in igneous rocks – volcanic glass), mica, hornblende. Granites are the most common building stone and are used very widely.

Notes

* The main rocks included igneous rocks – rocky soils in accordance with DSTUB.V.2.1-2-96 and GOST 25100-2011 "Soils. Classification"

** Outdated porphyrite. "Diabase" is not recommended for use in scientific and technical literature



Fig 1.3.4. The classification of igneous rocks is based on texture and mineral composition (Photos by Dennis G. Tasa and E. J. Tarbuck)

<https://www.facebook.com/451700441565888/photos/a.628161713919759/2141562292579686/?type=3&theater>

Forms of igneous rocks. The main forms of occurrence of intrusive igneous rocks are: batholiths, laccoliths, lapolites, veins, dikes, sills, and cover rocks, flows, volcanic cones and domes are characteristic for effusive rocks (Fig. 1.3.5).

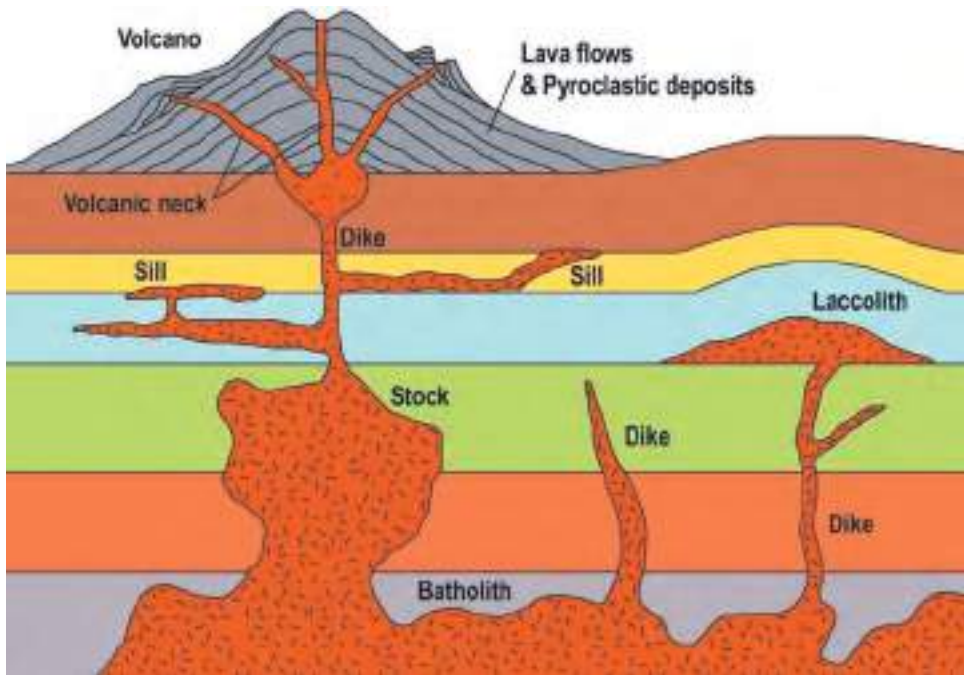


Fig. 1.3.5. The main forms of occurrence of igneous rocks
<https://jisudeka.blogspot.com/>

Batholith is the largest intrusive massif, having an elongated, rounded or complex shape in plan (Fig. 1.3.5 and 1.3.6). The area of batholiths is about 100 km², although they often have an area of tens of thousands of km². For example, the Andean batholith is 1200 km long and up to 100 km wide. The thickness of batholiths is from 3 to 15 km. Thus, batholith has the form of a giant lenticular; It is composed of intrusive rocks of acidic or medium composition – granites, granodiorites, and diorites.

Laccolite is a mushroom or loaf-like form of occurrence of igneous intrusive rocks, which is formed upon the introduction of magma between layers of sedimentary rocks. Sedimentary rocks rise above the intrusion in the form of a vault (Fig. 1.3.5 and 1.3.7).



Fig. 1.3.6. Rock «El Capitan» – part of the Sierra Nevada batholith, Yosemite National Park, USA. Photo by Yu. Iegupov



Fig. 1.3.7. Laccolith – Ayu-Dag Mount, Crimea. Sedimentary rocks, including intrusion, collapsed over time, and igneous, much stronger ones survived
<http://www.crimea-on-line.ru/images/mountain/audag08.jpg>

Lopolith is an interstate intrusion of a saucer-shaped form, according to the overlying layers in the moldings and folded structures facing downward (Fig. 1.3.8). The diameters of the lopoliths can reach tens of kilometers with a power of hundreds of meters. Most often, lopoliths are observed in platform areas where tectonic stretching and lowering of territories occur. Usually they are composed of igneous rocks with a basic composition. The largest ones are Bushveld in South Africa and Sudbury in Canada.

Vein is a magmatic body extended in two dimensions, formed as a result of filling a fractured space with rock or mineral matter (Fig. 1.3.9). Forms of occurrence of veins can be simple, stepwise, slab-shaped, branched, etc.



Fig 1.3.8. Lopolith bedding pattern



Fig 1.3.9. Golden vein

http://www1.geol.msu.ru/deps/petro/lections/Saz_petro/L2_19.pdf
<http://mtdata.ru/u23/photo00B7/20992293758-0/original.jpeg>

Dike is an intrusive body dissecting host rocks, the length of which is many times greater than the width, and the plane of the contacts is almost parallel (Fig. 1.3.10). The length of these formations varies from several tens of meters to hundreds of kilometers, and the width – from a few centimeters to 5–10 km. Dykes are common in areas of manifestation of active magmatic processes and often represent the supply channels of volcanoes.

Sill is an intrusive body in the form of a layer, the contacts of which are parallel to the stratification of the enclosing stratum (Fig. 1.3.11). Sills are formed upon the introduction of magma into sedimentary rocks parallel to the surfaces of layered strata. With a thickness of several meters, their length reaches 300 km. The thickness of the sill strata is most often 10–50 m, sometimes up to 600 m.



Fig. 1.3.10. Dike, Baranof Cross-Island Trail, Alaska

<https://userscontent2.emaze.com/images/ceaa0973-ed9c-4867-bbb7-a71872af3357/acadcd8e-42a2-4a80-b588-d850aa355e49.png>

http://gendocs.ru/gendocs/docs/2/1286/conv_5/file5_html_m7f0d75a8.png

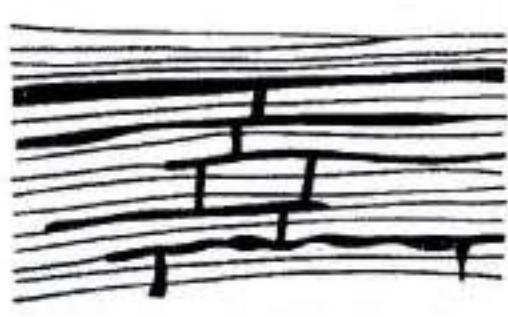


Fig. 1.3.11. Sill pattern

Solid sheets are the often occurrence of effusive rocks on the earth's surface. The upper surface of the integument is horizontal or has a slight slope. They uniformly spread over large areas, with a much smaller thickness. The lower surface is determined by the relief of the underlying terrain that existed during volcanic activity, the irregularities of which were filled with eruption products. In general, the upper and lower surfaces of the cover are almost parallel to each other. In places, there are entire systems of covers that lie one on top of the other, for example, Siberian and Indian traps (Fig. 1.3.12 and 1.3.13).



Fig. 1.3.12. Siberian traps, Yakutia

https://img-fotki.yandex.ru/get/6432/137106206.62a/0_18250e_8a80056a_orig.png

http://images1.raftaar.in/rphotos/h1/misc/m/image_seed_135_6331551_mahableshtar.jpg



Fig. 1.3.13. Deccan Plateau traps, India

Flow (lava) is a form of occurrence of solidified lava that poured out during an eruption of a volcano. Typically, flows are characterized by a large extent with a small width and thickness (Fig. 1.3.14). The length and power of the flow are

determined by the viscosity of the lava and the terrain slopes. Streams of acidic lavas are usually shorter (1–10 km) and powerful (up to 25–30 m), basalt flows are long (up to 60–80 km or more) and low-power (up to several centimeters).



Fig. 1.3.14. Lava flows of the flat Tolbachik volcano, Kamchatka
<http://static.keptelenseg.hu/p/582d19b4f39b7bfec84e4d4cf38e11d8.jpg>

The cone (volcanic) has the form of a geometric cone with a cut top. It is formed from the products of volcanic eruptions – lava flows and loose material around the vent. Fine clastic material (volcanic ash) forms slopes with an angle of $30\text{--}35^\circ$, and coarser material that accumulates near the crater creates a slope angle of up to 40° or more. Most of the world's largest volcanoes have complex cones, consisting of layers of volcanic tuff, ash, slag and frozen lava flows. On many slopes of the main cone, there are small parasitic cones and faults from which the lava flows also flowed (Fig. 1.3.15).

Dome is a form of occurrence of effusive rocks in the form of a “giant cork” that forms when very viscous granite lava solidifies in the volcano vent (Fig. 1.3.16). The accumulation of gases, superheated water vapor under a dome in a locked vent often leads to powerful explosions that destroy part of the volcano (and sometimes the whole!).

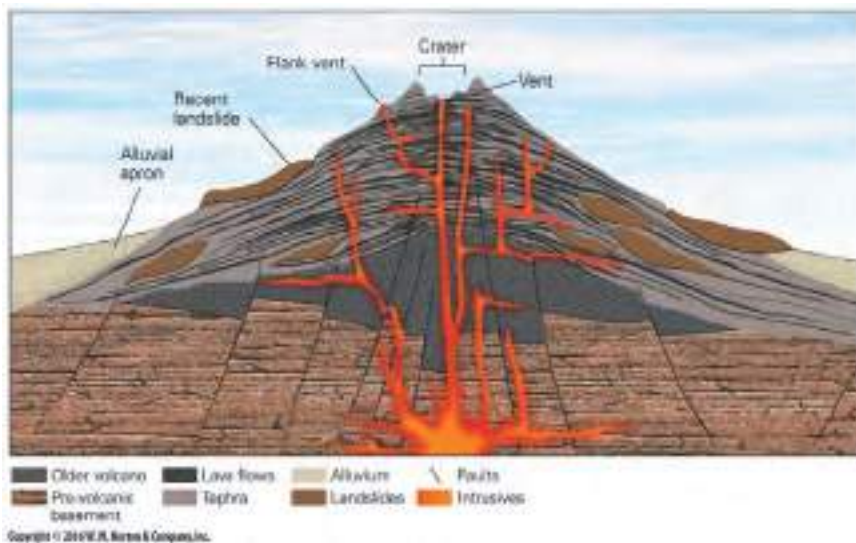


Fig. 1.3.15. Volcanic cone structure diagram

http://www.geo.hunter.cuny.edu/tbw/Iceland.Field.Trip/Lectures/5.volcanic.eruptions/Volcano.Structure.Eruptive.Style/volcano_structure__eruptive_sty.htm



Fig. 1.3.16. Very viscous lava, acidic composition, petrifying in the mouth of the volcano "locks" it

http://investments.academic.ru/pictures/investments/img1983993_kislava_lava_foto.jpg

Sedimentary rocks

Sedimentary rocks are formed near the Earth's surface or directly on it, as well as in water bodies and watercourses. The conditions for the formation of sedimentary rocks are characterized by relatively low temperatures (most often this is air temperature) and low pressure (atmospheric or "water column" pressure). Sedimentary rocks study the sections of geology "sedimentology" and "lithology".

Lithogenesis, which is called the process of sedimentary rock formation, usually consists of four stages:

1. formation of loose sedimentary material during the destruction of the original rocks under the influence of physical and chemical weathering, the activity of living organisms;
2. movement of sedimentary material under the action of gravity, water and air flows;
3. sedimentation and accumulation of sediment in air or water (this process is called sedimentogenesis);
4. transformation of loose sedimentary material into sedimentary rock as a result of natural compaction, often natural cementation (diagenesis).

The most important active factor in the formation of source material for sedimentary rocks is *weathering*. Weathering can be defined as the combined action of the processes of physical, chemical and biological destruction of rocks and minerals under the influence of temperature fluctuations, freezing / thawing cycles, gravitational movements, chemical effects of water, atmospheric gases and acids, the activity of microorganisms, plants and animals. Depending on the intensity of the impact of these processes on the rocks, physical, chemical and biological weathering is distinguished.

Physical weathering is caused mainly by the action of physical factors. Among these factors, the main role is played by temperature changes – diurnal and seasonal. Most rocks are aggregates of grains of various mineral composition that respond to temperature fluctuations in different ways. Mineral grains have differing coefficients of volumetric and linear expansion and, when heated or cooled, increase their volume or length by a different amount. For example, when heating granite from minus 25 ° C to + 25 ° C, the size of each quartz grain in the composition of the rock increases by 15%, and the grains of orthoclase and biotite are react differently. The amplitude of temperature fluctuations during the day is larger; the weakening of bonds between grains is stronger because of the difference in the coefficients of volume and linear expansion. As a result,

micro cracks occur in the rock. For physical weathering, a significant role is also played by crystallization forces when water freezes in cracks. Water turning into ice increases in volume up to 9%. In this case, the rock is wedged along micro cracks, which eventually transforms into macro cracks and the massive rock is gradually destroyed and divided into separate fragments.

Contribute to physical weathering and tectonic processes under the influence of which the rocks bend, crumple, they form cracks, gaps, faults – violation of the integrity of rock masses.

An essential part of physical weathering is the effect of gravitational forces that contribute to the differentiation of clastic material. Larger fragments accumulate on mountain plateaus, slopes, smaller ones – at the foot of the mountains and in lowering relief and the smallest are carried away by water and wind, sometimes tens and hundreds of kilometers from the collapsing rock mass.

Important factors of physical weathering are marine abrasion, river erosion and wind corrosion – mechanical destruction, grinding, and abrasion of the rock surface due to the influence of small solid particles picked up by sea waves, surface water flows or when particles are transported by wind. In addition, in the areas of high latitudes of the Arctic and Antarctic, as well as in high mountains, ice erosion is manifested. Glaciers, gradually sliding down the relief, abrade and crush the underlying rocks.

In general, the predominance of physical weathering of rocks is typical for the high latitudes of the Arctic, Antarctica and high mountain regions, as well as for the arid climate regions – deserts and semi-deserts, where significant insolation causes significant fluctuations in daily and seasonal temperatures.

Examples of rock destruction under the influence of mainly physical weathering are shown in Fig. 1.3.17.

The classification of sedimentary rocks is based on the methods of their formation: they are divided into three main genetic groups of clastic, organic, and chemical origin.

Clastic or terrigenous rocks are fragments of pre-existing rocks of various sizes. These can be non-cemented blocks, boulders, gravel, sand, loam, siltstone, etc., as well as cemented breccias, conglomerates, sandstones, among others (Fig. 1.3.18). As products of predominantly mechanical destruction, sedimentary rocks usually retain the most stable source minerals. Various clays are also referred to as terrigenous rocks, which consist of finely dispersed products of the deep chemical conversion of aluminosilicate minerals contained in the source rocks into new mineral species – clay minerals.



Fig. 1.3.17. Destruction of rocks under the influence of physical weathering: **a** – megaliths of intrusive rocks, Mountain Shoria; **b** – an array of sedimentary stratified rocks, The Tour Percée, Chartreuse Arch, French Alps; **c** – the effect of abrasion on a brick wall block; **d** – wind corrosion, Monument Valley, USA

a <https://hiddenandlittleknownplaces.blogspot.com/2016/09/gornaya-shoria-megalithssouthern.html>

b <https://www.tout-bon.com/picdump-174/>

c http://nengen.club/fy_coastal-wall-decor/

d Photo by Yu. Iegupov

Organogenic rocks are formed with the participation of living organisms, for example, siliceous and calcareous rocks that arise over time from the products of the extinction and accumulation of shells, siliceous and calcareous skeletons of marine organisms (for example, organogenic limestones, including shell lime). From marine microorganisms of animal and plant origin, strata formed chalk. With the accumulation of the conversion of plant residues, peat was formed first, and then brown and stone coal (Fig. 1.3.19).



Fig. 1.3.18. Sedimentary clastic rocks: **a** – blocks (Ordzhonikidze, Crimea), **b** – boulder conglomerate; **c** – pebbles; **d** – sand (sand dunes, Saudi Arabia); **e** – reddish loam and clay greenish-yellow (abandoned quarry in the village of Brazhniki, Kharkov district); **f** – marl (rock consisting of clay and carbonate material)

a Photo by V. Iegupov; **b** Photo by V. Iegupov; **c** Photo by V. Iegupov;

d Photo by S. Provotorov; **e** Photo by V. Iegupov;

f <http://s61.radikal.ru/i172/1202/5a/2447110a2a5b.jpg>

Chemo genic rocks include products of direct precipitation from solutions, which occurs especially intensely when water evaporates in a hot climate, for example, gypsum, rock and potassium salts (Fig. 1.3.20). Deposits of calcite-aragonite composition formed during sedimentation from flowing or standing underground water, are allocated into a separate subgroup – chemo genic deposits in caves.

Among sedimentary rocks, mutual compositional transitions between rock groups of different genesis are observed, resulting from mixing of the material, for example, marl is formed from clastic clay and organo genic calcareous material; limestones often have a mixed organo genic chemical origin.

In addition to the above, groups of pyroclastic – effusive-sedimentary rocks that are formed by the combined effect of effusive magmatism (during volcanic eruptions) and sedimentary lithogenesis factors (the effect of gravity, water, air, etc.). These rocks with an intermediate position between sedimentary and volcanic include – volcanic tuffs (cemented volcanic ash), pumice (arising from the rapid solidification of lava drops in water), tuff breccia, tuffites (a mixture of volcanic and detrital material in various proportions) (Fig. 1.3.21).



a



b



c



d



e



f



g

Fig. 1.3.19. Sedimentary organogenic rocks: **a** – shell rock; **b** – chalk (chalk mountains near the Oskol river in the Kharkiv region); **c** – coal; **d** – diatomaceous earth (siliceous rock, consisting of the remains of diatoms); **e** – micrographs of diatoms – microscopic algae of opal composition; **f** – coral reef and coral limestone formed from the remains of reefs (megalithic dolmens on the island of Malta)

a <http://img.board.com.ua/a/1043070345/wm/0-kryimskij-rakushnyak-rakushechnik-kamen-blok.jpg>

b <http://www.minipedia.org.ua/wp-content/uploads/2012/12/mel-myagkij-kamen.jpg>

c <https://25.img.avito.st/1280x960/2163830825.jpg>

d http://investments.academic.ru/pictures/investments/img1984904_Trepel.jpg

e <http://i.enc-dic.com/dic/colier/images/ph01232.jpg>

f <http://s52.radikal.ru/i138/1404/51/7c5752b2a561.jpg>

g <http://files.abovetopsecret.com/images/member/81eadab22194.jpg>

The most characteristic feature of all sedimentary rocks is their stratification – occurrence in the form of horizontal or inclined homogeneous layers, which is caused by sedimentation conditions. The composition of these rocks depends on the properties of the climate that existed during their formation. The fundamental difference between sedimentary rocks compared to igneous and metamorphic rocks is the possibility of the presence of petrified remains of plants and animals in their structure. The mineral composition of sedimentary rocks also differs significantly from igneous and metamorphic rocks. They are often characterized by a general heterogeneity related to their formation from various sources of matter. Recently, technogenic materials have been added to the natural components of sedimentary rocks.

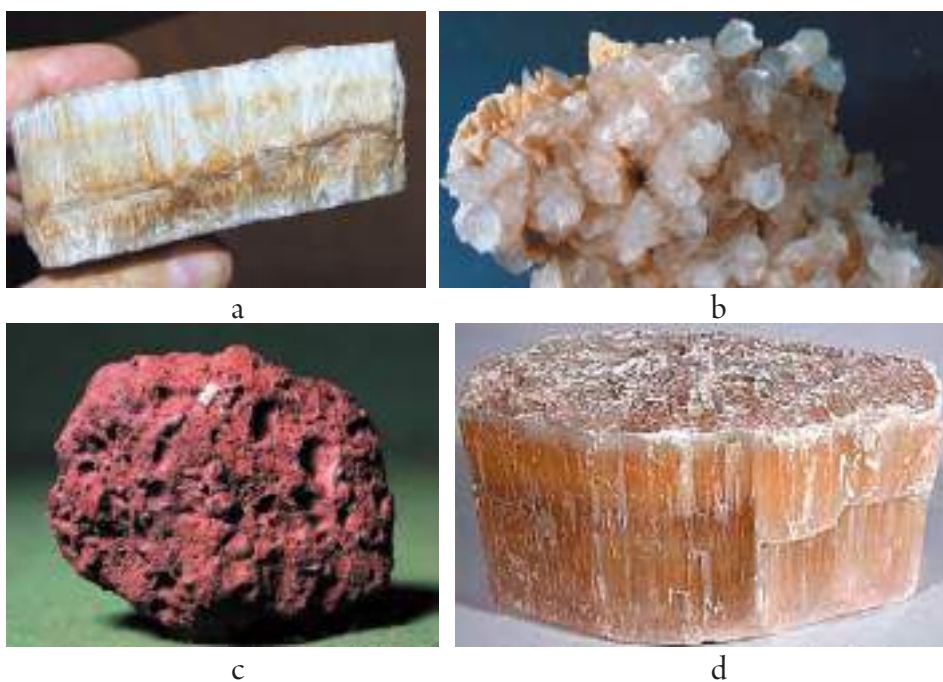


Fig. 1.3.20. Sedimentary chemogenic rocks:

a – rock salt from Kara-Bogaz-Gol Bay, Turkmenistan; **b** – dolomite;

c – bauxite – the main ore for aluminum; **d** – gypsum-selenite, Ural

a http://geo.web.ru/druza/m-celes_14Tu_3107.jpg

b http://3.bp.blogspot.com/-bAbhINORn4k/U1GzNEAB1rI/AAAAAAAAQb0/QL3x3ODmKp0/s1600/Dolomit_Rumunia_pseudomorfoza_po_kalcycie.jpg

c <http://kemoblast.ru/uploads/2012/02/Boksit.jpg>

d http://kalenikov.ru/doog/vbk/img_d_z_vbk/id101_gips_b.jpg

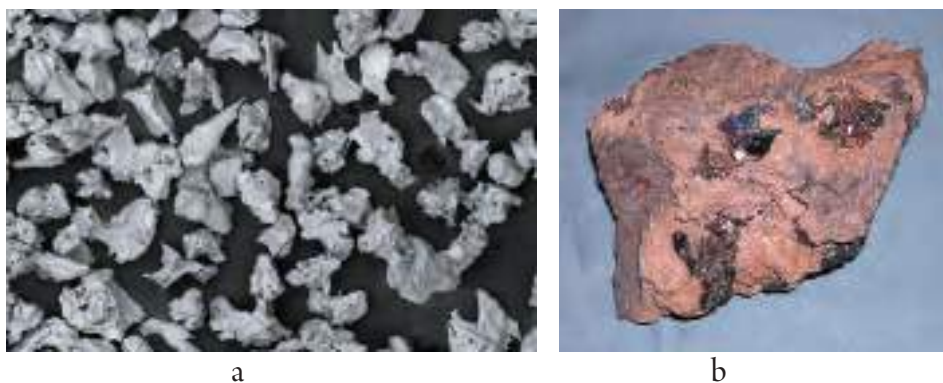


Fig. 1.3.21. Pyroclastic (volcanogenic-sedimentary) rocks: **a** – volcanic ash under a microscope; **b** – tuffit, consisting of volcanic, clastic and organogenic material

a <http://photo.sf.co.ua/g/309/4.jpg>; **b** <http://lavrovit.narod.ru/predlogenia/gem.4.jpg>

Relatively young (by geological standards) terrigenous complexes, represented by thick clays and loams, make up to 60% of the sedimentary rocks of the earth's crust. The next most common (15–17%) is loose and cemented clastic rocks and the size of their fragments varies from boulders, cobbles to fine sand and silt. The content of biogenic carbonate rocks in the earth's crust is 10–13%, and siliceous – 1–2%. Chemo genic rocks: limestones, dolomites, siderites, salts, etc. are contained in the earth's crust to the amount of 6–7%.

The classification of the main sedimentary rocks used in construction as foundations and for building materials, is given in Table 1.3.2.

Table 1.3.2

Classification of the main * sedimentary rocks

Clastic (terrigenous) rocks	Rocks without structural bonds between fragments		Rocks with weak structural bonds	Cemented rocks
	Angular	Rounded		
Coarse	Blocks	Boulder		Conglomerate Siltstone
	Crushed stone	Pebble		
	Granule	Gravel		
Sand	Sands		Cemented clay, mudstone	
Finely fragmented	Siltstone			Breccia
Fine clastic, silty and sandy clay			Clay, loess, loam, sandy loam	
Organ genic rocks	Siliceous		Diatomite	
	Carbonate		Organ genic limestones including shells and chalk	
	Carbon (caustobioliths)		Peat, brown coal, coal, natural asphalts, ozokerite	
Mixed organ genic mineral rocks and topsoils			Silts, sapropels, peat, silty clays, sandy topsoils	
Chemo genic rocks	Siliceous		Flints, siliceoustuff	
	Carbonate **		Limestone, calcareous tuff, dolomite, marl	
	Sulphate		Gypsum, anhydrite	
	Halide		Rocksalt, potassiumsalt	
	Allite		Bauxites	
Volcano genic sedimentary (pyroclastic) rocks	Non-cohesive loose		Cemented	
	Volcanic-detrital rocks, volcanic sands, ashes		Volcanic tuff, tuffit, tuff breccia, tuff sandstone, tuff aleurolite, tuff argillite, lava breccias	

Notes

* The main composition includes sedimentary rocks – rocky and dispersed soils in accordance with DSTUB.V.2.1-2-96 and GOST 25100-2011 “Soils. Classification”

** Carbonate rocks often have a mixed chemo genic-organogenic-detrital origin, for example marl, clayey limestone and dolomite, etc.

Metamorphic rocks

Metamorphic rocks are formed in the earth's crust with a significant change (metamorphism) of sedimentary or igneous rocks under the influence of high temperatures and pressures. The process of metamorphism takes place in most cases in the temperature range from 100 to 1000° *without melting* of the parent rock.

There are four main factors that cause metamorphic changes in rocks:

1. The proximity of the magma chamber and the associated heating of neighboring rocks (*contact metamorphism*). In this case, for example, sedimentary limestones and other carbonate rocks are transformed into metamorphic skarns, and clays – into hornfels.

2. The effect of overheated aqueous solutions, saturated with dissolved gases and active chemical compounds (*hydrothermal and pneumatolytic metamorphism*) upon cooling of magma leads to the formation of greisens, propylites, etc.

3. Considerable changes in the mineral composition and structure of the rock occur when it is immersed in the earth's crust, with simultaneous effects of high temperatures and pressures, lead to regional metamorphism. *Regionally metamorphosed* rocks (numerous types of schists, phyllites, gneisses) are characterized by a shale texture, the presence of a number of specific minerals (kyanite, etc.), sometimes the relict structures of the original rocks are preserved.

4. Under the influence of tectonic deformations, rocks are subjected to very strong pressure at a relatively low temperature. As a result, rocks of *dislocation metamorphism* (*dynamometamorphism*) arise – tectonic breccias, milonites and cataclasites.

The most typical metamorphic rocks are gneisses of different composition (widespread rock covering large areas in Europe), clay and crystalline schists, quartzite, marble, contact hornfels, skarns and amphibolite (Figs. 1.3.22 and 1.3.23). Variability in the genetics and in the mineral composition of the rocks, remarkably affect their physical and mechanical properties of metamorphic rocks.

The mineral composition of metamorphic rocks can vary in a very large range. They may consist of many complex silicates and very often only of a single mineral, for example quartz (quartzite) or calcite (marble) with a small amount of impurities. The main rock-forming minerals in these rocks are quartz, feldspars, pyroxenes, amphiboles and mica. Typical metamorphic minerals are also present: cordierite, garnets, distene, andalusite, and weakly metamorphosed rocks – talc, chlorite and actinolite.



Fig 1.3.22. Metamorphic rocks of massive texture: **a** – green marble; **b** – quartzite, often having a pink color; **c** – secondary quartzite; **d** – birch (a sign of gold ores); **e** – hornfels, with characteristic conchoidal fracture; **f** – a quarry of snow-white marble in Carrara, Italy

a http://www.gidrorez.ru/img/portfolio/mramor/mramor04_b.jpg

b <http://www.vip-monument.ru/wp-content/uploads/2009/10/malinovui-kvarcit.jpg>

c http://www.centropuccini.it/Aprender_italiano/images/carrara-marble-big.jpg

d http://www.ecosystema.ru/08nature/min/2_5_4_18.htm

e <http://www.catalogmineralov.ru/sample/1434.html>

f <http://all-minerals.ru/wp-content/uploads/2011/04/rogovik-600x250.jpg>

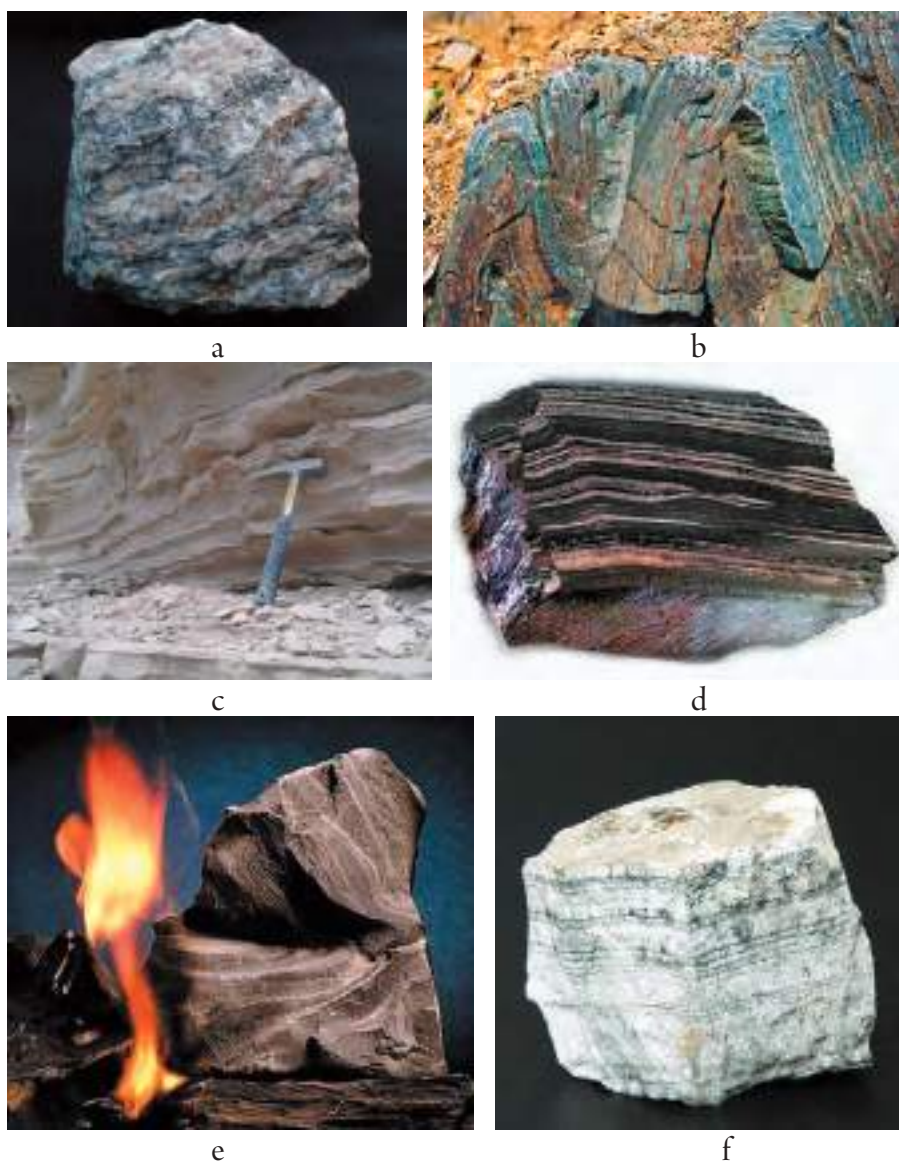


Fig. 1.3.23. Metamorphic rocks with a shale texture:

a – gneiss (the most common metamorphic rock); **b** – jaspilite; **c** – clay shale;

d – ferruginous quartzite (iron ore); **e** – oil shale; **f** – skarn

a <https://upload.wikimedia.org/wikipedia/commons/4/4e/Augen-gneiss-2.jpg>

b <http://www.photoukraine.com/i/articles/Zheleznaia%20Ruda%20Photos/010.jpg>

c <http://en.academic.ru/pictures/enwiki/71/GLMsed.jpg>

d http://irkipedia.ru/sites/default/files/2_5_4_3.jpg

e http://i.haqqin.az/108844_src.jpg

f <http://www.catalogmineralov.ru/mineral/skarn.html>

The classification of metamorphic rocks is based on their texture (sometimes chemical components) according to which, two subgroups of rocks are distinguished – massive and shale. The classification of the main metamorphic rocks as applied to construction and industry is given in Table 1.3.3.

Table 1.3.3

Classification of the main * metamorphic rocks

Rock composition	Texture	
	massive	shale
Silicate	Quartzite, hornfels, skarns, greisens, birch, propyl, secondary quartzites	Gneisses, shales (crystalline, clay, mica, talc, etc.), amphibolite
Carbonate	Marble	
Glanular		Jespilites, ferruginous quartzites
Organ genic mineral	Anthracite**	Oilshale

Note

* The composition of the main ones includes mainly metamorphic rocks – rocky soils in accordance with European Standards “Soil Classification”

** Anthracite – a variety of coal with the highest degree of coalification (metamorphism) traditionally refers to sedimentary rocks

Rock application

Rocks, as components of the earth’s crust, are used as the foundations to buildings and structures, building materials or raw materials for their production.

The study of natural foundations, their physical and mechanical properties is carried out by Engineering Geology – Soil Science and the interaction of soil bases with footings of overlying structures is studied by “Soil Mechanics”. It is noted that igneous and metamorphic rocks can serve as the best natural bases to structures and buildings. Sedimentary rocks like strong breccias, conglomerates, sandstones and thick clays may serve as strong foundation for buildings and structures whereas loose sands, flowing clays, peat, silt, gypsum and rock salt are weak. The possibility of using native rocks underlying a construction site as a natural foundation and also the possibility of producing local building materials is considered when performing geotechnical surveys.

Rocks have always served and are the main components of the most common building materials. The average qualitative assessment of the durability of some stone materials from various rocks is presented in Table 1.3.4. Examples

of their application in the production of building materials are given in table 1.3.5, and some examples of the use of rocks in the creation of various buildings and structures in Fig. 1.3.24.

Table 1.3.4

Qualitative assessment of the longevity of some rocks

Characteristic	Name of rocks	The appearance of signs of degradation (years)
Highly durable	Quartzite, fine granite, dense basalt	500–600
Durable	Coarse granite, gneiss, gabbro, diorite, syenite, labradorite, breccia	200–300
Moderately durable	White marble, sandstone, dolomite, dense limestone	100–150
Short life	Colored marble, loose limestone, volcanic tuff	25–75
Very short life	Gypsum, shellrock	5–15

Table 1.3.5

Examples of the use of rocks in the construction industry

Area of application	Rocks		
	Igneous	Sedimentary and Pyroclastic	Metamorphic
1	2	3	4
Quarry stone	Granite, gabbro, diorite, basalt, diabase, etc.	Lumps, boulders, conglomerate, breccia	Gneiss, quartzite, amphibolite, schistes, etc.
Crushed stone		Crushed stone, pebbles	
Gravel		Granules, gravel	
Sand		Various sands, volcanic sand	
Stone for hydraulic structures, road curbs and paving stones	Granite, gabbro, basalt, etc.	Breccia and other breeds of sufficient strength	Amphibolite, gneiss, quartzite
Tiles for floors, steps, wall cladding	Granite, syenite, gabbro, diorite, labradorite	Sandstone, breccia, volcanic tuff (for facing)	Marble, Quartzite, Gneiss
Acid resistant stone	Trachite, basalt		Quartzite
Stone casting	Basalt and others		

Table continuation 1.3.5

1	2	3	4
Wallblocks		Shell rock, tuffs, porous limestones	
Construction lime		Limestone, chalk, marl	
Hydraulic lime		Dolomite, Marl	
Portland cement		Limestone, gypsum	
Binders		Gypsum, clay, anhydrite	
Different types of glass	Volcanic glass	Quartz sand	
Brick		Clay, loam, sand	
Roofing materials		Clay	Roofingslates
Thermal insulation materials	Basalt fiber	Peat, shell rock, volcanic tuff, pumice	
Ceramics		Clay	



a



b



c



d



e



f

Fig. 1.3.24. The use of rocks in structures and monuments: **a** – basalt and volcanic tuff, sculptures on Easter Island; **b** – limestone, sphinx and pyramids, Egypt; **c** – quartzite, the tomb of Napoleon, France; **d** – white translucent marble, Taj Mahal mausoleum, India; **e** – labradorite, Shevchenko monument, Kharkiv; **f** – granite, Beketov monument, Kharkiv

a <http://k46.kn3.net/taringa/6/F/7/C/B/E/FabianTomasi/B01.jpg>

b [http://i.marktplaats.com/00/s/NTM5WDcyNg==/\\$
\(KGrHqRHJEkFC\(6JS39GBQpRZPvouQ~60_85.JPG](http://i.marktplaats.com/00/s/NTM5WDcyNg==/$ (KGrHqRHJEkFC(6JS39GBQpRZPvouQ~60_85.JPG)

c <https://www.proza.ru/pics/2011/06/07/529.jpg>

d [http://2.bp.blogspot.com/-fTcndu4mlj4/UO6upu4X5rI/AAAAAAAAAE68/
/2AIlwA7qWyg/s1600/Taj%2BMahal%2BWallpaper%2B05.jp](http://2.bp.blogspot.com/-fTcndu4mlj4/UO6upu4X5rI/AAAAAAAAAE68/2AIlwA7qWyg/s1600/Taj%2BMahal%2BWallpaper%2B05.jp)

e [http://dozor.kharkov.ua/content/documents/11611/
1161080/thumb-big-420x305-8bd9.jpg](http://dozor.kharkov.ua/content/documents/11611/1161080/thumb-big-420x305-8bd9.jpg)

f [https://uk.wikipedia.org/wiki/Сумська_вулиця_\(Харків\)](https://uk.wikipedia.org/wiki/Сумська_вулиця_(Харків))

#/media/File:%D0%9F%D0%B0%D0%BC%27%D1%8F%D1%82%D0%BD%D0%B8%
D0%BA_%D0%B0%D0%BA%D0%B0%D0%B4%D0%B5%D0%BC%D1%96%D0%BA%
D1%83_%D0%9E.%D0%9C._%D0%91%D0%B5%D0%BA%D0%B5%D1%82%D0%
BE%D0%B2%D1%83_%D0%B2_%D0%A5%D0%B0%D1%80%D0%BA%
D0%BE%D0%B2%D1%96.jpg

Test questions to chapter 1.3. Rocks

1. Definition of rocks.
2. The origin of the rocks.
3. Types of rocks and their ratio in the earth's crust.
4. Definition of igneous rocks. Ways of their origin.
5. The main forms of occurrence of intrusive rocks.
6. The principle of classification of the most important (for construction) igneous rocks.

7. Forms of igneous intrusive rocks.
8. Forms of igneous effusive rocks.
9. Sedimentary rocks and their formation.
10. The mechanism of action of weathering.
11. The principles of classification of sedimentary rocks.
12. Give examples of clastic (terrigenous) rocks.
13. Give examples of organogenic rocks.
14. Give examples of chemo-genic rocks.
15. Definition of metamorphic rocks.
16. Four main factors causing significant metamorphic changes in rocks.
17. Classification of major metamorphic rocks.
18. The use of rocks. The examples.
19. The durability of rocks.

Chapter 1.4. STRATIGRAPHY AND GEOCHRONOLOGY

Definition of stratigraphy and geochronology. The absolute and relative age of the rocks. Fossilized remains of organisms. Geochronological scale. Quaternary deposits.

The geological age and conditions of formation of rocks have significant influence on their properties which need to be considered when using rocks for construction purposes. Geological indices of the age of rocks are indicated in geological documentation namely: columns of boreholes, geological sections and maps. The general laws governing the formation and development of the earth's crust are studied by historical geology, that is, the occurrence of layers of sedimentary rocks for individual territories and their age – *stratigraphy* and *geochronology*.

Stratigraphy (from lat. Stratum – layer, ancient Greek. Γράφω – I write, I draw) is a section of geology that studies the occurrence of sedimentary (and pyroclastic) rocks by determining their relative geological age. Stratigraphy of any region is a sequence of sedimentary rocks composing the territory the position of other geological objects that are depicted on geological sections.

The basis of stratigraphy laid two fundamental theoretical principles: Steno's law of bedding and the law of conformity of flora and fauna of Huxley. According to the law of bedding, introduced in geology by Nicholas Steno back in the 17th century, the strata of rocks lying nearer to the surface, as a rule, are younger than those lying deeper. According to Huxley's law, layers containing the remains of identical fossil living organisms have the same geological age.

Geochronology is a branch of geology that studies the chronological sequence of formation and age of rocks which make up the earth's crust. We distinguish between absolute and relative geochronology.

Absolute geochronology establishes the so-called absolute age of rocks expressed in units of time (usually in millions of years). To determine the absolute age, methods based on the principles of radioactive decay of uranium, thorium, rubidium, the C^{14} carbon isotope and other elements contained in the minerals that make up the rocks, have been developed. For example, having determined the joint content of U^{238} and one of the products of its radioactive decay Pb^{206} in a uraninite mineral, it is possible to determine the time elapsed since the formation of the mineral and rock, that is, their absolute age.

The aim of relative geochronology is to determine the relative geological age of rocks, i.e. which deposits in the earth's crust are more ancient, and which ones are

younger. To indicate the relative age of the rocks, a system of special alphanumeric designations has been developed and presented on geological maps and sections of rocks of different ages, shown in various colors.

To determine the age of rocks and compare the stratigraphy of territories separated from each other (continents, countries, regions), the *paleontological method*, based on the study of fossilized remains and traces of extinct animals and plants buried in rock strata, is used: teeth and skeletons of fish, etc. (Figs. 1.4.1–1.4.4), but they often find traces of the existence of life on land like, imprints of leaves of trees, petrified skeletons of terrestrial animals, footprints, etc. (Figs. 1.4.5–1.4.7). A comparison of numerous fossils from different strata made it possible to establish the theories of the process of development of organic life on Earth and to distinguish a number of geological stages in the history of the planet with a complex of flora and fauna characteristic of each of them. Rocks formed during these stages form the basis of the general stratigraphic scale, and the time during which these rocks form is the basis of the geochronological scale.



Fig. 1.4.1. Petrified ammonites (a)
and mollusks (b),
Vienna Museum of Nature
Photo by V. Novgorodov

*Fig. 1.4.2. Trilobites are one of the first complex creatures on Earth, Vienna Museum of Nature
Photo by V. Novgorodov*



Fig. 1.4.3. Racoscorpion

The remains of crustaceans were found on the third potash horizon of Belarus-Potassium. These arthropods from the order Eurypterida, at least 360 million years old, inhabited the Paleozoic Devonian. They are the largest arthropods that ever lived on Earth. The found Racoscorpion has a record length of 34 cm.

<http://www.palese.by/2012/06/Ostanki-drevnejshego-rakoskorpiona-obnaruzheny-na-rudnike-Belaruskaliya/>



Fig. 1.4.4. Imprint of plant and, presumably, the trace of the young pterodactyl on a plate of coal, Blagodatnaya mine, Pavlograd, Ukraine

<https://tsn.ua/tsikavinki/nadnipropetrovschini-znayshli-skelet-ditinchati-pterodaktilya-foto.html>



Fig. 1.4.5. Tooth of megalodon and modern white shark

Megalodon (Greek Μέγαλοδούς – big tooth) is an extinct shark that existed in the period from the Late Oligocene (~ 28 million years ago) till Pleistocene (~ 2 million years ago). This species of sharks was gigantic and reached a length of 16 meters and a weight of 47 tons, was one of the largest predators in the entire history of the Earth. This “super predator” was fed by large marine inhabitants – cetaceans and large fish.

http://archaeology.kiev.ua/imaginators/new/4ee8d0f02cdad_image007.jpg



*Fig. 1.4.6. Dinosaur fossil skull, Vienna Museum of Nature
Photo by V. Novgorodov*



Fig. 1.4.7. Giant sea monster, Vienna Museum of Nature
Photo by V. Novgorodov

The geochronological (*chronostratigraphic*) scale is a scale of relative geological time, built on the basis of the stages of the formation of the earth's crust defined by historical geology and established by paleontology – the history of the development of various life forms on Earth. It is a sequence of stratigraphic elements in accordance with the time of their formation. The geochronological scale has the form of a complete ideal geological column of all earth deposits without gaps and is a standard for correlation of various local stratigraphic units. The boundaries between the stratigraphic elements pass through significant events of geological changes in the earth's crust or stages of the evolution of living organisms. An example of a geochronological scale is shown in Fig. 1.4.8.

Chrono stratigraphy is a section of stratigraphy that aims to establish the age of geological objects to periodize the history of the Earth. On the geochronological (*chronostratigraphic*) scale, the most modern version of the chronology of the development of our planet is given.

Continuous work to standardize and update the International Chronostratigraphic Scale – International Stratigraphic Chart (ISC) is carried out by the International Commission on Stratigraphy (ICS) – the largest and oldest commission in the International Union of Geological Sciences (IUGS).

Its main purpose is to accurately capture the global stratigraphic units (groups, systems, departments), which are the basis for the elements of time (era, periods, epochs) of the International Geochronological scale, thus setting common standards of fundamental scale for reflecting history of the Earth.

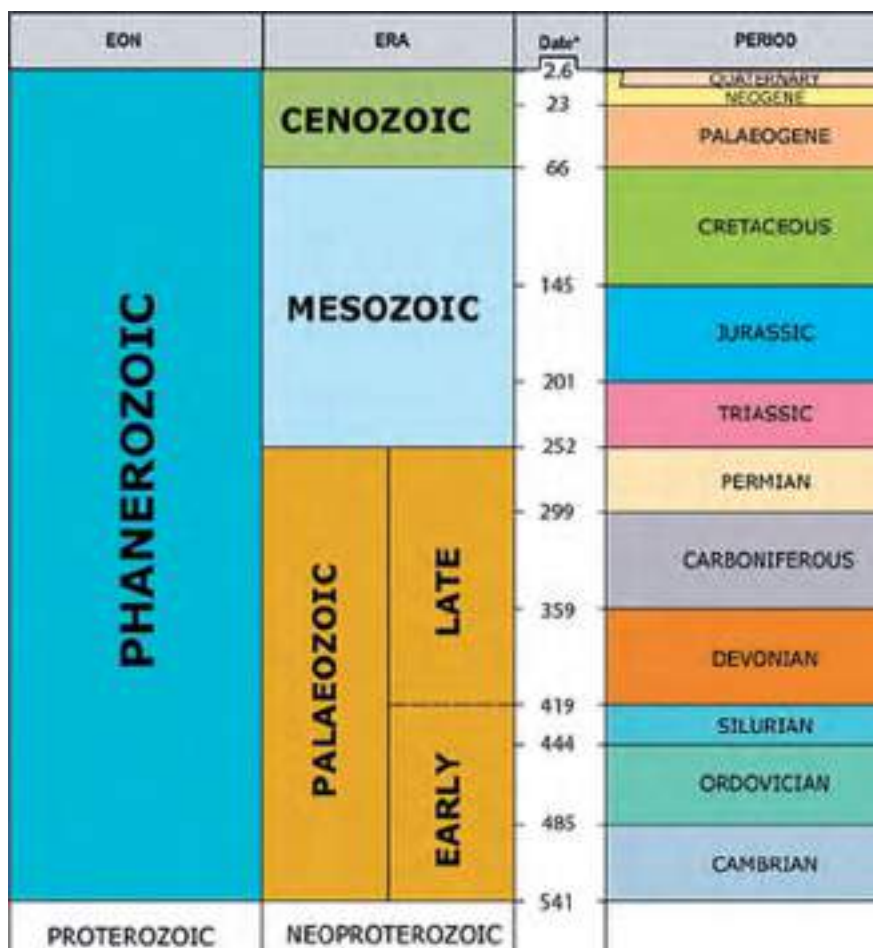


Fig. 1.4.8. Geochronological scale (simplified version)
<https://www.bgs.ac.uk/discoveringGeology/time/timechart/home.html>

The Stratigraphic Information Sub-Commission is developing a Global Boundary Strat type Section and Point (GBSSP) stereotype summary table, based on which the International Chronostratigraphic Scale is periodically updated and improved. The modern geochronological scale is the result of almost two centuries of work by geologists. The modern version of the ISC scale is given according to the data obtained during 2018 (Fig. 1.4.9).

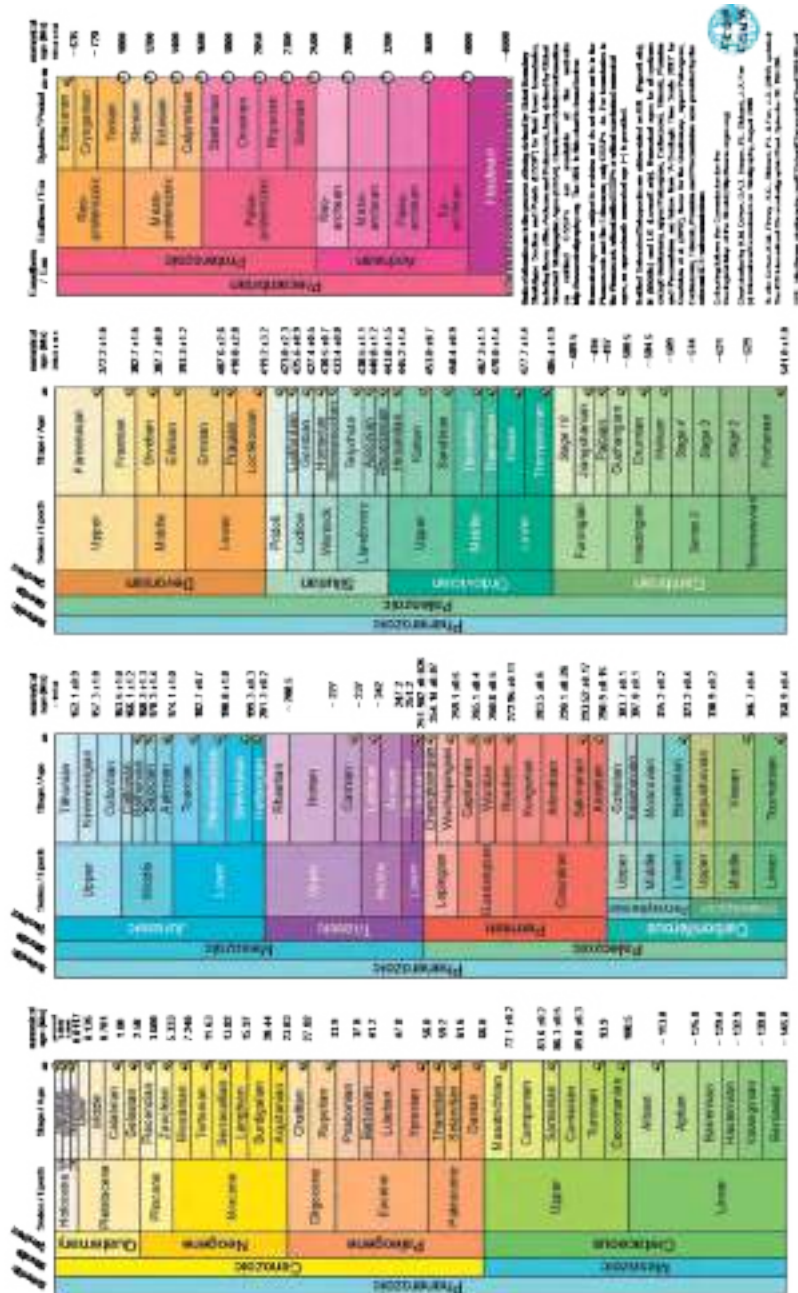


Fig 1.4.9. Modern version of the International Chronostratigraphic Scale (ICC)
<http://www.stratigraphy.org/ICSchart/ChronostratChart2018-08.jpg>

Geochronological scale – reflects the natural stages in the history of the Earth in an ascending order from the oldest to the modern stage. In the upper left corner is the Holocene (i.e., the geology of “our time”). In the lower right is the earliest period of the planet.

The basic units of the divisions of this scale are: eons, eras, periods, epochs, centuries. Stratigraphic divisions are an integral part of the geochronological scale and its materialistic interpretation. The main object of the geochronological scale is geological time and on the other hand, the object of the stratigraphic part of the scale is rock complexes formed during this geological time. Each geochronological unit corresponds to a stratigraphic unit: era – group, period – system, etc. (Tab. 1.4.1). In some literature, groups are called era themes, age is called series and tiers are called stages.

Table 1.4.1

Correlation of geochronological and stratigraphic units

Segments of geological time on a geochronological scale	Complexes of rock layers on a stratigraphic scale
Eon	Eonotema
Era	Group (Erathema)
Period	System
Epoch	Age (series)
Century	Tier (stage)

The names of each unit in the geochronological scale come from ancient Greek words (ἀρχαῖος – ancient, φανερός – explicit, ζωή – life, etc.) or from the place where they were first discovered. In addition, each unit has its own strictly defined color (for example, Jurá – blue, Neogene – lemon yellow, etc.) and an index that consists of the initial letters of the unit’s name and numbers, for example, the names of eras (groups) are indicated by two capital letters: Archean – AR, Cenozoic – KZ, etc. Periods (systems) are denoted by a single capital letter: Quaternary – Q, Jurassic – J, Cretaceous – K. Epochs (divisions) are indicated by digital subscripts: Late Triassic – T₃, Middle Triassic – T₂, Early Triassic – T₁. Tier Index placed to the right of the main index in the form of one or two lowercase letters in the name of the tier. If in one system there are tiers whose names begin with the same letter, then two letters are used. At the same time, in the index of the older tier, one lowercase initial letter from the name of the tier is indicated, and in the index of younger tiers there will be two letters from the name of the tier (first and nearest consonant). For example, the French layer of the Upper Devonian

D_3f , the Famennian layer of the Upper Devonian – D_3fm ; the L landoverian tier of the lower Silurian – S_1l , the Ludovian tier of the upper Silurian – S_2ld .

Names of systems (periods) and tiers (centuries) were given most often, in accordance with the geographical names of the territories where these deposits were found. The name of the Cambrian system comes from the Latin word Cambria (the name of Wales as part of the Roman Empire), Devonian – from the county of Devonshire in England, Perm – from the city of Perm, Jurassic – from the mountains of Jura, France. Examples of geographical names of tiers (centuries) are: Danish, Bashkir, Moscow, Campanian, Cognac (Champagne and Cognac provinces in France). In honor of the ancient tribes, the Jordanian-Silurian systems (tribes of the Celtic-Jordanian and Silurian tribes) were named. Sometimes the names associated with the predominant composition of the rocks were used, for instance, the coal system was named because of the presence of a large number of coal seams, and the Cretaceous is due to the wide distribution of chalk deposited in the Cretaceous.

The longest geochronological units, uniting several eras, are called eons. Currently, two eons are distinguished: Cryptozoic (or Precambrian) and Phanerozoic. The duration of the more ancient – Precambrian eon is about 5/6 of the entire geological history of the Earth (Fig. 1.4.10).

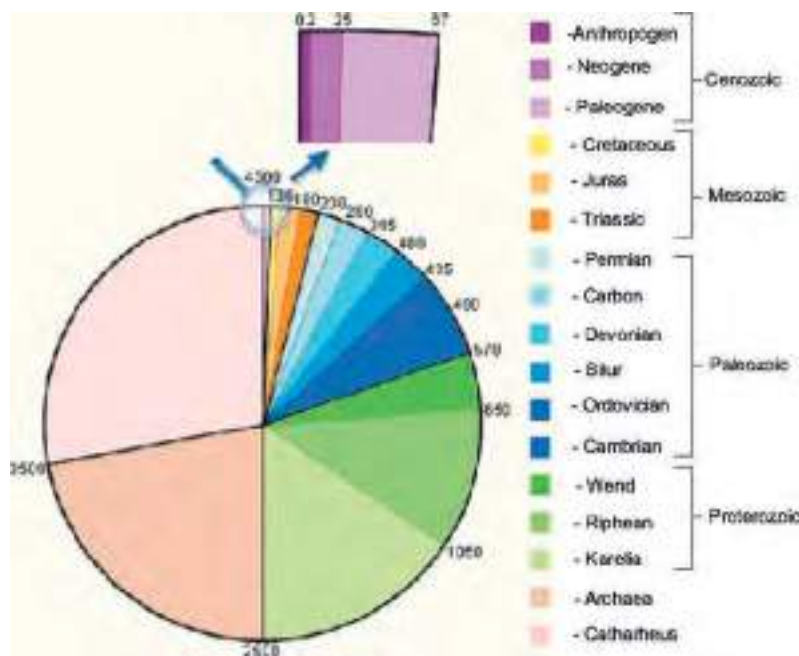


Fig. 1.4.10. Duration diagram of geochronological divisions of the geological history of the Earth
<http://ppt4web.ru/images/1152/28782/310/img1.jpg>

The Cryptozoic aeon (the time of a hidden life) unites two eras: the Archean and Proterozoic, lasting over a period of about 4 billion years. The time before the Archean era (from ~ 4.6 to 4.0 billion years ago) was called Hadean. At this early geological stage, the formation of the Earth took place, which became evident from the differentiation of substances inside the planet. Areas of basaltic crust started to appear, at first in molten state.

The Archean era (AR) is an ancient era, covering a period of time from 4 billion years to 2500 million years ago. It is subdivided into eo-, paleo-, meso- and neo-archaea, each lasting ~ 400 million years. Towards the end of the Archean, during the Soam and White Sea tectonic cycles, the formation of a real continental crust takes place. During the eoarchean era on Earth, a hydrosphere is formed in the form of shallow oceans and sections of the protocontinental crust in the form of islands. The first primitive unicellular organisms started to appear.

Proterozoic era (PR) is the era of primary life (proto-life), divided into three periods of time – paleo Proterozoic, mesa Proterozoic and neo Proterozoic. Temporary boundary between the Proterozoic periods was between 2500 million years and 541 million years. During the Paleoproterozoic (Karelian cycle), a turning point occurs: at the end of this period, huge sections of the earth's crust become rigid and stable, forming real platforms. By the end of the Proterozoic (Baikal cycle), all the continents of the southern hemisphere are connected into a single mainland Gondwana. The basic structures of five geosynclinal belts appears. About 800 million years ago, the Pacific Ocean is formed. The climate is warm everywhere, but in the Neoproterozoic there is a global glaciation of the Earth. The atmosphere is gradually saturated with oxygen up to 1% of the current content. The first multicellular organisms appeared.

Phanerozoic eon (time of apparent life) – includes three eras: Paleozoic, Mesozoic and Cenozoic. Deposits formed at this time are characterized by many reliable residues of organic origin. The beginning of the eon was about 541 million years ago.

The Paleozoic era (PZ) is an era of ancient life, which includes six periods: the Cambrian (Є), Ordovician (O), Silurian (S), Devonian (D), Carboniferous (Carbon) (C) and Perm (P). The time interval between them was 541.0–252.17 million year.

During the Cambrian, Ordovician and Silurian (*Caledonian tectonic cycle*) on the Earth there were 6 ancient platforms. The largest transgression (sea level rise) occurs with a maximum in Ordovician. Gondwana remains land.

At the beginning of the Silurian, glaciation occurs. At the end, the supercontinent Eriya is formed. In the Cambrian period, many new groups of organisms quickly appear (the so-called “Cambrian explosion of life”). During Ordovician, oceans are populated by cephalopods. The first fish appear in the Silurian and life on land emerges in the form of scorpions and later the first plants.

During the Devonian, Carboniferous and Permian periods (*Herzing cycle*), a new continent of Angaris appears, which, together with Eria, unites in Laurasia. Laurasia then merges with Gondwana, forming a single continent Pangea, but soon – at the end of Permian period, it begins to split. In the Devonian, amphibious and spore plants appear; in the Carboniferous period – the appearance of trees and reptiles; and at the end of Perm, the first great extinction of organisms, when about 95% of all existing species disappeared.

The Mesozoic era (MZ) is the era of middle life, divided into three periods: Triassic (T), Jurassic (J) and Cretaceous (K). The time interval is 252.17–66.0 million years. During the Mesozoic, the Pacific tectonic cycle occurs. On Earth there is one continent, two oceans and three geosynclinal belts. The planet Earth is mostly occupied by land and the climate is hot. In the Triassic period, the first dinosaurs and primitive egg-laying mammals appear. During the Jurassic period, is the blooming of dinosaurs, the appearance of marsupial mammals and the first birds; in the Cretaceous – the extinction of most dinosaurs and the emergence of the first placental mammals.

The Cenozoic era (KZ) is an era of new life, in which three periods are distinguished: Paleogene (P), Neogene (N), Quaternary (anthropogenous) (Q). The era began 66.0 million years ago and continues until today. Cenozoic corresponds to the Alpine tectonic cycle. On Earth, there are only two geosynclinal belts. The ocean of Tethys disappears. From the end of the Neogene, the formation of integumentary glaciers began in Antarctica. The areas of the continents in the Neogene were larger than actual ones: all the shallow shelves were the land part of the continents. In the Paleogene period, during the Eocene, the first modern mammals appear, and in the Oligocene – the first anthropoids. In the Pleistocene era of the Quaternary – the emergence of man; Periodic glaciations and retreats of mainland ice occur. During the Holocene (modern) era, the extinction of many large mammals (mammoths, etc.) is observed.

The most striking and illustrative example of the reflection of the geological history of the Earth in sedimentary rock layers is the Grand Canyon in the Grand Canyon National Park, USA (Fig. 1.4.11).



Fig. 1.4.11. The Grand Canyon, Arizona, USA. Photo by Iu. Iegupov

The Grand Canyon National Park is considered by many geologists to be the best geological landscape in the world and a unique “geological miracle”.

The geological section of the Grand Canyon region is one of the most complete and well-studied rocks on our planet. The oldest rocks in the canyon are 1840 million years old. The outcrops contain 40 main layers of sedimentary rocks, most of which were formed in warm shallow seas and near ancient, vanished sea shores in western North America. In addition to marine sediments, land deposits are also represented here, for example, the lithified sands of the former dunes of the ancient desert.

According to geological standards, the Grand Canyon is very young – it was formed over the past 6 million years. Here, both ancient and younger deposits are found, for example, ice age fossils in caves, lava flows up to 1000 years in the western canyon, etc. Examples of some canyon rocks are shown in Fig. 1.4.12.

Genetic Types of Quaternary Deposits

Quaternary deposits lie directly on the surface of the earth, overlap the older and more important (by thickness) pre-Quaternary deposits and therefore are most often used as the foundations of various buildings and structures. Quaternary sediments are mainly of continental origin and depending on the formation conditions, they are subdivided into various genetic types with diverse composition, forms, physical and mechanical properties.



Fig. 1.4.12. The absolute and geological age of some characteristic rocks in the Grand Canyon, Arizona, USA:

- a** – Nankoweap sandstone, 900 mln years old, Neoproterozoic; **b** – Carbon Canyon limestone, 780 mln years old; **c** – Awatubi limestone, 750 mln years old; **d** – Tapeats sandstone, 525 mln years old, Cambrian; **e** – sanded spring deposits, Holocene.

Photo by Iu. Iegupov

Quaternary deposits have a relatively small thickness (few to tens of meters), which can quickly change in plan and section up to wedging. On the surface of the earth, they often form particular relief forms: plains, river terraces, slopes, drift cones, landslide steps and dunes.

Depending on the genetic type of the deposited rocks, an alphabetic index is added before the designation of their age, for example, alluvial (river) deposits – a, glacial deposits – g, and so on.

Designations of the genetic types of deposits of the Quaternary system are given in table. 1.4.2.

Table 1.4.2

Symbols of the genetic types of Quaternary sediments

Index		Name and characteristics of deposits
Old	New	
1	2	3
glQ	gQ	Glacial. Sand and clay deposits formed during the melting of glaciers.
fglQ	fgQ	Fluvioglacial (water-glacial). Sediment water flows; size of debris from boulders to clay particles.
lQ	lQ	Limnos (lacustrine). For a humid climate – terrigenous (from clay to gravel) and organogenic precipitation are characteristic and for a dry climate – chemogenic precipitation.
alQ	aQ	Alluvial (river) are deposits of all channel water flows, including temporary. Among the alluvial can be named: channel, flood plain and sedimentary. Channel – represented by sorted gravel-sand sediments (on the plain) or pebbles (in the mountains); flood plain – with a thin cover of sandy loam and loam with sand lenses; the old ones consist of dusty clay deposits, often with interbeds of silt and peat.
elQ	eQ	Eluvial. (Eluvium is a weathering product that is not carried away by water but stored at the original place of formation). The composition of eluvium varies in depth: clays with rubble or gravel lie at the surface and in the lower part of eluvium in the form of gravels and boulders.
colQ	cQ	Colluvial (talus deposits) – debris accumulated on the slopes or at the foot of mountains when it is moved under the influence of gravity.
dpQ	grQ	Gravitational deposits (landslide, delapsive deposits) are formed when large masses of clay rocks creep down the slope.
solQ	sQ	Solifluction. These deposits are formed during the slow viscous-plastic flow of soils. Their composition is diverse: from clay and loam to crushed stone and block aggregates. Solifluction is characteristic of permafrost regions, as well as a humid tropical climate.
dlQ	dQ	Diluvia deposits are formed as a result of accumulation on the slope of sandy-clay material brought from above by rain and melting water. On the gentle slopes, sandy-loamy deposits prevail while on the steep mountain slopes of the some countries sandy-loamy-gravel deposits (mountain diluvium) prevail.
lQ	LQ	Loess and loess-like deposits of various genesis: aeolian deposits, alluvium, diluvium, and eluvium. Composition: predominantly dusty particles with significantly less clay and sand particles.
plQ	pQ	Pluvial (drift cones). Formed during the deposition in the foothills of the material brought from the mountains by shallow rivers and temporary streams. Large fragments – pebbles, gravels are deposited in the upper parts of the drift cones, and sand and clay material in the middle and lower parts
hQ	hQ	Swamp mineral and organic sediments accumulating in swamps. Peat prevails among them, which is now transformed into fossil coals.

Table continuation 1.4.2

1	2	3
eo1Q	vQ	Aeolian (wind) deposits are formed by the accumulation of material carried by the wind. Composition: aeolian sands, loess, volcanic ash and dunes may form on the surface of the earth.
	mQ	Marine sediments at the bottom of modern and ancient seas and oceans. Most often, these are clayey silts, calcareous or siliceous clayey silts and volcanic silts.
	βQ	Volcanic deposits: lava, ash, pumice and other products of volcanic eruptions
	πQ	Mud volcanic: products of eruptions of mud volcanoes – clayey, less often sandy deposits
	tQ	Technogenic (anthropogenic): various artificial, bulk, alluvial deposits and the cultural layer. According to the method of formation and composition, there are: construction, mining, industrial and household deposits. Composition: industrial waste, slag, ash, construction and household waste, displaced sands and clay rocks.
prQ	prQ	Covers (problematic deposits). In terms of their origin, specialists have different points of views.
	RQ	PreQuaternaryDeposits
<i>Deposits of mixed genesis.</i> Formed by the simultaneous action of several geological factors. Examples: lake-alluvial – laQ, diluvia-pluvial – dpQ deposits.		

In engineering-geological documentation, geological indices of Quaternary deposits are often written in the following abbreviated form. For example, instead of aQ_4 , aIV is written, and both mean alluvial Holocene deposits; dQ_2 – dII – diluvia Middle Pleistocene (Mid Quaternary) deposits, and so on.

Test questions to chapter 1.4. Stratigraphy and Geochronology

1. The definition of stratigraphy.
2. What is the essence of the law of stratification of Steno and the law of conformity of flora and fauna of Huxley?
3. Definition of absolute geochronology and its purpose.
4. What is relative geochronology?
5. Characterization of the paleontological method.
6. What is a geochronological (chronostratigraphic) scale?
7. The ratio of geochronological and stratigraphic units.
8. List the main eons and eras of the history of the Earth.
9. Examples of genetic types of Quaternary deposits.

PART II.

ENDOGENOUS PROCESSES

The modern appearance of the Earth, the condition and properties of rocks in the earth's crust were formed as a result of the action of geological, physico-chemical, hydro-meteorological and a number of other processes occurring in the upper part of the earth's crust and on the earth's surface. Most of these processes are endogenous, exogenous or anthropogenic (associated with human activities) in nature. These processes and the phenomena associated with them, significantly affect both the life of mankind as a whole, and in separate territories, infrastructure, and construction projects.

Endogenous processes (from the Greek *Endon* – inside and *genes* – birth) are called global geological processes that occur mainly due to the internal energy of the Earth. In addition, their origin and flow are affected by gravitational effects of space objects on the Earth, as well as centrifugal forces due to the rotation of the Earth. According to modern scientific theories, endogenous processes occur as a result of the constant differentiation of matter inside the planet under the influence of gravity. Components with a large specific gravity tend to the center of the Earth, while lighter ones rise up and concentrate at the surface. When the planet was formed as a result of this process, a dense metal core was formed in its center. Another source of energy for the movement of matter can be the decay energy of radioactive elements. It accounts for ~ 12 % of the energy spent on tectonic processes, while gravitational differentiation is about 82 %. The continuous generation of heat in the deep bowels of the Earth leads to the formation of convective flows directed to its surface. The temperature difference in the hot core of the Earth and the temperature on the earth's surface can reach ~ 5–6 thousand °C. The rocks heated in the deep zones of the Earth expand, while their density decreases, and they move closer to the surface, giving way to lowering colder and, accordingly, heavier masses that have given part of the heat to the earth's crust. This process of heat and mass transfer due to the movement of light hot masses up and the movement of heavier colder masses down is continuous and takes the form of very slow convective flows.

In some areas, foci or even layers of partial melting of the substance may occur under an appropriate combination of conditions: rock composition, temperature and pressure in the bowels. Such an intermittent "layer", called

the asthenosphere, exists in the upper mantle, and magma is formed in it. Convection movements of magma are the cause of vertical and horizontal stresses and movements in the lithosphere.

The endogenous processes that form the earth's crust determine its nature and properties; under their action, the main forms of the mega relief of the Earth's surface are created – platform regions, mountainous countries and hills, huge depressions that enclose oceans and seas, etc.

The main types of manifestations of endogenous processes on Earth are: tectonic movements of the earth's crust, igneous, volcanic and metamorphic processes, as well as seismic activity.

Chapter 2.1. TECTONIC MOVEMENTS AND ROCK DISLOCATIONS

Tectonic movements of the earth crust. Lamination and folding. Plicative and disjunctive disorders and their impact on construction

Tectonic (from the Greek Tektonike – building art, creation) is defined as a process which causes vertical and horizontal movements of the earth's crust, as a result of which global tectonic structures are formed like mountain-folded areas, troughs, depressions, deep faults, etc. During movements, tectonic disturbances occur – changes in the initial massifs of rocks. These changes are particularly observed in sedimentary rocks, which are initially deposits in horizontal layers, and due to tectonic disturbances, these layers are crushed into folds or torn into separate blocks. Tectonic movements, finally, give the shapes and structures of the earth's crust observed by geologists.

Modern forms and outlines of continents and oceans were formed as a result of movements of plates of the lithosphere for many hundreds of millions of years. There are three main types of relative plate movements: discrepancy (divergence), in the form of *rifting* and *spreading*; convergence expressed by *collision* and *subduction* and *transform fault* (Fig. 2.1.1).

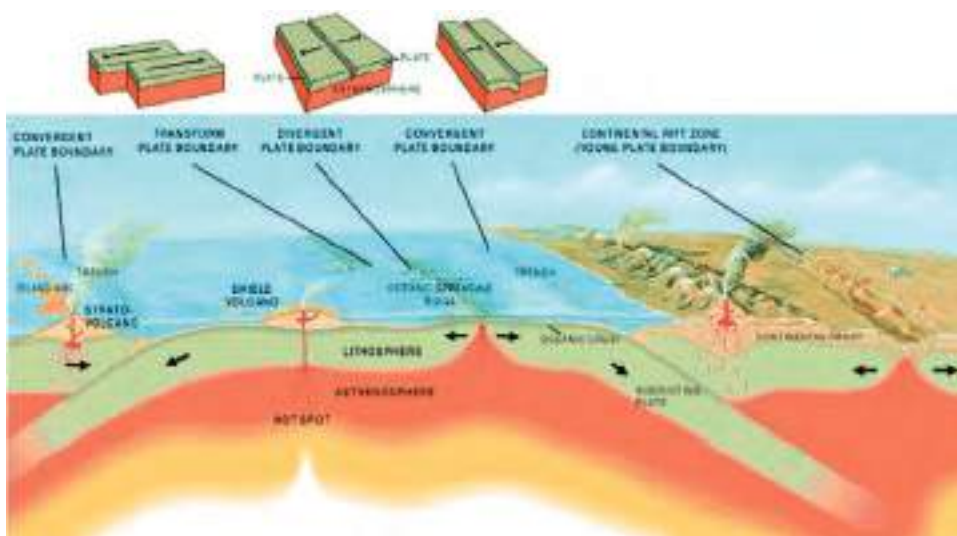


Fig. 2.1.1. Scheme of the main types of movement of the lithospheric plates
https://www.researchgate.net/figure/Figure6Crosssectionofplatetectonicmodel_fig2_288345537

Rifting is a process of rupture and mutual extension of the blocks of the earth's crust in continental and oceanic rift zones. A rift (from the English rift – cleft, gorge) is a linearly extended several hundred kilometers (often over 1000 km) slit-like structure of deep origin. Most continental and oceanic rifts have widths in the range of 30–70 km; however, narrower rifts are also known, for example, 5–20 km in the Dead Sea region and wider ones – 200–400 km in the Red Sea.

Currently, the most active system on the continents of the planet is the system of East African rifts where there is a thinning and ruptures of the continental crust, sometimes manifesting on the earth's surface (Fig. 2.1.2).

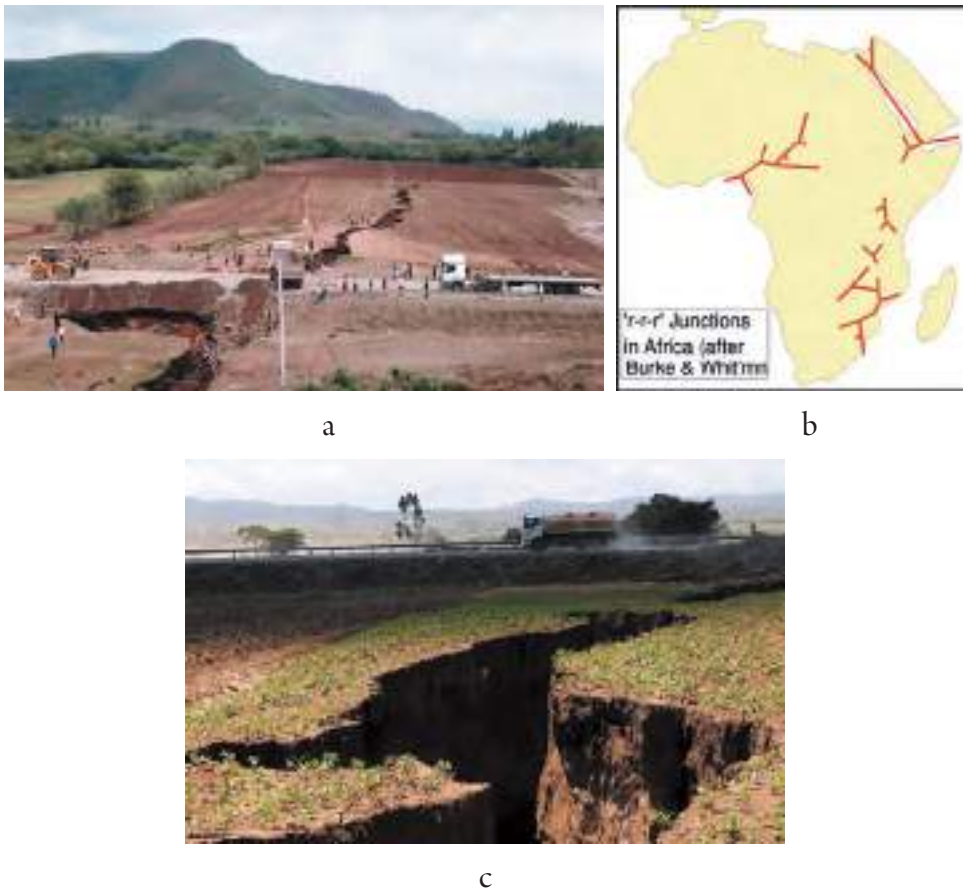


Fig. 2.1.2. Africa Rift Pattern (a) and Kenya ground breaks in 2019 (b, c)

a <http://plate-tectonic.narod.ru/image44w.gif>

b <https://www.colombia.com/tecnologia/ciencia-y-salud/una-inmensa-grieta-en-kenia-esta-partiendo-a-africa-en-dos-185762>

c <https://qz.com/africa/1242704/is-africa-splitting-into-two-continents/>

In some places (Afar – near the Aden Strait), the oceanic crust is in the process of formation and the development of which, is likely to give rise to a new ocean in future. Rifts of this type are formed as a result of the uplift of large, domed masses of hot mantle material – plumes that lift and stretch the crust. Active rifts are characterized by intense volcanoes (Fig. 2.1.3).



Fig. 2.1.3. Volcanic landscape in the rift zone, Ethiopia
http://debri.ru/uploads/posts/2011-03/1299650944_40.jpg

An example of a passive-type rift with a complex structure is the Baikal Rift System. Volcanism is currently absent in this area, but active tectonic movements, causing earthquakes, are observed. However, recently (in terms of geological time) volcanoes were active in neighboring smaller rift faults, and in Mongolia volcanism in the Quaternary period was developed very widely.

The deepest Lake Baikal on Earth (1642 m) (Fig. 2.1.4) was formed as a result of a shear along a huge fault crossing Eurasia from south-west to north-east, and the Baikal basin was formed due to a smaller fault that passed at an angle to the main one.

Spreading – a geodynamic process, defined as impulsive multiple pushing of the block-oceanic crust and filling the released space with magma. Spreading processes are observed mainly within the mid-oceanic ridges within the oceanic

crust, and in these areas it is much younger than at the edges of the oceans. The area of the earth's crust during spreading in the middle of the oceans increases and its decrease is observed on the periphery of the oceans due to subduction and collision of continents.



Fig. 2.1.4. Lake Baikal contains 19% of the world (!) freshwater reserves
<http://it.wallpaperswiki.org/wallpapers/2012/10/Beautiful-Lago-Baikal-485x728.jpg>

A *collision* (from Latin collision) of continents is a collision of lithospheric continental-type plates, resulting in crushing of the earth's crust and the formation of mountain-folded areas with a very complex internal structure. An example of a collision is the Alpine mountain belt formed during the “closure” of the ancient Ocean Tethys as a result of the movement of the African plate towards the Eurasian. Ocean area Thetis first shrunk from the Mesozoic era and by now this ocean has ceased to exist with the formation of the residual basins – the Mediterranean, Black, Azov and Caspian Seas. The Hindustan Plate at one time separated from Africa and moved to the northeast, also “collided” with Eurasia, forming the highest mountains of the Himalayas on the planet (Fig. 2.1.5). Continental collision is a relatively very long process. For example, in the areas

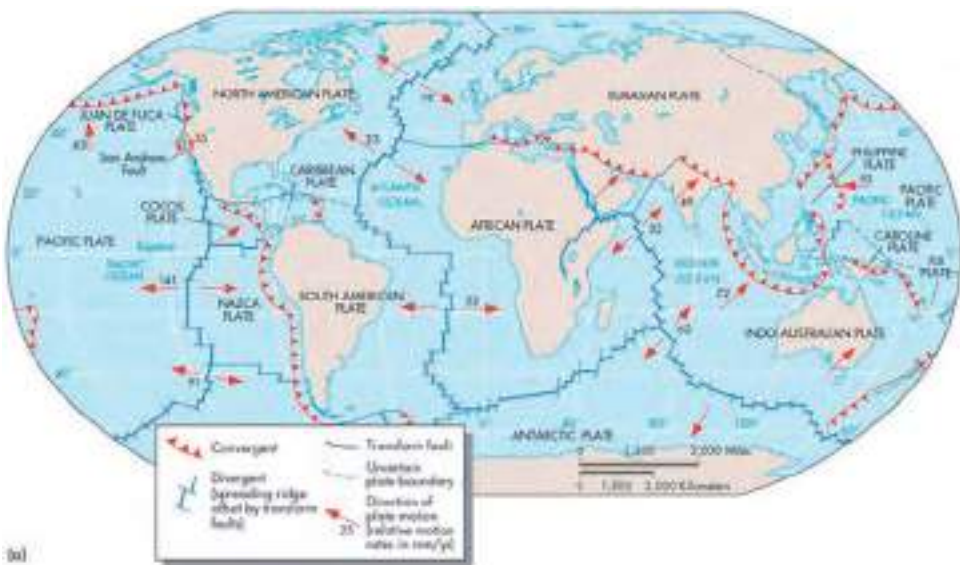
of contact between the Eurasian and Hindustan plates, it began in the Eocene (~ 55 million years ago) and is currently ongoing.



Fig. 2.1.5. The Himalayas are the highest mountains on Earth. View from Everest
<http://photography.nationalgeographic.com/wallpaper/photography/photos/best-wallpapers-2010/snow-veiled-peaks/>

Subduction is an interaction of lithospheric plates in which large sections of the earth's crust are immersed underneath others. Most often, it occurs in extended linear zones along which the oceanic crust moves under a continental plate or island arc and plunges into the mantle (Fig. 2.1.6). The process of this interaction of lithospheric plates in subduction zones is accompanied by active volcanism and seismicity. The average speed of movement of oceanic plates is 5–7.5 cm / year. There is a certain balance of matter in the lithosphere: the volumes of the oceanic crust plunging into the mantle in the subduction zones are approximately equal to the volumes of the crust formed in the spreading zones. At the same time, continental crust thickness is constantly increasing in subduction zones due to accretion, that is, “stripping” (by the principle of a bulldozer) and intensive crushing of the upper layers from an immersed plate. The most typical example is the subduction zone off the west coast of South America, where on one side of the continent the world's longest (9000 km) Andes mountains with high altitudes (Akongua peak 6962 m) were formed, and on the other, deep-sea

troughs in the ocean (depth of 7000 m and more). At the junction of the Pacific and South American lithospheric plates there is a constant voltage, which is a source of earthquakes and volcanic eruptions. Other examples are subduction zones near the Aleutian, Kuril and Japanese islands, the Kamchatka Peninsula, the islands of Sumatra, Java, New Zealand, etc. The large-scale absorption of the oceanic crust along the periphery of the Pacific Ocean (Pacific Ring of Fire) may indicate a reduction process of these oldest existing oceans of the planet.



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Fig. 2.1.6. Map of the directions of motion of lithospheric plates

http://fiden-2.phys.uafl.edu/webproj/212_spring_2015/Ariel_Ellison/Ariel_Ellison/page1.html

A *transform fault* is a type of fault located at the boundaries of the lithospheric plate and one of the three types of plate boundaries. The movement of the blocks of the earth's crust relative to each other occurs mainly horizontally in the direction along the fault, that is, the crust at the fault location does not thicken and does not sink into the mantle (in contrast to the zones of collision and spreading). Most of the transform faults are located at the bottom of the oceans near the active zones of the mid-ocean ridges, where the borders of the plates are formed in zigzags. Faults occur between crustal blocks that move parallel to each other at different speeds. They are oriented almost perpendicular to the mid-ocean ridges; the crust in such zones is divided into segments with an average width of 400 km.

A classic example of a transform fault is the San Andreas California fault (Fig. 2.1.7), which separates the North American Plate from the Pacific. The 1300-kilometer San Andreas fault is one of the most seismically active areas of the planet: the displacement rate of the plates relative to each other is 0.6 cm per year, and strong earthquakes with a magnitude of more than 6 occur on average every 22 years. This fault poses a very serious seismic hazard to the west coast of the United States, threatening the cities of Los Angeles and San Francisco.



Fig. 2.1.7. San Andreas Fault, California, USA. View from space
<https://geographyofrussia.com/razlom-san-andreas/>

Neo tectonic movements. These are modern tectonic movements that took place back in history as reported in documents, and some of which were measured instrumentally. The direction of movement can be vertical and horizontal. Modern vertical movements are quite widespread. Some areas of northern Europe in Sweden, Finland and Norway, as well as the Kola Peninsula in Russia, where the surface elevation rate reaches 25 mm / year, can serve as examples of modern positive, i.e. upward movements of the earth's crust. The main Caucasian ridge rises at a speed of 10–12 mm / year. The territories of Donbass (10.3 mm / year), cities like Kharkiv (3.9 mm / year), Vilnius (3.8 mm / year) among others, are rising. In the folded belt of the Pamir and Tien Shan, the amount of positive displacements in places reaches 50 mm per year.

The current negative (downward) movement of the earth's surface occurs in most of the territory of the Netherlands at a speed of up to 40–60 mm a year;

currently, one third part of the country's territory is below sea level. Significant areas of the West Siberian and Caspian lowlands, northern Crimea, the Kamchatka Peninsula, Sakhalin Island, the city of St. Petersburg (3.6 mm a year) are declining.

Vertical positive neo tectonic movements can be replaced by negative movements and can even alternate. So, starting from the IV century BC, the territory on which the ruins of the ancient Greek city of Hersonissos are located in Crimea, was flooded four times by the sea, and then rose above sea level. The cycle of marine transgression/regression was 500–600 years.

Modern tectonic movements must be taken into account when building on the shores of the seas, when creating hydrotechnical and other critical structures.

Lamination and folding. Folded and discontinuous dislocations of rock layers.

Sedimentary rocks are formed from rock fragments, chemical sediments and the remains of organisms that accumulate at the bottom of the oceans, seas, lakes, in rivers, intermontane valleys and other relief depressions and as a rule, initially occur in the form of horizontal layers. A *layer* is a relatively flat geological object that is homogeneous in composition and structure, bounded by practically parallel surfaces: the upper boundary of the layer is called the *roof*, the lower –

the sole. The term “reservoir” is usually used for layers of minerals, such as coal, salt, limestone, so on.

The types of layering reflect the characteristics of the natural conditions in which sediments accumulate. In this regard, four main types of layering are distinguished: horizontal (parallel or straight), oblique, lenticular and wavy (Fig. 2.1.8).

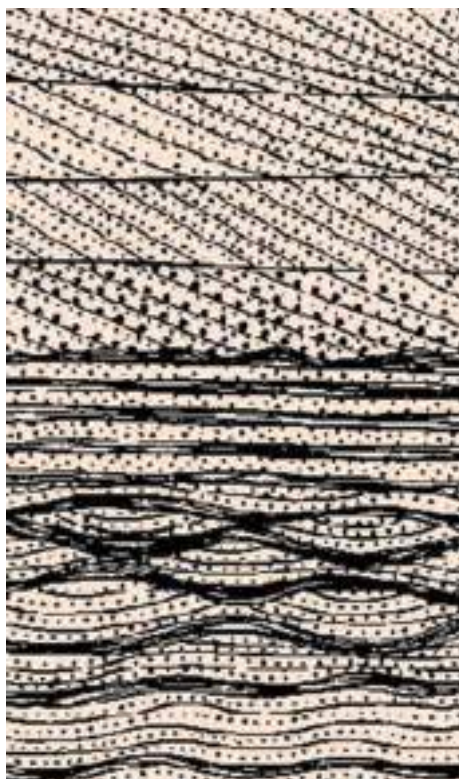


Fig. 2.1.8. Types of lamination:

- a – oblique;
- b – horizontal;
- c – lenticular;
- g – wavy

http://kaz2.docdat.com/pars_docs/refs/140/139872/139872_html_m66ddaf84.jpg

Oblique stratification is formed by the movement of water flows or mainly in one direction, for example, this occurs in rivers, with constant sea currents or constant winds. In alluvial (i.e. river) sediments, oblique stratification has a predominant slope in the direction of water movement – downstream; in marine sediments, the layers have a large thickness and a slight slope. In shallow water, a very thin, interwoven oblique stratification is formed, which has different directions.

Horizontal layering, when the roof and the sole of the layers are parallel, indicates a relatively sedentary or motionless environment in which sediment accumulated. Such conditions arise in lakes or deep sea basins below the level to which excitement and currents reach.

Lenticular stratification is formed during the fast and variable nature of the movement of water or air environment, for example, in the sea surf zone or in the valleys of fast moving rivers. It is characterized by the diversity and variability of lenticular bedding, shapes, composition and thickness of individual interlayers.

Wavy layering is formed during movements that have a periodic shift in opposite directions, for example, during ebbs and flows, coastal disturbances in shallow areas of various water bodies.

The primary occurrence of most sedimentary rocks is almost horizontal with an inclination angle of not more than 1° . Bedding with steeper angles of $3-10^\circ$ can occur on the slopes of terrestrial and underwater elevations, canyons, etc. The initial occurrence of layered strata is relatively rare – it is disturbed by subsequent tectonic movements in the earth's crust, which leads to a change in the tilt angles of the layers, the formation of folded and discontinuous dislocations (violations).

Plicate dislocations (from latine *Plico* – fold and *dislocatio*– displacement) are called disturbed bedding and plastic deformations of rock layers without their visible discontinuities. This type of dislocation includes the occurrence of layered strata in the form of monoclines, flexures and folds. The main cause of plicate disturbances is most often endogenous processes associated with the activity of the Earth's underlying forces (tectonic, magmatic). There are also plicate disturbances caused by exogenous processes, such as landslides, movements of large ice masses (glacier – dislocation), but tectonic processes have a predominant effect, in particular, horizontal compression occurring during collision of lithospheric plates.

Monoclinic occurrence occurs when, as a result of tectonic movements, horizontally occurring rock layers become inclined at the same angle in a large

area. Monocline is the simplest form of plicate dislocations (Fig. 2.1.9 a). It is widely represented in strata of sedimentary rocks covering young and ancient platforms. There are slightly inclined (up to 15°), gentle ($16\text{--}30^\circ$), steep ($31\text{--}79^\circ$) and vertical ($80\text{--}90^\circ$) monoclines.

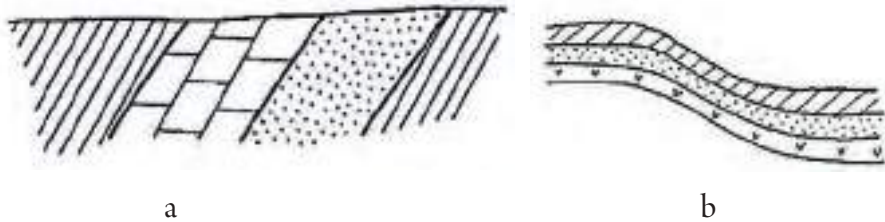


Fig. 2.1.9. The simplest plicate disorders: **a** – monocline; **b** – flexure
<http://biofile.ru/geo/23218.html>

Flexures are ledge-like violations of horizontally or obliquely occurring layers (Fig. 2.1.9 b). Flexures most often occur during tectonic displacements up or down the blocks of neighboring rocks. At displacements with small amplitude, discontinuities do not occur, but the thickness of the rocks in the shear zone (here the layers have a slope) is often less, compared to horizontally lying layers. In the structure of flexures, the lower, connecting and upper wings are distinguished. The connecting wing is a section in which the layers have a steep slope with less thickness.

Folded deformations or folds are zigzag bends of rock layers without gaps. This type of dislocation is most common. For example, the mountain system of the Greater Caucasus is characterized by complete folding, that is, all visible outcrops of rocks are folds, continuously merging into each other. Such folding is formed in the case of extremely active tectonic processes, which takes place in the Caucasus.

Depending on the size in the profile section, the following are distinguished: mega-folds with fold size (half wavelength) 1000 m or more; macro folds – between 50 and 1000 m (Fig. 2.1.10); meso-folds – 0.1–50 m; micro folds – less than 0.1 m.

The folds, the layers of which are curved in the middle up in the form of an arch, are called *anticlines*. At these folds in the middle (core), older rocks come out and can be observed in outcrops, older rocks and on the wings – younger ones. The folds, the layers of which are bent down, are called *synclines*. They have younger rocks in the middle part and older wings.



Fig. 2.1.10. Macro folds in the Zaskar Valley, Tibet
http://phototour.pro/kcfinder/upload/images/Max/Zaskar/Near_Padum_Zaskar.jpg

The two main forms of folds are anticlines and synclines (Fig. 2.1.11).

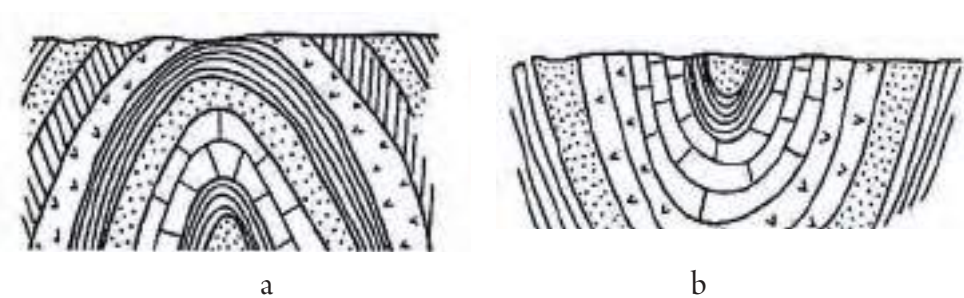


Fig. 2.1.11. The simplest forms of folds: **a** – anticline; **b** – syncline
<http://biofile.ru/geo/23218.html>

Depending on the position of the folds in space, the following varieties are distinguished (Fig. 2.1.12, 2.1.13).

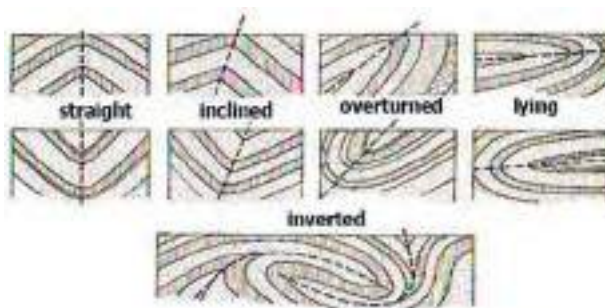


Fig. 2.1.12. Varieties of folds (the axial surface is indicated by a dotted line):

Straight folds – the axial surface is vertical and the wings fall in different directions at the same angles. **Inclined (oblique) folds** – the axial surface is inclined to the horizon and the wings fall in different directions at different angles. **Overtured folds** – the axial surface is steeply inclined, and the wings are inclined to one side at different angles. These folds distinguish between normal and overtured wings. **Lying fold** – the axial surface is parallel to the horizontal surface. The wings are inclined to one side at the same angle.

Inverted (diving) folds – the axial surface bends below the horizontal surface

http://geo.sfedu.ru/ucheb/files/obgeol/teoria/disl/skl_osi.gif



Fig. 2.1.13. Direct synclinal mesa fold, California, USA

<https://upload.wikimedia.org/wikipedia/commons/thumb/d/df/SynclineCalico.JPG/960px-SynclineCalico.JPG>

Disjunctive (discontinuous) dislocations (from latine *Disjunctivus* – dividing) are discontinuities in the continuous occurrence of geological objects. Discontinuous dislocations are formed as a result of intense tectonic movements in the earth's crust, which are accompanied by discontinuities in the rocks and

often displacement of layers relative to each other along these discontinuities. Disjunctive structures are more widespread than plicate ones.



Cracks are the smallest gaps without displacement observed in most mountain rocks, with the exception of weakly compacted and loose massif. Gaps with displacements are developed less frequently and are concentrated mainly in areas of intense mountain building and other tectonic processes. The amplitude of the displacements can vary within a very wide range: from a few centimeters to kilometers, and the width of the faults can reach several meters.

The main types of discontinuous dislocations include faults, reverse faults, overthrusts, grabens and horsts (Fig. 2.1.14, 2.1.15).

Fig. 2.1.14. Rock faults with offset Normal fault from Ptolemais, Greece
<https://www.pinterest.ru/pin/179932947598980584/?lp=true>

Often there are disjunctive disturbances with two or more rupture surfaces, for example, complex faults, reverse faults, horsts and grabens (Fig. 2.1.16).

Horst (from German *horst* – nest) is the displacement in the form of a block of the earth's crust sharply raised above the surrounding area along vertical or steeply falling tectonic faults (faults in faults). The height of horsts can be several

hundred meters and even kilometers, the length is tens of hundreds of kilometers with a width of tens of kilometers. Examples of horsts are Altai, the Black Forest, Sierra Nevada, Harz, Roraima (Fig. 2.1.17).

Graben (from German *Graben* – ditch) – a piece of ground crust, shifted downward from the surrounding area along steep or vertical tectonic faults. The length of the grabens reaches hundreds of kilometers with a width of about tens hundreds of kilometers. Grabens are usually formed in the zones of extension of the earth's crust – rifts (Fig. 2.1.18). The largest graben system of the East African rift contains large and very deep lakes Victoria, Nyasa, Tanganyika.

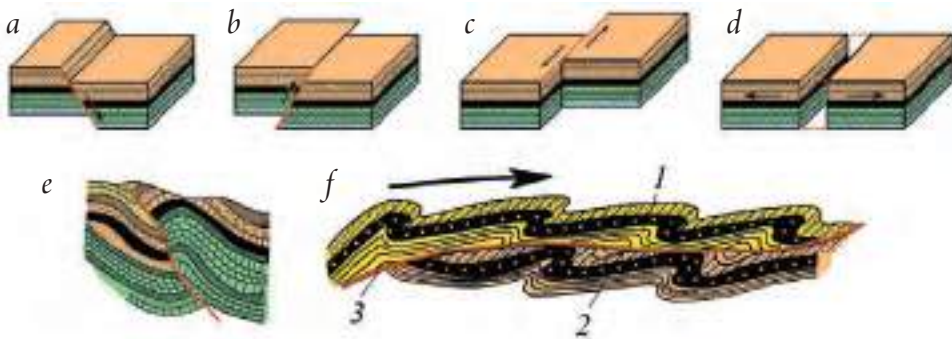


Fig. 2.1.15. Discontinuous dislocations

(arrows indicate the direction of displacement, the red line indicates the discontinuity surface, called the displacement):

- a** – discharge – discontinuous violation, in which the moving block of the earth's crust fell down in relation to the motionless;
- b** – uplift – a discontinuous violation, when the moving part of the earth's crust rose as a result of tectonic movement relative to the motionless one; angle of inclination of the mixer from 45° to 90° ;
- c, d** – shifts – discontinuous violations with horizontal parallel displacement or extension of blocks;
- e** – thrust – displacement, in the form of pushing one mass of rocks onto another at a fault with an inclination angle of less than 45° , and the layers lying on the upper side of the fault are shifted up, and from the bottom – down;
- f** – scoop (French *charriage*, from *charrier* – to carry or drive) or alpinotype thrust – very gentle thrust of large scales with the creep of the upper massif of rocks hundreds of meters thick (1) onto the underlying massif (2) almost a horizontal displacement (3) and rock displacement by several kilometers

<https://studfiles.net/preview/2269158/page:10/>

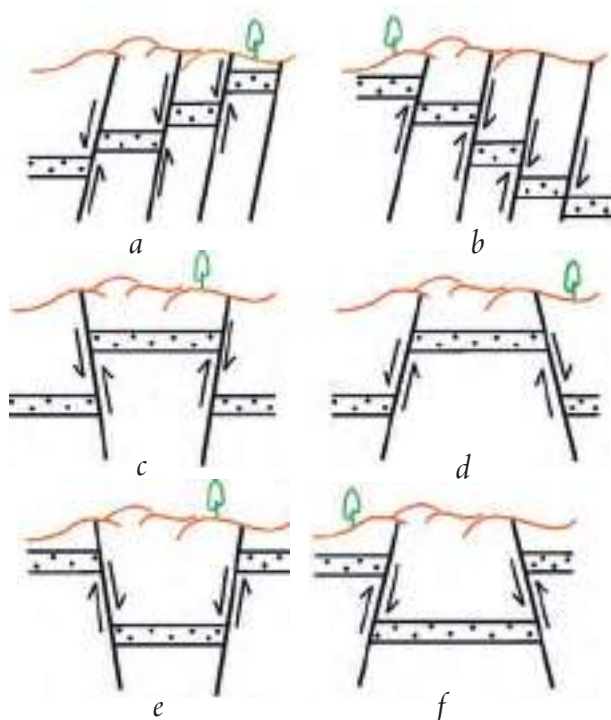


Fig. 2.1.16. Disjunctive disorders with several gaps: **a** – complex discharge; **b** – complex uplift; **c, d** – horsts; **e, f** – grabens

<http://gps.kh.ua/wp-content/uploads/2017/03/%D0%BC%D0%B5%D1%82-%D0%93%D0%9D%D0%93-14-04-2017-.pdf>



Fig. 2.1.17. Horst – Mount Roraima. It is a plateau (tepui) with an area of about 34 km² at the junction of Brazil, Venezuela and Guyana. The highest point of this massif is 2723 m above sea level. The plateau on all sides is limited by vertical cliffs with numerous waterfalls. Dense clouds constantly hang over Roraima, often there are tropical downpours. Only one relatively safe trail leads to the plateau. According to reports on an expedition to the area of this mountain, Arthur Conan-Doyle wrote the novel "The Lost World"

<http://i.imgur.com/AbdTfxz.jpg>



Fig 2.1.18. Graben in the Wallaby Rift, Kenya
<http://wildtraveler.com.ua/trash/statica/505/000033.JPG>

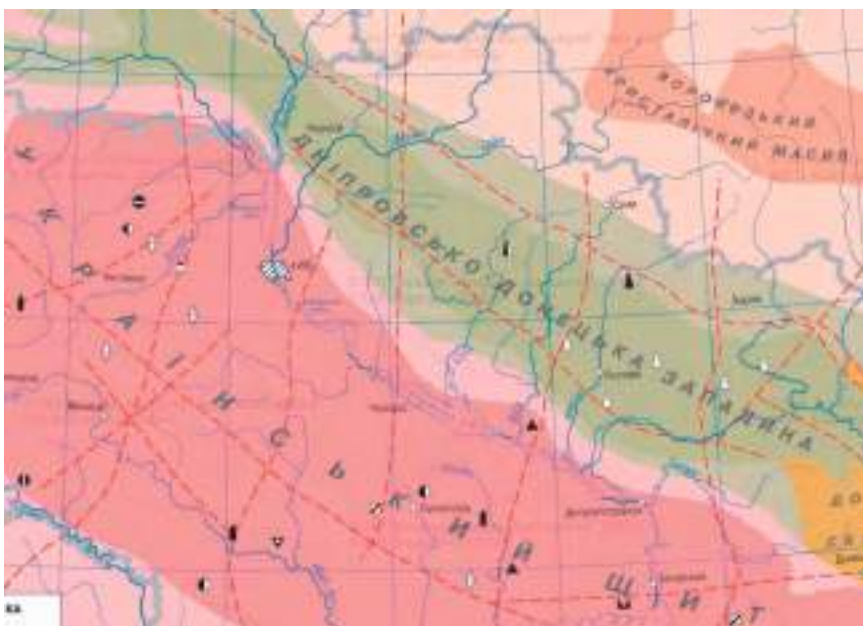


Fig 2.1.19. North eastern section of the tectonic map of Ukraine.
Red dashed lines indicate deep faults; dark gray – Dnieper central graben
<https://geomap.com.ua/uk-g8/864.html>

It should be noted that ancient tectonic disturbances of the Earth's crust can be almost invisible on the Earth's surface, since as a result of weathering processes for hundreds of thousands and millions of years, the elevations are destroyed, and the depressions are filled with sedimentary material. For example, the central graben of the Dnieper-Donets depression, stretching along the left bank of the Dnieper (Fig. 2.1.19), does not stand out on the ground, despite the fact that the immersion depth of the crystalline basement blocks in its middle (south-west of the Kharkov region) reaches 15 km, and on the slopes of the Dnieper, foundation rocks come to the surface.

Construction in conditions of tectonic disturbances

Dislocation of rocks at the sites of the projected foundations of buildings and structures, as a rule, worsens the construction properties of natural soil bases. This is manifested in significant differences in the properties of soils in different areas of disturbances, their fragmentation and fracture, and, as a result, uneven settlement under load. Sometimes there is the modern activity of disturbances, i.e., tectonic movement of soils, which can dramatically complicate the conditions of construction and operation of objects.

Thus, from a technical point of view, the most favorable areas for construction are those where rocks occur in the form of a continuous thickness or alternating horizontal layers of significant thickness with a uniform composition. In this case, the foundations of buildings and structures are based on a soil foundation in which uniform settlement occurs under the weight of the building and its greatest stability is guaranteed.

Dislocation of rocks, complex folds, and especially disjunctive disturbances, significantly complicates the engineering and geological conditions of construction – the homogeneity of the soil of the base of structures is violated, crushing zones, faults are formed and the strength of the rocks decreases. Due to discontinuous violations, displacements of rock blocks can occur, the regime of groundwater changes significantly: their increased inflow into construction pits and into underground structures is possible. All this, contributes to the uneven compressibility of the soil of the base and deformations of the building or structure due to the differential settlement of its various parts. It is especially unfavorable to place buildings on the lines of tectonic faults. Therefore, in areas where tectonic complications are expected, it is especially important to conduct thorough engineering-geological and geotechnical surveys at the site of future construction.

Control questions to chapter 2.1. Tectonic movements and rock dislocations

1. Definition of tectonic movements and their types.
2. Characteristics of rifting.
3. Characterization of spreading.
4. Characteristic of the collision.
5. Characterization of subduction.
6. Characterization of transform faults.
7. What are neo tectonic movements?
8. The definition of layering and its main types.
9. The main types of folded dislocations.
10. The main types of explosive dislocations.
11. Construction in conditions of tectonic disturbances.

Chapter 2.2. MAGMATISM AND VOLCANOES

Intrusive and effusive magmatism. The nature of volcanic eruptions. Post volcanic processes. Benefits of volcanism

Magmatism is called the underlying processes and phenomena associated with the formation and movement of magma from the bowels of the Earth to its surface, due to the internal heat and gravitational field of the Earth. Magma is a natural high-temperature melt formed in separate foci in the lithosphere and upper mantle, mainly in the asthenosphere.

Two types of magmatism are distinguished – *intrusive and effusive*. With *intrusive magmatism*, magma does not reach the earth's surface, but actively penetrates into the overlying rocks, partially melts them and solidifies in the cracks and voids of the earth's crust. With *effusive magmatism* (volcanism), magma reaches the Earth's surface and cools down to a resulting solid material of various types. In both cases, magmatic rocks are formed as a result of solidification of the melt. Forms of manifestation of one or another type of magmatism depend on a number of geological and tectonic conditions during the formation and movement of magma through the earth's crust.

Intrusive magmatism: If rising magma does not reach the Earth's surface, but cools down inside the earth's crust, deep magmatic bodies are formed – intrusions. The shape of these bodies can be very diverse and, in turn, is determined by the composition and physical properties of magma, as well as the nature of the strata of the host rocks.

There are two main ways magma is introduced into the enclosing stratum:

- magma can penetrate along the bedding planes of sedimentary rocks or along cracks and faults crossing the enclosing stratum may raise the roofing layers or, conversely, cause deflection of underlying layers under the effect of its mass;
- in the case of the introduction of large masses of magmatic melt, roof rocks collapse, which sink and assimilate with the melt, i.e. magma itself forms a space which it ultimately occupies.

Various mechanisms of intrusive bodies depend on the mechanism of magma incorporation in the resulting mass. The main types and conditions of occurrence of igneous intrusive bodies are discussed in chapter 1.1.3.

Effusive magmatism: This kind of magmatism is observed if magma rising from depths reaches the Earth's surface and pours onto it in the form of lava flows, i.e.

magma which is poured onto the surface turns into lava. Lava differs from magma in that it contains almost no volatile components (gases and water vapor), which, during eruption and a sudden drop in pressure, are released from the magma into the atmosphere. When magma erupts on the surface, three main types of volcanoes may be encountered: plane or flat volcano, fissured and central.

Plane volcanoes, representing the “seas” of molten lava, existed only at the very early stages of the Earth’s formation. At that time, the earth’s crust was much thinner than it is nowadays and, in some areas, it could completely melt and magma outflows occurred over vast areas. Currently, volcanoes of this type are absent on Earth.

Fractured volcanoes are outpourings of lava to the surface from extended cracks and faults. The propagation of fissured volcanism in some periods of the Earth’s development was very widespread. Now, fissured volcanoes are limited in distribution and are found only in certain areas, for example, the Laki and Krafla volcanoes in Iceland (Fig. 2.2.1) including some volcanoes in Kamchatka. Fractured outflows are also widespread on the slopes of large volcanoes in the Hawaiian Islands. So, on the southeastern side of the Kilauea volcano, a stream of liquid lava 6.5 km long and only a few centimeters thick spilled from a crack 9 km long. Fissure-type eruptions, apparently, are widely developed in the underwater faults of the Mid-Atlantic Ridge, East Pacific Rise, and in other active zones of the World Ocean.



Fig. 2.2.1 Eruption of the Krafla Fracture Volcano, Iceland

http://www.auburn.edu/academic/science_math/res_area/geology/camp/Fissure1.jpg

The central type of volcanoes. Most modern volcanoes are central type volcanoes. As a result of eruptions of such volcanoes, cone-shaped structures are usually formed – strata volcanoes, composed of alternating layers of eruption products: solidified lava, tephra (volcanic ash), pumice, and volcanic glass. Photos of some volcanoes of this type are shown in Fig. 2.2.2, 2.2.3.



Fig. 2.2.2. Mount Kilimanjaro. This is no longer an active stratovolcano on the border of Tanzania with Kenya. Kilimanjaro is the highest point in Africa (5,892 m above sea level) and the largest free-standing mountain in the world. The volcano is famous for its snow-capped peak, which, despite its proximity to the equator, rises above the savannah
http://wallaroo.ru/wp-content/uploads/2014/04/Kilimanjaro_paulshaffner-1024x648.jpg

Since the advent of the science of volcanology, experts have tried to calculate the total number of fire-breathing mountains on Earth, but until now the exact numbers are not known, although 1532 volcanoes are listed in the catalog of the Smithsonian Institution, considered to be the most reliable. The problem of calculating volcanoes is associated with poor knowledge of the bottom of the oceans, where there may be many but not yet been discovered. For instance, in the Pacific Ocean it is assumed that there are at least 10 thousand places of outpouring of lava.

According to some scientists, about 75% of all the volcanoes of the planet are on the ocean floor, and their total number can reach 6000.



Fig. 2.2.3. Volcano Bromo. This is an active volcano, which is part of the Tengger mountain range in the east of Java. The top of the volcano exploded, and now the crater spews white hydrogen sulfide smoke. The volcano is surrounded by the so-called “sea of sand” (Laut Pasir) with dark volcanic sand

<https://cattur.ru/asia/indonesia/bromo.html>

On land of our planet, most volcanoes are now periodically activated, and for long periods of time they are in a “sleeping” mode. In sleeping volcanoes, the signs of volcanism are manifested only in the form of outlets of water vapor, fumaroles (outlets of various gases), hot (maybe boiling) lakes and geysers. Extinct (conditionally) volcanoes include those that did not resume their activities during the history of mankind. Most volcanoes are located in zones of tectonic activity at the edges of lithospheric plates (Fig. 2.2.4), although there are a number of exceptions, for example, very active Hawaiian volcanoes located in the middle of the Pacific plate.

Classification of volcanoes by the nature of eruptions. Volcanic eruptions are of different individual nature: they can be accompanied by explosions and earthquakes or proceed quietly.

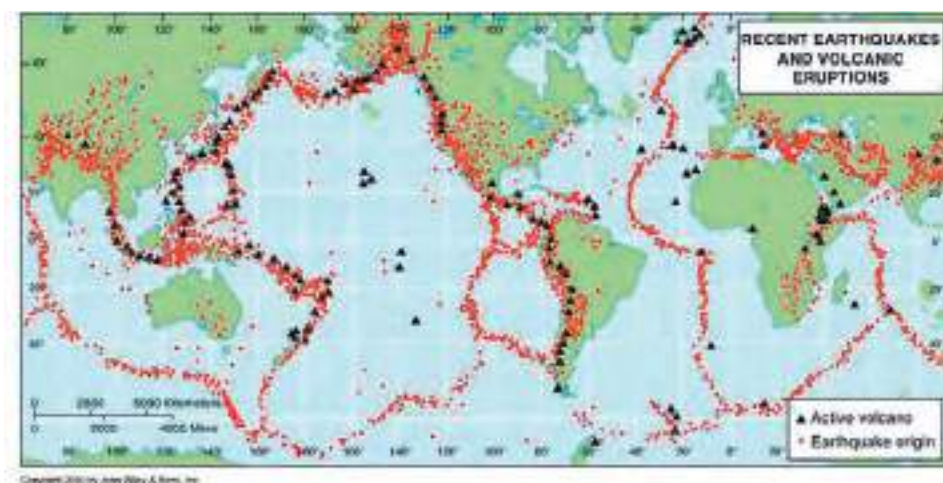


Fig. 2.2.4. Map of active volcanoes (black triangles) and recent earthquakes (red circles)
https://geo.bsu.by/images/pres/oz/oz_zaoch/oz_zaoch_5.pdf

Volcanoes by the nature of eruptions are divided into three categories: lava, gas-explosive and mixed. The nature of the eruption, in turn, is determined by the composition of the lava and its temperature, on which depends the degree of viscosity, mobility of the lava and the amount of gas contained in it. During volcanic eruptions, three main processes are observed:

- effusive (lava) – the outpouring of lava from the mouth of a volcano and its spreading over the earth's surface;
- explosive (gas-explosive) – explosion and outward release of a large amount of pyroclastic material (solid eruption products);
- extrusive – squeezing magmatic substances to the surface in a liquid or solid state.

In a number of cases, the simultaneous action of these processes and their complex combination are observed. In each category of eruptions, individual types of volcanoes are distinguished, which are called the most characteristic volcanic eruption of this type (Tab. 2.2.1).

The Hawaiian type of eruptions is characterized by outpourings of liquid, very mobile lava of basaltic composition, as a result of which huge flat shield volcanoes form (Fig. 2.2.5). Pyroclastic material almost does not stand out. During eruptions, lava fountains are ejected through the central channel or lateral faults and flow down the slopes with streams of small thicknesses along tens of kilometers. Lava can accumulate in old craters, forming lava lakes. The Hawaiian type, in addition to the Hawaiian volcanoes, is close to the eruptions of the volcano La Fournaise

on the island of Reunion (Indian Ocean) and the Great Fissure Tolbachinsky eruption in Kamchatka.

Table 2.2.1

Classification of volcanoes by the nature of eruptions

Type of eruption	Type of volcano	Typical volcanic eruptions and years	Location
Effusive (lava)	Hawaiian	Mauna Loa (1950), Kilauea (1959)	Hawaiian Islands
	Icelandic	Lucky (1782), Hekla (2000)	Iceland
Explosive (gas explosive)	Krakatau	Krakatau (535, 1680, 1883)	Indonesia
	Bandaysan	Bandai san (1888)	Japan
	Katmaisky	Kathmai (1912)	Alaska
	Gas explosive funnels	Maars	Germany, France
Extrusive	Peleysky	Mont Pele (1902)	Martinique, Antilles
Mixed	Plinian (ethno-vesuvian, volcanic)	Vesuvius (79, 1944), Etna (1226 BC–2013), Vulcano (183 BC, 1890)	Italy
	Strombolian	Stromboli (regularly for 2400 years)	Italy



Fig. 2.2.5 a – Kilauea Volcano. This is the youngest of the chain of volcanoes involved in the formation of the Hawaiian Islands and one of the most active volcanoes on Earth.

It is very low and flat, which distinguishes it from most volcanoes. Arisen in 1952, it erupted 33 times, the last eruption began on January 3, 1983 and continues to this day
<https://news.day.az/world/864687.html>



Fig. 2.2.5 b – Piton de La Fournaise in eruption (Reunion Island, Indian Ocean) – April 2020
<http://www.ipreunion.com/volcan/reportage/2020/04/07/volcan-recap-volcan-recap,117202.html>

The Icelandic type is characterized by eruptions of very liquid basaltic lava with inclusions of clastic and pyroclastic material, with the formation of flat shield volcanoes. Eruptions occur mainly through cracks.

Krakatau type of eruptions. A characteristic feature of this type of eruptions is sudden explosions of high power, accompanied by the release of a huge amount of ash, lappillas and volcanic bombs into the atmosphere. A grandiose explosion of the Krakatau volcano located in the Sunda Strait between the islands of Sumatra and Java occurred in 1883. The roar of the explosion was heard at distances up to 5000 km, and a column of volcanic ash rose to 100 kilometer high. A giant funnel (caldera) arose on the site of Krakatau Island, into which ocean waters collapsed and instantly boiled. Gigantic waves, 20–40 meters high, formed (tsunami), from which up to 40 thousand people died in the coastal regions of Indonesia. In 1927, the Anak Krakatau volcano (Child Krakatau) rose from the sea on the site of an exploding old volcano. The volcanic island continues to grow, adding up to a height of 7 meters every year. The last eruption of Anak began in April 2008 and continues to this day (Fig. 2.2.6).



Fig. 2.2.6. Anak Volcano Island, Krakatau, Indonesia

<https://aviav.ru/vlasti-indonezii-izmenili-rezhim-proleta-v-rayone-izverzheniya-anak-krakatau.html>

Earlier, one of the strongest eruptions of the Krakatau type occurred in 1815 on the Indonesian island of Sumbawa where the Tambora volcano explosion occurred. A huge amount of ash (about 100 km^3) was thrown from the crater to a height of 20 km. At the same time, volcanic bombs up to 13 m in diameter were scattered at a distance of up to 40 km and 150 km from the volcano the thickness of the layer of precipitated ash reached half a meter. During the explosion and its consequences more than 100 thousand people lost their lives.

Bundaysan type (gas or phreatic eruption). This type of central eruption includes those when, after a very long period of silence, the activity of the old volcano, which was considered extinct, suddenly resumes. The activity of the volcano consists in very strong, but very brief explosions, which are accompanied by emissions of huge masses of water vapor and fragments of solidified lava, in the complete absence of molten material. This was the eruption in 1888 of the Japanese volcano Bandai-San, which had been silent for more than a thousand years. The cause of such eruptions is considered to be a gradual accumulation of heat from the decaying source and a slow increase in vapor pressure from atmospheric waters penetrating into the depths to the state of explosion.

The Kathmay type of eruptions consists in the release of hot gas, emissions of volcanic sand and pumice debris, originating mainly from a system of numerous cracks. A gigantic eruption of this type occurred in 1912 near the Kathmai volcano in Alaska, when up to 16 km^3 of finely divided material was deposited in the Valley of Ten Thousand Smokes over an area of 140 km^2 , which completely smoothed the relief. The eruption occurred from the emerged volcano Novarupta and cracks at the bottom of the valley.

Gas explosive funnels (Maars) are cylindrical or funnel-shaped craters of a gas explosion that occurs without an outpouring of lava. Sometimes they are surrounded by peculiar shafts of rocks raised by the explosion. The depth of modern maars reaches 400 m, the surface diameter is from 200 m to 3.2 km. Typical maars are found in Germany (the Eifel volcanic massif, Fig. 2.2.7) and in France (Auvergne). They are often filled with water. Maars are formed as a result of a single explosion of great strength, caused by the penetration of groundwater and their contact with hot rocks.



Fig. 2.2.7. Volcanic craters – Maars, Germany
<http://www.turkcebilgi.com/uploads/media/resim/maare.jpg>

The Pele type of eruptions is characterized by the formation of grandiose red-hot pyroclastic flows or scorching clouds (Fig. 2.2.8), as well as the formation of a volcano in the vent and the growth of extrusive domes from extremely viscous lava. This type of eruption got its name from the volcano Mont-Pele or Montagne-Pele (French: Montagne Pelée – Bald Mountain), located on the island of Martinique (Lesser Antilles). On May 8, 1902, the explosion destroyed the top of an awakened volcano, and a red-hot heavy cloud escaping from the vent destroyed the city of Saint-Pierre (Fig. 2.2.8, 2.2.9).

The clouds escaping from the crater of the Pele volcano were a mixture of hot asphyxiating gases, hot stone fragments and molten glassy matter. This mixture, being too heavy to climb up, flowed down the slope, sweeping away everything in its path.

Its speed was such that 30 thousand inhabitants died before they could understand what had happened. A black cloud pierced by lightning bolts rolled down the slope of Mont Pele at a speed of almost 150 km/h and swept the city 9 km away from the eruption. The temperature of this incandescent cloud apparently reached 800 °C. Its mechanical action was unbelievably strong. The thickest trees were uprooted; all the walls of the stone buildings, perpendicular to the direction of the cloud's movement were destroyed ground level. The fiery cloud that destroyed the city scattered almost as rapidly as it appeared and there was literally nothing left of the city but



Fig. 2.2.8. Pyroclastic flow – a hot gas-ash cloud
http://www.photovolcanica.com/Pictures_V2/Picture_MS10_0717.html



Fig. 2.2.9. The city of Saint-Pierre
after passage of a red-hot cloud
https://specialcollections.bloglib.cam.ac.uk/wp-content/uploads/2012/09/Y307E_19.jpg

flaming ruins. Everyone in the city and in the harbor died, including sailors on ships. One only man who survived was Augusto Cyparis, a prisoner in a local prison who was serving his sentence in a stone cell without windows. The stone walls of the prison did not have time to heat up and as such, the prisoner was protected, escaping with burns only. The catastrophe that claimed the lives of thirty thousand of his fellow citizens was a matter of fate for him. Four days later, rescuers released him, and the governor of the island pardoned the prisoner. Augusto Cyparis joined the circus troupe and traveled the whole world as a prisoner of Saint-Pierre, telling his story and showing scars from burns.

Peleus eruptions are usually preceded by strong underground tremors. Volcanic magma is inactive, has extreme viscosity and contains a large amount of gas. Eruptions are accompanied by strong explosions, and since the main vent is often blocked by a dome of solid lava, liquid lava often makes its way through side cracks. Upon reaching the surface from the crater, the lava, due to its considerable viscosity, is squeezed upwards in the form of a huge stone “cork” forming an obelisk (Fig. 2.2.10).



Fig. 2.2.10. The top of the Mont Pele volcano 10 months after the eruption

<http://scbist.com/blogs/admin/310-mon-pele-vydoh-preispodnei.html>

At the same time, heated gases, drops of liquid lava and ash, which form scorching clouds from the hot products of the eruption, burst from under the “plug”.

Six months after the eruption, Mont-Pele surprising phenomenon occurred: a sharp tooth began to grow from its crater – an obelisk of solidifying lava. Starting from November 4, 1903, every day, it went up to a height of three meters. The shape and size of the obelisk were constantly changing. Either its top will collapse so much that it will drop to a height of 15 meters, then it will extend up to a height of 50 meters. At night, the obelisk shone especially brightly in

cracks and in those places from where the blocks came off. By summer 1903, the height of the cone reached 375 meters with a diameter of 100 meters at the base and the walls of the cone were dotted with deep vertical grooves because during squeezing, the lava material was still very viscous. Lumps breaking off from the obelisk and falling to its foot by the end of 1903 filled up the remaining space of the crater and almost hid the part of the obelisk that had been preserved by then.

Plinian (*Ethno-Vesuvian, volcanic*) is a type of eruption in which extremely powerful explosive emissions of lava, various gases and steam are released from the volcano, accompanied by massive loss of volcanic rock fragments and pyroclastic lava flows. The name is associated with the name of the ancient Roman writer and scientist Pliny the Elder, who died in the city of Stabia and watched the eruption of Vesuvius in 79 AD. Volcanoes characterized by this type of eruptions, besides Vesuvius (Fig. 2.2.11), include many Mediterranean volcanoes (Etna, Vulcan and others), stratovolcanoes forming the Pacific Ring of Fire, for example, St. Helens (USA), Fuji (Japan), Readout (Alaska) (Fig. 2.2.12). In addition, this type is characteristic to the so-called “super volcanoes” – almost flat volcanic territories located over huge spaces filled with magma, such as the Yellowstone Caldera in the United States.



Fig. 2.2.11. Vesuvius Volcano, Italy. The only active volcano in continental Europe. It is one of the most dangerous since up to 3 million people live in its environs, including in Naples. More than 80 of its significant eruptions are known. The most famous happened on August 24, 79 CE, when the ancient Roman cities of Pompeii and Herculaneum were destroyed

http://g.io.ua/img_aa/large/1655/54/16555401.jpg



*Fig. 2.2.12. Eruption of the Redoubt Volcano, Alaska, 1990.
It belongs to the Plinian type – the same as the eruption of Vesuvius*
<https://i.ytimg.com/vi/XzMtpSzYERl/maxresdefault.jpg>

Eruptions of the Plinian type volcanoes occur with large explosions, ejecting a large amount of lava, which freezes in the air and falls onto the slopes of the volcanic cone and into adjacent territories in the form of volcanic ash, sand, lapilli and volcanic bombs (Fig. 2.2.13).



Fig. 2.2.13. Volcanic bomb
<https://deacademic.com/dic.nsf/dewiki/201362>

Huge pressure and exhaust gases break through the clogging plug of the volcano, throwing boiling clay and stone blocks from the walls of the crater into the air. Within a few hours during the eruption of the Plinian type, several cubic kilometers of material can be thrown out onto the surface through volcanic channels. Pyroclastic flows and scorching clouds form from ash clouds. An erosion column consisting of volcanic ash (Fig. 2.2.12) often reaches the stratosphere, where the particles scatter and begin to act as a powerful light filter, which prevents the penetration of solar radiation to the surface of the Earth. This, in turn, leads to a sharp decrease in air temperature causing the “volcanic winter effect”. After especially large eruptions, cooling was noted on all continents of the Earth.

Lava, flowing from the crater, slowly moves in separate streams at a relatively low speed. So, the lava of Vesuvius at the initial moments can have a speed of about 1 m/s, and then the speed gradually decreases to several meters per minute or less. The length of the lava flows is relatively short: some end in the first kilometers, some reach 15 up to a maximum of 30 km. A characteristic feature of volcanoes of this type is the occurrence of side or parasitic craters, located on the slopes of the main volcano. A clear example of this type is the Etna volcano, Sicily.

The Strombolian type of eruptions is characterized by periodic gushing from the main lateral crater or fissure on the slope with basalt lava. Emissions of lava or clouds of gas and ash of small capacity and volume can be regularly repeated, often at regular intervals – from a few minutes to an hour. At the same time, the erupted lava has a viscous consistency and its flows are of short duration. Fragments of the lava are represented by semi-liquid volcanic bombs, lapilli and smaller droplets that freeze during flight in the air. The Strombolian type of eruptions is named after the Stromboli volcano (Fig. 2.2.14), located on one of the Liparsky (Aeolian) islands in the Tyrrhenian Sea, in the north of Sicily. Volcanic activity of Stromboli began about 200 thousand years ago, but then it went to the surface of the sea, two kilometers from the current volcanic island. From the first Stromboli, a rock 50 m high, called Stromboliccio, has been preserved. And the practically unceasing eruptions of modern Stromboli began from 2400 to 3000 years ago. In manuscript documents, they are recorded around 1000 AD.

Sailors and fishermen during that time avoided the island of Stromboli: flashes of fire, the smell of sulfur and clouds of ash inspired superstitious fear, but over time they appreciated the benefits of the volcano: its fire showed them the way at night, and later sailors began to call it “Tyrrhenian lighthouse.”



Fig. 2.2.14. Stromboli volcanic eruptions are low in intensity and very regular
<http://picaboom.ru/wp-content/gallery/118-vulkan/1.jpg>

Post-volcanic processes that occur after the eruption of a volcano can last for very long time. Post-volcanic processes and phenomena can be both dangerous and useful. Volcanic gases contain chemical elements that form compounds harmful to human health, which can cause poisoning and damage the airways and eyes. But at the same time, hot mineral springs formed in volcanic areas often have healing properties, helping with various diseases.

Magma in areas of active volcanism cools quite slowly, which leads to the appearance of characteristic phenomena, the main ones are: fumaroles, geysers, and mud volcanoes.

Fumaroles (Italian *fumarola*, from lat. *Fumo* – smoke) are gas outcrops through the cracks and openings located in the craters, on the slopes and at the foot of volcanoes (Fig. 2.2.15). Fumaroles can be activated before the eruption of the volcano, but more often this occurs after the eruption. The gas exiting from the cracks can be either steam from heated groundwater, or it can be a product released from magma. Fumaroles are often dangerous due to the high concentration of toxic gases – for example, sulfur dioxide, which can damage the health of local residents and animals.



a



c



b

*Fig. 2.2.15. Fumaroles on the slopes of volcanoes: **a** – Readout, Alaska*
<https://www.iconspng.com/image/87118/mt-redoubt-20090321-1237756418-ak231;>

b – Forpickd, Alaska
[http://vmestah.ru/wp-content/uploads/2014/09/Fourpeaked.jpg;](http://vmestah.ru/wp-content/uploads/2014/09/Fourpeaked.jpg)

c – Ebeko, on the island of the same name of the Kuril island chain, where roaring fumaroles are known
<http://www.zadumka.org/wp-content/uploads/2013/11/Фумарола-на-вулкане-Эбеко-Курильские-острова-25-метра.jpg>

Fumaroles can be:

- dry with a high temperature (650–1000° C) – they usually do not contain water vapor and gases mainly consist of chlorine compounds;
- acidic – less hot than dry with a temperature of 400–600° C; they contain HCl, SO₂, H₂S, water vapor and sublimates of iron, magnesium, aluminum and manganese chlorides;
- alkaline – the composition includes alkaline compounds, gases of ammonia salts and ammonia sublimates, ammonium sulfates and fluorides, steam and water; temperature – 200–400° C;
- hydrogen sulfide with temperature in the range of 100–300° C and contain sulfur compounds, which are intensively deposited at the exit points;
- carbon dioxide (*mofetta*) – mainly consist of carbon dioxide, with an admixture of methane, nitrogen compounds and are the coldest as compared to the previous ones. Mofetta (Italian mofetta – the place of fetid fumes on the earth) are fumaroles with a temperature of 100° C and below. The hollows where the mofettas are located are called death valleys, as domestic and wild animals get suffocated.

A large number of fumaroles is available in regions with active volcanic and post-volcanic activity: in Yellowstone National Park in the USA, in the “Valley of Ten Thousand Smokes” in Alaska, Kamchatka, the Kuril Islands, Iceland, Italy and Chile.

Geysers (from Iceland. *geysa* – gush) are hot springs that periodically gush out with hot water and steam, often to a considerable height. Their name comes from “Geysir”, the name of the most famous source of this type in Iceland (Fig. 2.2.16). Geysers arise in those areas where at a relatively shallow depth (several tens or hundreds of meters from the surface) there is a rapid increase in temperature reaching the boiling point of water. The frequency of emissions of a steam-water mixture of various geysers ranges from several minutes to several days.

The appearance of geysers requires particularly favorable conditions that develop in rare areas on Earth.

Most geysers are located in Yellowstone National Park, USA – about two hundred. The largest in the park is the Giant, which emits steam and water up to a height of 40 meters with a period of 3 days and the “Old Servant” (fountain height – 42 meters, every 50–70 minutes). One of the most picturesque is the Castle geyser (Fig. 2.2.17).

There are about 30 geysers in Iceland, among which, besides the “Old Geysir”, one of the most active geysers on the planet stands out – “Strokkur”,

erupting every 5–10 minutes, and “Jumping Witch (Grill)”, gushing with steam-water mixture every 2 hours at a height of 15 meters.

The largest geyser in the world-famous “Valley of Geysers” in Kamchatka – “The Giant”, emits jets of water to a height of 40 meters and steam several hundred meters high. In total, there were about 100 geysers in Kamchatka before the debris flow in 2007, of which about 20 large ones.

The activity of geysers can stop or even permanently stop due to changes in the bowels, earthquakes and other factors. Thus, the largest and most powerful New Zealand geyser Waimangu on Earth existed from 1899 to 1904. It threw out about 800 Tons of water during each eruption, and the stone fragments captured by the stream rose to a height of more than 450 meters. It gushed irregularly with a period of five to thirty hours. The action of this geyser ceased after the water level in the lake, located nearby, decreased by 11 meters and, apparently, it fed the geyser.

The action of geysers is caused by the contact of water filtered from above with superheated rocks from a nearby magma chamber, after which water under the action of geothermal energy quickly heats up, boils and is thrown up with force. The outlet channel of the geyser has bends that prevent free access to the surface of the steam and cooling water by convection (Fig. 2.2.18). After the outflow, the water in the geyser gradually cools, re-seeps into the hot rocks, boils and again gushes.



Fig 2.2.16. Geysir, Iceland, which gave the name to all modern geysers
<http://dic.academic.ru/pictures/wiki/files/68/DSCN3788.JPG>



Fig. 2.2.17. Geyser "Castle", Yellowstone National Park, USA
<https://drscdn.500px.org/photo/101440025/m%3D2048/a47203938a2798a9f9cd78324190aef0>

Geysers having an alkaline composition contain dissolved silica. At the opening of the outlet channel, deposits of siliceous tuff (geyserite) can form a cone up to several meters high.

As a result of the formation of vapor bubbles at a depth, the liquid level in the geyser channel rises up to its outflow onto the surface, while a drop in pressure leads to boiling of the remaining water, the formation of a large volume of superheated steam and a steam-water jet ejected to a great height. Most of the erupted water returns to the geyser channels through cracks from the surface of the earth. However, the presence at a shallow depth of recently solidified magma indicates that part of the water may be of magmatic origin. Such constrictions differentiate geysers from the much more common hot springs. Although no one has yet been able to see exactly what this plumbing looks like, it must be something like this diagram.

Mud volcanoes are a kind of hot springs, which are filled with a clay substance of a flowing mud-like consistency (Fig. 2.2.19). On the surface of the earth they are either rounded depressions (*salses*) or cone-shaped elevations with a crater (*mud hills*). From such a cone, either periodically, mud masses erupt

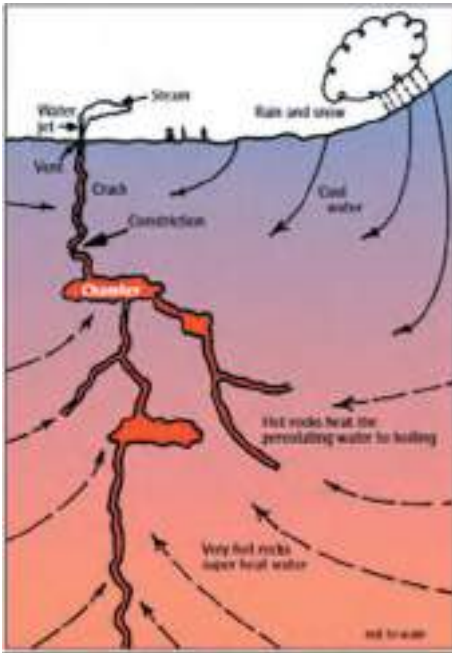


Fig. 2.2.18. Scheme of action of a geyser
<https://www.yellowstonetreasures.com/2015/01/20/yellowstone-geyser-eruptions-how-do-they-work/>

on the surface along with gases, often containing oil and mineralized water. The dimensions of a mud volcano range from large elevations, such as Bolshaya Kaniza, Azerbaijan, to tubercles of several centimeters high. They are often found in areas of active seismicity and volcanism, as well as in areas of oil and gas fields. The dirt in the volcano due to gases often bubbles, has an elevated temperature and can have a different color. With a high concentration of sulfur in the mud, its color will be yellowish, and iron, in combination with other elements, gives a red shade.

For the formation of a mud volcano, several conditions are necessary – a sufficient concentration of post-magmatic gases or underground accumulations of petroleum gases, the presence of pressurized groundwater, as well as highly cracked clay rocks that can liquefy.



Fig. 2.2.19. Mud volcanoes in the Gobustan reserve
<https://ilham-ahadli.livejournal.com/8083.html>

The mechanism of operation of mud volcanism is as follows: gases (methane, hydrogen sulfide and others) emitted from the cooling magma chamber or oil deposits rise upward in tectonic faults. If clay rocks liquefied by pressurized groundwater are found on their way, the gases squeeze the clay mass to the surface.

The nature of eruptions of mud volcanoes is very diverse. Sometimes an eruption occurs very slowly and calmly – liquid mud just spills over the edge of the crater. The amount of spilled mass may vary depending on the season and the amount of precipitation entering the area where the mud volcano is located. In the spring, the mud in the volcano is usually thinner, and closer to the fall, it is thicker in the form of very large bubbles (Fig. 2.2.20). A gas-mud bubble swells over the crater of the volcano, which bursts when it reaches the limits of the mud



Fig. 2.2.20. A large bubble in a mud volcano, Taman Peninsula

<https://aanapa.ru/ekskursii/gryazevie-vulkany-tamani/>



Fig. 2.2.21. The only mud volcano in the Ukrainian Carpathians

<http://www.doroga.ua/Handlers/ContentImageHandler.ashx?ReportImageReportID=665&Size=Big&FileName=P1230471.JPG>

film tension. Combustible gases released together with dirt can ignite, forming torches (Fig. 2.2.21). Occasionally, eruptions are very powerful, for example, the eruption of the volcano “Goreloe hell” (Taman) in 1794, which was heard at a distance of up to 50 kilometers.

This object arose after the 1977 earthquake at the site of the ozokerite mining on the outskirts of the village of Starunya, in the Ivano-Frankivsk region. It does not emit any smoke but mysteriously gasps bubbles of bitumen puddles, oozes oily liquid and most importantly the vent burns with an eternal flame.

Most of the mud volcanoes – about 350 of the 800 known on Earth, are located on the Absheron peninsula in

Azerbaijan – also common in Turkmenistan (Nebit – Dag region), in the basins of the Black and Azov Sea (Taman and Kerch peninsulas), Romania, Italy, Iceland and the United States.

The largest mud volcanoes have a diameter of up to 10 km, and the cone height reaches 500–700 m. Two major stages are distinguished in the activities of the largest mud volcanoes: explosive (short-term with rather strong eruptions) and griffin (longer and quieter in the intervals between eruptions). The eruption of large mud volcanoes can be accompanied by powerful emissions of gases, solid debris and waste. In Azerbaijan from 1810 to the present, eruptions were observed from 50 volcanoes and approximately 200 known eruptions occurred. Gases come out from deep layers of the earth and immediately ignite, while the flame height above the volcano reaches a kilometer (Garasu volcano). In the griffin stage, liquid mud slowly flows out of mud volcanoes or a dense mass of crumpled rock is squeezed out – breeding breccia.

Sometimes industrial and human activities can trigger the activation of mud volcanoes or even the emergence of new ones. If eruptions occur in populated areas, this can significantly affect people's livelihoods, such as the Lucy mud volcano, which arose in 2006 in the Sidoarjo district of Java and erupts quite far (Fig. 2.2.22).

On May 28, 2006, Lapindo Brantas, a geological company, began drilling an exploratory well and at the first stage, a thick clay layer was drilled at depth in the range of 500–1300 m.



Fig. 2.2.22. Consequences of the eruption of the Lucy mud volcano (from the abbreviation Lumpur and Sidoarjo, indon. lumpur – mud), Indonesia

https://upload.wikimedia.org/wikipedia/commons/thumb/e/e6/Home_sunk_by_mud_flow.JPG/1280px-Home_sunk_by_mud_flow.JPG
<http://www.foxnews.com/scitech/2011/02/25/indonesian-mud-volcano-erupt-quarter-century/>

Then, having drilled through sand and volcanic ash, they reached a rock filled with marine carbonate and water under an abnormally high pressure. During the second stage of drilling to a depth of 2834 m, a small release of water, steam and gas occurred on the surface of the earth 200 m south-west of the well. The next two eruptions occurred on June 2 and 3, about a kilometer north-west of the well. During these eruptions, mud and hydrogen sulfide came to the surface at a temperature of 60°C . The resulting volcano began to emit 7–150 thousand m^3 of waste daily. By September 2006, streams of hot mud flooded the surrounding villages and fields on an area of about 2.4 km^2 , which forced 11,000 people to evacuate the region. Houses, rice fields, factories, and shrimp farms were destroyed. Due to the strong subsidence of the earth (up to 2 m) and the breakthrough of the barrier wall by mud flows, a gas pipeline exploded on November 23, 2006, resulting in deaths.

To prevent the spread of debris around the already flooded area, a system of earthen dam was created, and mud was also pumped to a river located to the south. In addition, in February 2007, an attempt was made to block the mouth of the volcano with concrete balls. After plunging several hundreds of such balls into the vent, the outflow of mud stopped for 30 minutes and then resumed.

In April 2008, Lucy volcano began to fail under its own weight, which led to the formation of a caldera, the depth of which can reach 150 meters. The mud spread over an area of 6.5 km^2 , forcing about 36 thousand inhabitants from 12 nearby villages to leave their homes. A layer of debris flow up to 15 meters thick completely flooded the building.

Despite all attempts to extinguish the eruption, the activity of the volcano continues, and it is not known when it will stop. There are estimates by which the eruption will continue for another 30 years.

The benefits of volcanism.

Volcanic activity is one of the most dangerous natural phenomena, before which people still feel defenseless. History describes a huge number of eruptions with irreversible consequences, which were accompanied by the death of thousands of people and global environmental disasters.

The modern science of volcanology can quite accurately predict volcanic eruptions. Almost every active volcano has stations or instruments that allow monitoring of its condition. The standard solution for the threat of a dangerous eruption is the evacuation of the population of neighboring villages and cities, but sometimes they organize alternative protective measures. For example, in 1983,

during the eruption of Etna on the Sicilian Island, a special channel was created for lava flow, which saved the nearby villages from the threat of destruction.

The struggle of the inhabitants of the Icelandic town of Vestmannannaeyjar with their volcano, the eruption of which began on January 23, 1973 is also of interest. About 200 people remaining after the evacuation of the population stopped the lava flow creeping to the port with fire hoses. Cooled by water, the lava solidified. Then powerful jets of sea water from a special ship that entered the port joined in the struggle. After that, permanent pipelines were installed to supply water for cooling the lava. As a result of such measures, it was possible to save most of the city and the port, while none of the people was injured. The fight against the volcano lasted almost six months.

A positive example of the use of volcanic activity is the use of geothermal energy. The heat created by the volcanic source is used for heating cities and towns, and for the operation of thermal power plants due to the existing favorable conditions in the volcanic regions. For example, in Iceland's heat supply systems, the entire heat carrier is natural geothermal water. The main problem encountered is often the excessively high temperature of the water and also the high content of corrosives.

Petrified products of volcanic eruptions (basalt, lava breccia, volcanic tuff, pumice, volcanic sand, etc.) are widely used in the construction industry. The soil on the slopes of many volcanoes, due to the high content of volcanic ash, has high fertility and is widely used in agriculture.

Another useful component of endogenous processes is the use of geothermal waters and mud for balneological purposes. The high content of substances useful for human health (bromine, iodine, radon, and many others) in thermal springs and mud volcanoes contributes to the organization of numerous resorts and medical institutions.

Test questions to chapter 2.2. Magmatism and volcanoes

1. Definition and types of magmatism.
2. Features of intrusive magmatism.
3. Volcanism and types of volcanoes.
4. Classification of volcanoes by the nature of eruptions.
5. The nature of post-volcanic processes.
6. Definition of geysers and the principle of their activities.
7. Mud volcanoes and their features.
8. The importance of volcanism: positive and negative sides.

Chapter 2.3. SEISMIC PHENOMENA

Seismic phenomena (from the Greek *seismos* – earthquake) are endogenous, much less anthropogenic processes and phenomena associated with earthquakes and their consequences. Earthquakes threaten many vast, often densely populated territories and even entire countries, such as Japan, Nepal and Haiti. The greatest danger of earthquakes lies in the poor predictability of the time of their occurrence, intensity and possible consequences. Earthquakes are multidirectional oscillations of the earth's crust, which are also manifested on the earth's surface caused by the action of seismic waves. Seismic waves are felt by people as strong, intense earthquakes. Seismic stations, created to observe and study the fluctuations of the earth's crust, register about 500 thousand earthquakes of various strengths every year, out of which, approximately 100 thousand are felt by people and about a thousand earthquakes cause damage. Over the past hundred years, up to 20 tremors with a force of six or more points were recorded annually.

Earthquakes are the most dangerous of natural processes, leading to severe disasters with the destruction of entire cities and deaths of tens to hundreds of thousands of people. According to rough estimates, in the period from 2000 BC till present, earthquakes and the resulting failures, landslides, fires, tsunamis, floods and other consequences claimed the lives of more than 13 million people.

According to historical chronicles, the largest number of people died as a result of an earthquake in summer 1201 in Egypt and Syria where over a million people lost their lives. The great Chinese earthquake that occurred in January 23, 1556 in the provinces of Gansu and Shaanxi, claimed the lives of approximately 830,000 people.

In Europe, one of the most destructive and deadly was the *Great Lisbon earthquake*. It happened at 9:20 a.m. on November 1, 1755 and in a few minutes turned the capital of Portugal, Lisbon, at that time one of the largest cities in the world, into ruins. About 90 thousand of 275 thousand people living in the city were killed. The epicenter of the earthquake was in the Atlantic Ocean, about 200 kilometers southwest of the Portuguese coast. The earthquake occurred in the morning on a Catholic holiday – All Saints Day, and most people at that time were in temples. Believers in God's punishment for human sins saw this as retribution. According to the preserved chronicles, the earthquake lasted from three and a half to six minutes, causing huge faults in the earth up to five meters

wide, which separated the city center from the rest of it (Fig. 2.3.1). The survivors after the first push rushed to the port, which seemed safe, and saw that the water had receded from the coast and the bottom of the ocean with numerous visible fragments of sunken ships. A few minutes after the seismic shock, a huge tsunami flooded the harbor and city center, followed by two more huge waves. The areas of the city where the tsunami did not reach were destroyed by fires that lasted five days. Most of the city's buildings were destroyed, including the famous palaces, cathedrals and libraries. Buildings that were not destroyed by the earthquake burned down in flames. Currently, seismologists estimate the magnitude of the Lisbon earthquake at about 8.7 on the Richter scale.

This is the first earthquake studied by modern scientists, which served as the beginning to the emergence of the science of seismology.



Fig. 2.3.1. The Great Lisbon Earthquake of 1755 (old picture)

<http://ucrazy.ru/other/1441355814-nezvanye-gosti-iz-glubin-okeana.html>

One of the most catastrophic in destruction was the Shinsai earthquake from Japanese, meaning “Great”), which occurred on September 1, 1923 in Japan. 575,000 homes were destroyed in the cities of Tokyo and Yokohama and the death toll exceeded 140,000. As a result, there were significant changes in the relief and the depth of the seabed in Sagami Bay went down by 400 meters.

The strongest earthquake in North America in the entire history of seismic observations and the second most powerful after the Chilean one, was the Great Alaskan earthquake (Fig. 2.3.2), which occurred on March 27, 1964. The epicenter of the earthquake was located at 120 km from the capital of Alaska – the city of Anchorage and at a depth of 20 km at the junction of the Pacific and North American tectonic



Fig 2.3.2. Terrain after the Great Alaskan earthquake, 1964

<https://tastemylife.files.wordpress.com/2010/10/alaska37.jpg?w=465&h=334>

plates, where a concussion up to 9.2 points, in magnitude, occurred. At the same time, the Pacific Ocean plate shifted under the continental North American plate.

The largest number of victims in the twentieth century was recorded during the Tangshan earthquake that occurred in East China in 1976, about 700 thousand people died and tremendous damage occurred (Fig. 2.3.3).



a



b

Fig. 2.3.3. The consequences of the 1976 earthquake in the city of Tangshan, China:

a – the destroyed bridge

http://upload.tsingming.com/museum/7/7_20100919122033_828166.jpg;

b – curved rails

http://www.lindagall.com/petit_disasters/large/Earthquake-in-Tangshan.jpg

Examples of damage due to some earthquakes are shown in Fig. 2.3.4, 2.3.5.

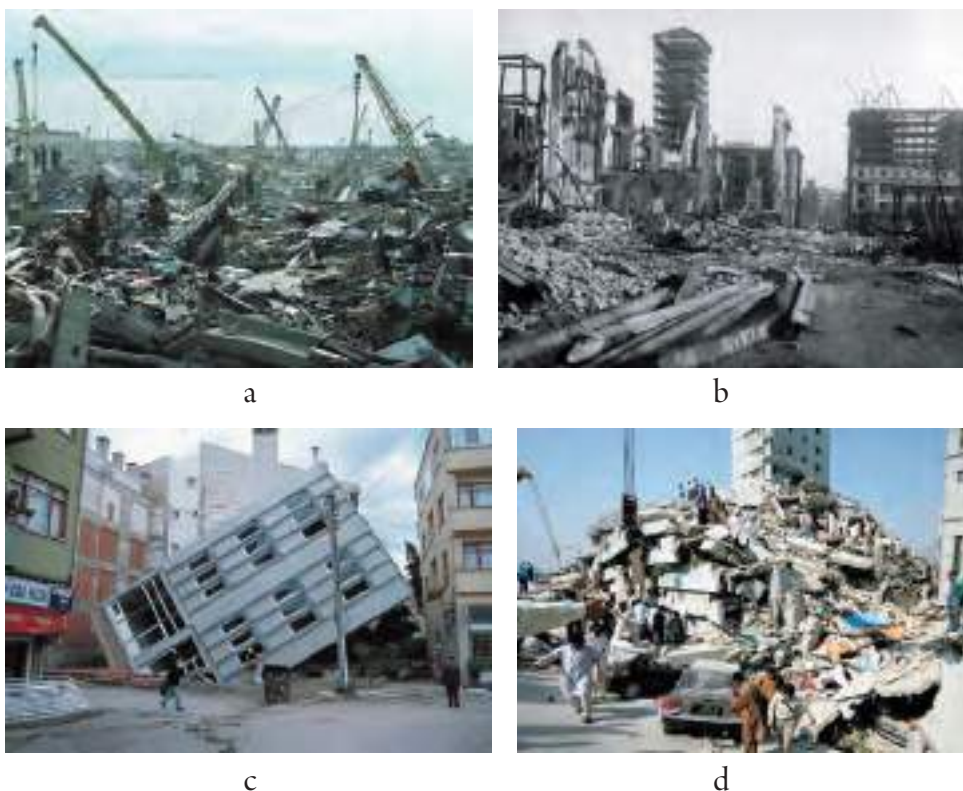


Fig 2.3.4. Consequences of earthquakes: **a** – San Francisco, USA, 1906

<https://userscontent2.emaze.com/images/5e267f86-3c6a-42f8-b9ab-71ed75f48cf7/4b70a258-3e01-4f08-9277-9508d9b28ee6.jpg>, **b** – Neftegorsk, Sakhalin, 1995. <http://goroda-prizraki.narod.ru/neftegorsk/014.jpg>, **c** – Izmit, Turkey, 1999. http://www.mygenerationweb.it/media/k2/items/cache/211fb1d06f9479a7650fc3bb47b93c8b_XL.jpg, **d** – Hindu Kush, Pakistan, 2015. https://lh4.googleusercontent.com/-mJTWQ46_dJWUivT5nm0zjG9qfErDFN0QWmJAQ8kVPaEj8pUkRMiMgeE7eHNE8w0SGlZiWCiTjDL7jTUI1pYKbQuns09848z9p6Mv_Mnft-1yKD9wrHvDPv0fQDDSTzlBA6f4eMh

Earthquakes in Crimea have occurred since ancient times, but the most famous and devastating Crimean earthquakes occurred on June 26 and on the night of September 11–12, 1927.

The June 26 earthquake on the South Bank had an intensity of 6 points. The September 12, 1927 earthquake was much stronger, causing significant damage resulting in deaths (3 people) and casualties (65 people). The earthquake focus was stretched along the coast under the seabed, south of Yalta. Before the earthquakes, an unusual disturbance was observed in perfectly calm weather

in the form of a small swell, outwardly similar to the “boiling of the sea”, which made the fishermen rush back to the shore.

The most powerful shocks led to the destruction of buildings of the coastal strip from Alushta to Sevastopol. In Alushta several hotels and the tower of the Genoese fortress were damaged, in Alupka – the Vorontsov Palace and the Swallow’s Nest (Fig. 2.3.5). Many highways were blocked and numerous landslides occurred on the mountains. In the vicinity of Yalta, 70% of buildings suffered and in the city itself, several hotels and residential buildings were damaged. Within half a day, 27 strong shocks occurred, and over several days more than 200 seismic shocks were recorded.

Huge columns of smoke and fire appeared over the sea near Sevastopol. At Cape Lucullus, a flare of fire was observed with a height of about 500 m and a width of about two kilometers. These lights were visible even from Evpatoria, a city located quite far. From the sayings of eyewitnesses in Feodosia, a city situated about 30 km away from the main source of the earthquake, fire pillars were also seen from faraway.

Flashes of fire above water, according to experts from the National Agency for Marine Research and Technology of Ukraine, were probably associated with the ignition of methane coming from the bottom of the sea through cracks formed during seismic movements. According to other hypotheses, hydrogen sulfide could have burned, which then dissolved in the lower layers of the Black Sea and under certain conditions, was released in the form of gas which flared up on the surface of the sea.



a b

Fig. 2.3.5. Destruction during the Crimean earthquakes of 1927:
a – the Swallow’s Nest castle, Alupka
[http://журналкрым.рф/uploads/posts/2015-07/1438185678_](http://журналкрым.рф/uploads/posts/2015-07/1438185678_lastochkono-gnezdo-posle-zemletreseniya-1927-goda.jpg)
[lastochkono-gnezdo-posle-zemletreseniya-1927-goda.jpg](http://журналкрым.рф/uploads/posts/2015-07/1438185678_lastochkono-gnezdo-posle-zemletreseniya-1927-goda.jpg);
b – residential building in Balaclava
<http://www.krimoved-library.ru/images/ka2002/1-45.jpg>

The largest earthquakes of the 21st century include the Indian Ocean earthquake that occurred on December 26, 2004, with a magnitude of 9.3. From the ensuing tsunami on the coasts of Thailand, Indonesia, India and Sri Lanka, nearly 250 thousand people died.

As a result of the earthquake on the island of Haiti, magnitude 7.0 on January 12, 2010, 220 thousand people died and 300 thousand were injured leaving 1.1 million homeless.

Several earthquakes with magnitudes between 3.2 and 7.9 occurred in Nepal on April 25–28, 2015, where 7 thousand people were killed and more than 14 thousand injured, including alpinists in the Everest region.

Types of earthquakes, their causes and mechanism of occurrence

In the broad sense, the term earthquake can be understood as any tremor of the Earth's surface, and more precisely, it is a short-term tremor of the Earth's surface caused by seismic waves during the sudden release of energy in the bowels of the earth's crust or upper mantle. Most of the known earthquakes are caused by seismic shocks during sharp shifts of tectonic plates, and they are called *tectonic earthquakes*. Their number is up to 95% of all seismic tremors and they are most intense ones. By the cause of their occurrence earthquakes are distinguished as *tectonic*, *volcanic*, *landslide (denudation)* and *man-made (anthropogenic)* earthquakes (Tab. 2.3.1).

Table 2.3.1

Classification of earthquakes by causes of occurrence

Earthquake type	Percentage of total	Maximum magnitudes
Tectonic	almost 95 %	up to 9.5
Volcanic	up to 5 %	up to 8
Landslide (denudation)	<1 %	< 5
Technogenic (anthropogenic)	<0.1 %	up to 7

Tectonic earthquakes

During the movement of tectonic plates of the lithosphere (due to thermal convection of mantle material in combination with dynamic effects arising from the Earth's rotation), stresses and elastic deformations of rocks accumulate at the boundaries of plates (rarely in the middle) caused by resistance to movement from neighboring plates. Most earthquakes (as well as volcanic eruptions) on Earth occur at the edges of the Pacific Ocean, bearing the name "Pacific

Fire Belt.” Another area of high seismicity – the “Mediterranean-Trans-Asian” extends from the Mid-Atlantic Range through the Mediterranean basin and the adjacent folded mountains (Alps, Carpathians, Crimea, and the Caucasus), Iran, the Himalayas, and East Asia up to the Pacific Ocean. The “Atlantic-Arctic” belt passes through the Mid-Atlantic underwater ridge, Iceland, Jan Mayen Island and the Lomonosov underwater ridge in the Arctic (Fig. 2.3.6).

Earthquakes also often occur in rift fault zones and depressions, such as the Red Sea, Lake Tanganyika and Nyasa in Africa, Issyk-Kul and Baikal in Asia.

Earthquakes in the middle of tectonic plates occur in places of intense mountainous areas, under anticlinal folds – mountains formed when the layers bend upward in the form of a vault. These folds occur under the action of compressive forces and when such rock stress is removed due to a sharp movement, earthquake occurs. One of the fastest growing folds in the world, causing strong tremors, is located in California. The Ashgabat earthquake of 1948 in the foothills of Kopet-Dag is also of the same type.

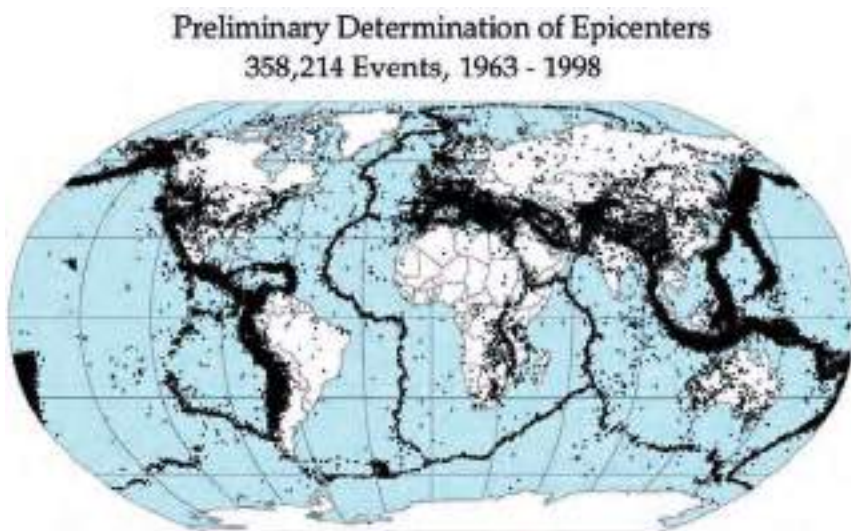


Fig. 2.3.6. Epicenters of earthquakes (indicated by black dots) that occurred during 1963–1998, a total of 358,214 events

<http://www.link2universe.net/wp-content/uploads/2013/04/dati-epicentri.jpg>

An earthquake is a quick transition of potential energy accumulated in elastically deformed (compressible, shifted or stretched) rocks of the lithospheric plates into energy that changes the structure and occurrence of rocks into the form of a sharp break at the source of the earthquake, as well as

into the energy of vibrations of neighboring rocks, up to the earth surface. This transition occurs when the mechanical ultimate strength of the rocks is exceeded (due to discontinuity and a shift in the earthquake source), causing propagation of vibrations in the form of *seismic waves*.

The term *hotbed* of a tectonic earthquake refers to a limited enclosed volume of rocks, in which, in a short period of time (up to 1–3 minutes), one part of the volume has shifted with respect to the other. On the site of such a displacement, seismic waves are generated, that propagates in all directions and can lead to destruction at a large distance outside the focus. *The hypocenter* of an earthquake is the area in which the shift occurs. *The epicenter* of the earthquake is the vertical projection of the hypocenter on the earth's surface.

At some point after the start of the earthquake, forces arise that prevent the mutual displacement of the blocks along the formed faults – due to friction in the compressed areas and other restrictions on the surfaces of the blocks. Part of the energy remaining in the seismic array causes stresses on the newly formed contacts, which after some time overcome the friction resistance again, causing a movement and a new impulse of lesser force than at the time of the main earthquake. There can be up to several tens or even hundreds of such *aftershocks*, following a strong earthquake which gradually weakens over several days or even months. In this case, individual aftershocks may approach the strength of the main earthquake. Sometimes before earthquakes relatively weak tremors occur – *foreshocks*.

Types of seismic waves

The oscillations that propagate from the source of the earthquake have the character of elastic waves whose propagation velocity depends on the elastic properties and density of the rocks. Seismologists distinguish three main types of seismic waves: *longitudinal, transverse and surface waves* (Fig. 2.3.7).

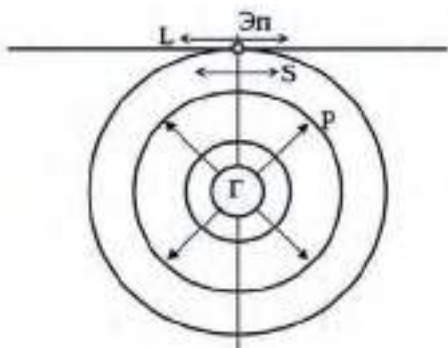


Fig. 2.3.7. Seismic wave propagation:

Γ – earthquake hypocenter;

Θ – epicenter of the earthquake;

P – longitudinal waves;

S – transverse waves;

L – surface waves

<http://textarchive.ru/>

[images/1284/2567475/62cf2cd4.gif](http://textarchive.ru/images/1284/2567475/62cf2cd4.gif)

Longitudinal or primary waves – P-waves (from Latin *prima* – first) propagate in all directions from the hypocenter and reach the earth's surface first. When a longitudinal wave propagates, each rock particle, water or gas medium undergoes compression followed by relaxation, which creates a reciprocating motion in the direction of wave propagation. These waves can propagate in all media: solid, liquid and gaseous, so in granite their speed is 5 km/s, in water – 1.45 km/s, in air P-waves take the form of sound waves and, accordingly, propagate with the speed of sound – 0.33 km/s. The propagation velocity of P-waves at great depths reaches 13.6 km/s (at the boundary of the mantle and the Earth's core), near the Earth's surface it decreases to 5–6 km/s, so they have a speed one and a half to two times greater than the transverse waves.

Transverse or secondary waves – S-waves arise as a result of the reaction of an elastic medium to a change in shape under bending forces. With the passage of transverse waves, each particle of the rock oscillates perpendicular to the line of direction of wave propagation. S-waves propagate only in a solid medium. The speed of their movement in the earth's crust is 3–4.5 km/s, and near the mantle/core border reaches 7.3 km/s.

Surface or long waves – L-wave is the third type of waves that arise at the interface between a solid and air medium, i.e. on the earth's surface and spread in all directions from the epicenter. Among the surface, Rayleigh waves and Love waves are named after the scientists who developed the mathematical theory of their propagation. During the passage of Rayleigh waves, the trajectories of the rock particles are vertical ellipses perpendicular to the wave propagation plane. In Love waves with rock particles, lateral vibrations in the horizontal plane occur. Surface waves propagate in all directions from the epicenter on the Earth's surface, affecting only the uppermost layers of the earth's crust. Their amplitude is greater than the above-mentioned waves and their speed is in the range of 3–3.5 km/s. Surface long waves, like sea waves, can cause oscillations of the earth's surface with an amplitude of up to a meter. It is due to these waves that the earth's surface, with buildings, people and everything on it, sways from side to side and up and down, leading to their destruction.

When studying seismic waves, the speed of their passage through various rocks is especially important. At different distances from the hypocenter and epicenter, the arrival of waves is not recorded simultaneously. Using this property, seismologists can quite accurately determine the coordinates of the epicenter using time records of wave recording at seismic stations located at different distances from the source of the earthquake. So, surface waves propagate more slowly

and, therefore, arrive at observation points later. Transverse waves propagate on average 1.75 times slower than longitudinal waves. Therefore, people who are in the epicenter of a strong earthquake are exposed to different waves at different times: they are pushed and shaken in different directions with different accelerations. Cases are described when, after tremors, people were thrown to such a height that they could not survive after falling. Fortunately, such powerful strikes are quite rare.

Earthquake witnesses often literally hear it, since longitudinal seismic waves are similar to sound waves. At a certain frequency of oscillations in the range of human hearing, that is, more than 15 hertz, they are converted into sound waves when they reach the surface, and a low-frequency “hum” is often heard before the main phase of the earthquake.

Earthquakes are classified depending on the depth of their focus. Most earthquakes (surface) occur at a depth of down to 70–100 km from the Earth’s surface and rarely, down to 300 km. But there are deep-focus earthquakes that occur at very great depths. For example, such an earthquake with magnitude 7.6 occurred in 1970 in Colombia at a depth of 650 km. A maximum of 720 km deep hypocenters was recorded during earthquakes in Indonesia in 1933, 1934 and 1943. The classification of earthquakes by the depth of their hypocenters is given in table. 2.3.2.

Table 2.3.2

Classification of earthquakes by the depths of their foci

Name	Depth range	Percentage of total
Surface	<100 km	51 %
Intermediate	100–300 km	36 %
Deep focus	300–720 km	13 %

The strength of an earthquake on the surface of the earth as a whole depends on the depth of the focus: the closer it is to the surface of the earth, the greater the strength of the earthquake at the epicenter. The most dangerous are earthquakes with foci located in the earth’s crust at a depth of 3 to 50 km.

Tsunami (from the Japanese “Tsu” – port). Earthquakes (or powerful volcanic eruptions) occurring at the bottom of oceans, often generate gigantic sea waves which reach the coast and can rise to a very high altitude. Waves, generated during a *tsunami* often bring disastrous consequences to coastal areas. The height of the waves at the epicenter reaches 5 m, off the coast – up to 10 m and in coastal areas (depending on the ground relief) may rise up to 50 m

(Fig. 2.2.8). The speed of tsunami reaches 900–1000 km/h and they mostly (up to 80%) occur on the Pacific coast. Tsunamis are much less common in the Atlantic Ocean – Lisbon earthquake, 1755 and in the Indian Ocean, 2004.

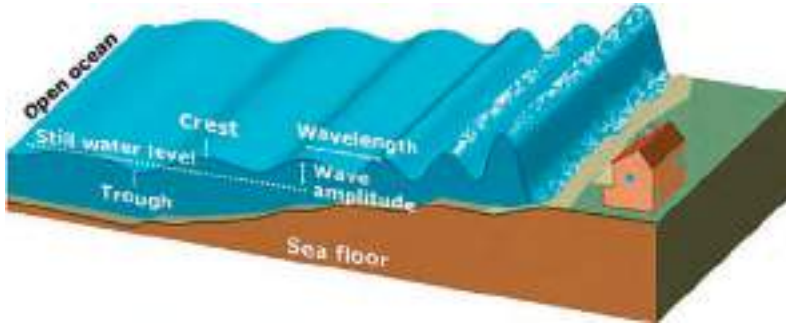


Fig 2.3.8. Tsunami occurrence pattern
<http://tsunami.org/tsunami-characteristics/>



a

http://img.chan4chan.com/img/2011-12-21/j01_RTR2JTXO.jpg

The Sendai earthquake and tsunami near Honshu Island, Japan (magnitude 9.0) March 13, 2011 killed 13 439 people and 14 867 people went missing. A major accident occurred at the Fukushima nuclear power plant (Fig. 2.3.9, 2.3.10, 2.3.11).



b



c

Fig 2.3.9 **a** –beginning of the tsunami on the coast of Honshu, Japan, 11. 03.2011;
b, c – Tsunami

http://pds.exblog.jp/pds/1/201505/21/01/c0072801_135634.jpg

<http://www.slowfood.it/wp-content/uploads/2015/12/alluvione.jpg>



a

b



c

d



e

Fig. 2.3.10 a, b, c, d, e. Consequences of an earthquake and tsunami

a http://ktpress2.mediaon.co.kr/data/photos/201103/pp_25412_1.jpg

b <http://media.search.lt/GetFile.php?OID=228579&filetype=4>

c <http://lh4.googleusercontent.com/-kClzgWVHtc/TX0-QVI55hI/AAAAAAAAACsI/tzEiuZukeq8/s1600/Japan+01.jpg>

d <http://daypic.ru/wp-content/uploads/2011/03/6101.jpg>

e <http://lionsclubsorg.files.wordpress.com/2011/03/japan-tsunami-ap110311113416.jpg?w=2800&h=1915>



Fig. 2.3.11. Fire extinguishing at the Fukushima-1 nuclear power plant, Japan
<http://easyread.ph.126.net/HS4uFL-Px2ZO5YJxu6hM1A==/8796093022347367745.jpg>

Earthquake strength assessment

To assess the magnitude of earthquakes, the Richter scale is most commonly used, but there are also other intensity scales like the MSK-64 among others.

The magnitude of an earthquake (from lat. *magnitudo* – greatness, importance, significance) is an indicator that characterizes the energy that was released during an earthquake in the form of seismic waves. The magnitude of an earthquake is a dimensionless quantity which is proportional to the logarithm of the ratio of the maximum amplitude of waves generated in a particular earthquake and the amplitude of a standard earthquake. There are a number of differences in the methods for determining magnitudes of nearby, remote, shallow and deep focus earthquakes. Magnitudes of different types of waves differ in magnitude.

The magnitude scale was first developed in the United States by the seismologist Charles Richter in 1935. The modern improved Richter scale contains arbitrary units ranging from 1 to 9.5, which are calculated by vibrations recorded by seismographs during an earthquake. The Richter scale uses a logarithmic scale, and every integer value on the scale indicates an earthquake ten times larger in power than the previous one. For example, an earthquake with magnitude 6.0 on the Richter scale will cause 10 times more severe ground vibration than an earthquake with magnitude 5.0 and with a magnitude of 7.0 will

be 100 times stronger as compared to magnitude 5.0. In principle, the magnitude scale has no upper limit but there are physical limits to the amount of energy released in the earth's crust.

The scale of the intensity of earthquakes is based on the external manifestations of tremors and is assessed by the actual data on the destruction, objects, buildings and structures and loss of lives. Unlike the magnitude of an earthquake, which expresses the amount of seismic energy released during the earthquake, the intensity scale determines how much it affected materials and lives on earth.

In different countries, the intensity of earthquakes is sometimes estimated differently. Japan adopted the 7-point scale of the Japan Meteorological Agency – the Shindo scale; in the USA – a 12-point modified Mercalli scale (MM); in the European Union, Ukraine, Russia and other countries of the former USSR, the Medvedev-Shponheuer-Karnik 12-point scale (MSK-64) has so far been used. By the principle of their creation, all of these scales belong to the category of seismic scales of the Mercalli family. The inventor of the original scale was the Italian scientist Giuseppe Mercalli, who laid the foundations for its use in 1883 and 1902, and the scale was named after him. To assess the degree of intensity of the earthquake, it uses Roman numerals from I to XII. It is used to determine the intensity of an earthquake when there are no direct data on the strength of earthquakes, for example, due to the lack of appropriate equipment (seismographs).

Now the Mercalli scale is used mainly in the United States and the MSK-64 is the basic regulatory document for European countries. Since 1998, a more modern European macro-seismic scale (EMS-98) has been applied in the EU countries (Tab. 2.3.3).

Table 2.3.3

Earthquake Intensity Scale (EMS 98)

Point	Earthquake strength	A brief description
I	Imperceptible	Not felt by people. It is noted only by seismic instruments.
II	Barely tangible	It is felt only by individuals who are in a state of complete rest on the upper floors of buildings, and very sensitive pets.
III	Weak	It is felt in the rooms by some people. People at rest indoors feel a swing or a slight trembling.

Table continuation 2.3.3

Point	Earthquake strength	A brief description
IV	Widely observed	Recognized by the slight rattling and vibration of objects, dishes and windowpanes, creaking doors and walls. Inside the building, most people feel the concussion.
V	Strong	Feeling of an earthquake inside the building, but not by everybody who are outside the building. Many sleepers wake up and some run out into the street. Buildings experience a slight concussion. Suspended objects swing significantly. The dishes are ringing. The vibrations are strong. Objects with a high center of gravity, may fall. Doors and windows swing.
VI	Light damage	The vast majority of people feel an earthquake inside buildings. People are scared and run out of building. Small objects are falling. Slight damage to most ordinary buildings; for example, thin cracks in the plaster.
VII	Damage	The vast majority of people run out of buildings. Furniture moves, most items fall from shelves. Many buildings are moderately damaged: small cracks in the walls; partial collapse of chimneys.
VIII	Severe damage	Inverted furniture. Most buildings suffer significant damage: chimneys fall; large cracks in the walls; some buildings may partially collapse.
IX	Destructive	Monuments and columns fall. Many buildings are partially destroyed, some completely.
X	Very destructive	Most buildings are completely destroyed.
XI	Devastating	Almost all buildings are completely destroyed.
XII	Completely destructive	All ground and underground structures are very badly damaged or destroyed.

The magnitude scale should not be confused with the earthquake intensity scale in points (according to the 12-point system), which is based on the external manifestations of tremors – the effects on people, objects, buildings and structures and natural objects. At the current level of development of seismology, during an earthquake, its magnitude first becomes known, which is determined by the seismograms of the instruments, and not the intensity, which is determined only after some time and after receiving information about the consequences. Examples of modern use of terms in the assessment of earthquakes are given in table 2.3.4

Table 2.3.4

Use of terms in earthquake assessment

Proper use	Previous use	Misuse
«Magnitude 6.0 earthquake»	«An earthquake of magnitude 6 on the Richter scale»	“Magnitude 6 earthquake”; “6 magnitude earthquake on the Richter scale”
“An earthquake of intensity 6 on the EMS-98 scale (or Mercalli, or MSK-64)”		

The approximate correlation between earthquake magnitudes and points on a 12-point scale is given in table. 2.3.5.

Table 2.3.5

The ratio of magnitudes and earthquake scores

Richter Magnitude	12-point intensity
2.0 and less	I-II
3.0	III
4.0	IV-V
5.0	VI-VII
6.0	VIII
7.0	IX-X
8.0 and more	XI-XII

To date, the strongest earthquake recorded by seismologists has occurred in southern Chile in the province of Antuko, on May 20, 1960. At the beginning there was a very strong earthquake with a magnitude of 7.1 and two days later, on May 22, a disaster occurred in the same area: magnitude 9.5 according to Richter and maximum 12 points according to Mercalli.

Volcanic earthquakes

Volcanic activity is accompanied by explosive emissions of huge volumes of steam and gases into the atmosphere, which causes seismic and acoustic vibrations. The rise of high-temperature magma from the bowels of the volcano to the surface is accompanied by cracking of overlying rocks, which in turn also causes seismic and acoustic effects. These movements lead to a series of small earthquakes – “volcanic tremors” and micro-earthquakes. Typically, these

effects are rather weak, but their occurrence sometimes allows giving a correct forecast of the start time of the volcanic eruption. Signs of a volcanic earthquake are the coincidence of its source with the location of the volcano and a relatively small magnitude.

The signs of volcanic earthquakes almost do not differ from the phenomena observed during tectonic earthquakes, but their intensity is usually much lower. Nevertheless, examples of very powerful earthquakes occurring simultaneously with volcanic eruptions are known. A very strong volcanic earthquake was observed during the eruption of the volcano Krakatau in Indonesia in 1883, which destroyed half of the volcano and shaking from it caused destruction on the islands of Sumatra, Java and Borneo. The beginning of a major eruption may be accompanied by a strong earthquake, for example, in the city of Pompeii during the eruption of Vesuvius in 1979. The eruption of the Bundai-San volcano in Japan in 1988 was accompanied by a severe explosion of volcanic gases, crushing an entire mountain 670 m high, composed of strong andesites. On the Kamchatka Peninsula, numerous volcanic earthquakes regularly occur which are associated with the activity of the volcanoes Klyuchevskaya Sopka, Shiveluch and others.

In general, volcanic-type earthquakes are weaker than tectonic ones, but they last long (weeks and months) and are repetitive. Danger to people during such earthquakes is relatively rare.

Collapse (denudation) earthquakes

These are relatively weak earthquakes that occur in areas where underground voids or mining works are common. Their magnitude usually does not exceed 5.0, and they do not occur often – the proportion of landslide earthquakes does not exceed 1 % of the total number of earthquakes. The immediate cause of ground vibrations is the collapse of the roof of caves or a large underground mines or tunnels. Karst caves, leaching cavities are formed when groundwater easily dissolves soluble rocks (deposits of rock salt, gypsum, limestone, chalk, etc.) and carry away the substances, leaving voids behind. Later, the roof, having lost stability, collapses, thereby causing small fluctuations in the rocks. Obviously, the centers of such earthquakes are at shallow depths and seismic waves propagate nearby. Typically, the distribution area is tens of square kilometers, although, for example, in 1915 in the Vovchansk volost of the Kharkiv province, the impact of a landslide earthquake covered an area of up to 100 km in diameter. In Kharkov city, located at a distance of about 80 km from the proposed epicenter, houses

shook, windows rang, doors opened and lamps swayed. Crashing earthquakes were observed near Riga (1908), in Estonia, Karelia, and the North Caucasus.

A special kind of landslide earthquakes is seismic oscillations that sometimes occur during large landslides. For example, as a result of a giant landslide on April 25, 1974 near the Mantaro River in Peru, seismic waves equivalent to a moderate tectonic earthquake were recorded.

“Mountain strikes” – another form of landslide earthquake often occurs. They happen when stresses arising in the underground mining section cause large masses of rocks to detach sharply from the face with an explosion, giving rise to seismic waves. Mountain strikes are not uncommon in the mines of China, Germany, Poland, Russia, Japan and other countries. They are especially common in South Africa, where platinum and diamonds are currently mined in the world’s deepest mines – up to 4.5 km.

Man-made (anthropogenic) earthquakes

These earthquakes are associated with civil engineering and military activities, as well as mining. Carrying out underground nuclear explosions, extracting large amounts of water, oil or gas, coal and other minerals from the bowels of the earth can cause seismic shocks. Artificial (induced) seismicity can also be caused by an increase in hydrostatic pressure while injecting various liquids into the deep horizons of the earth’s crust, during hydraulic fracturing, particularly during the production of shale gas.

Weak and sometimes even moderate earthquakes can be caused by the creation of large reservoirs. The accumulation of a huge mass of water in the reservoir bowl leads to a significant increase in hydrostatic pressure on the underlying rocks.

For the first time, such phenomena have been observed since 1935 in the state of Arizona, USA, where the famous Hoover Dam was built and the Lake Mead Reservoir was filled (Fig. 2.3.12). Over the next ten years, about six hundred tremors of magnitude up to 5.0 were observed. No earthquake was recorded earlier in this area.

The probability of occurrence of induced seismicity depends on the pressure of the water column in the reservoir bowl, that is, it increases with increasing dam height. So, induced seismicity was caused by less than 1% of dams with a height of the order of a few tens of meters. During the construction of dams with a height of about 90 m, seismicity arose in 10% of cases, and for dams with a height of more than 140 meters, it increased in 21% of cases. Examples of the occurrence

of sufficiently strong induced earthquakes with magnitudes up to 5.0 are known during the construction of the Aswan Dam in Egypt, the Koyna Dam in India, the Carib in Zimbabwe; Nurek and Toktogul hydroelectric station in Tajikistan.



Fig. 2.3.12. Lake Mead Reservoir and Hoover Dam (221 m high) on the Colorado River, the border of Arizona and Nevada, USA. The creation of a reservoir led to the transformation of the surrounding area into an area of increased seismicity
Photo by Iu. Egupov

Injection of various liquids into the underground space can substantially increase the seismicity of a particular area. Such methods are widely used in oil production, used to get rid of toxic industrial and household waste. For the first time, a negative effect was discovered in the Denver area in the state of Colorado, USA, where wastewater was pumped into a well drilled in fractured granites to a depth of 3600 m in 1962. Over the previous eighty years, only three weak seismic events were noted here and over the next eight years after the wastewater pumping – 610 seismic events were recorded. Seismologists found that the frequency of weak tremors is directly dependent on the volume of fluid injected.

The reverse process can also cause tremors – pumping large volumes of liquid (oil, water or gas) from the bowels of the earth. For example, the development of the Gazli deposit in the Bukhara region of Uzbekistan provoked severe earthquakes on April 8 and May 17, 1976. Their focus was located at a depth of 20–25 km, with magnitudes – 7.0 and 7.3 respectively, and the seismic effect at the epicenter

reached 9–10 points on the MSK-64 scale. Eight years later (March 20, 1984), the next strong earthquake occurred with a magnitude of 7.2 in almost the same focus, but slightly shifted to the west. As a result of these earthquakes, the Gazli oil industry workers village, located 30 km from the epicenter, was almost completely destroyed.

Earthquakes can be triggered by underground nuclear explosions (Fig. 2.3.13). A reliable case was recorded in 1968 during tests at a test site in Nevada (USA), when the magnitude of the main seismic shock during the explosion was 6.3, and later a series of aftershocks followed – earthquakes with magnitudes up to 5.0.



Fig. 2.3.13. A funnel at the site of an underground nuclear explosion of a 104-kiloton charge on July 6, 1962. Photo: National Nuclear Security Administration / Nevada Site Office
<http://2.bp.blogspot.com/-boD2hZT1m1A/Tnina2NaWRI/AAAAAAAAAZ4/jrZyhpoXdXI/s1600/SedanCrater.jpg>

According to some reports, the catastrophic earthquake of December 7, 1988, where 350 thousand people died in north Armenian cities of Leninakan, Spitak and others (Fig. 2.3.14), occurred as a result of testing four types of geophysical bombs that caused an artificial earthquake.

The likelihood of man-made earthquakes and significant displacements of the earth's surface increases with an adverse combination of man-made influences and the characteristics of natural seismic conditions. This can lead to emergency

and catastrophic situations, such as ruptures of gas and oil pipelines, destruction of residential and industrial buildings, large hydraulic structures, which can also cause death and casualties. Human losses, as well as enormous economic damage from such incidents, are also accompanied by significant environmental damage.



a

<http://twitter.com/hashtag/%D1%81%D0%BF%D0%B8%D1%82%D0%B0%D0%BA?lang=fi>



b

Fig 2.3.14 **a, b** – Consequences of the earthquake of December 7, 1988 in the north of Armenia

<http://abisoghomyan.wordpress.com/2013/12/07/%D5%A4%D5%AA%D5%B8%D5%AD%D6%84-1988/>

Seismic zoning

Earthquakes occupy one of the first places among natural disasters in their devastating consequences, the number of victims and the destructive impact on the environment.

Over the ten-year period from 1999 to 2010, the number of deaths from strong earthquakes in the world increased by 8.6 times compared with the average (over the previous 50 years) indicators for the decade. The graphical illustration showing the number of victims of violent earthquakes for the period from August 1999 to January 2010 is shown in Figure 2.3.15. A straightforward trend indicates the significant increase in the death toll over the decade.

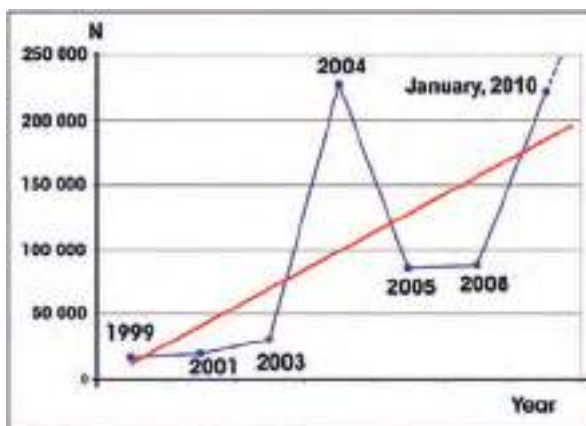


Fig 2.3.15. Graph of the number of deaths from strong earthquakes for the period from January 1999 to January 2010 (Compiled by E. N. Khalilov, 2010, according to the USGS). Blue color is a graph of the number of deaths from strong earthquakes in individual years. Red color – a straightforward trend, reflecting a growing trend in the number of deaths
<http://yarkov.org/scientists-report/>

It is impossible to prevent earthquakes, but however, their devastating consequences and the number of victims can be reduced by applying special standards for earthquake-resistant construction and conducting awareness-raising events in seismically active areas to make the population aware about the threat of earthquakes and how to apply precautionary measures. The seismic hazard does not decrease every year, but grows in direct connection with the economic development of new, including seismically active territories and the intensification of human impact on the Earth's lithosphere (the construction of large hydraulic structures, the extraction of gigantic volumes of mineral resources, etc.). An increased risk is also associated with the placement of nuclear power plants and other environmentally hazardous facilities in seismically active regions, since even minor earthquakes can disrupt their normal functioning.

The development of practical measures to protect against earthquakes should begin with the creation of reliable maps of seismic zoning.

Seismic zoning is the allocation on a large territory, usually a whole country, of regions with varying degrees of intensity of expected earthquakes. Seismic zoning data is helpful in the design and construction of structures, taking into account the necessary seismic resistance of buildings and structures and other practical tasks for seismically dangerous areas. To compile seismic zoning maps, historical data, instrumental observations by seismographs, geological and tectonic and geophysical maps are used. Since the effect of earthquakes on the Earth's surface is usually expressed in seismic scale scores, zones with predicted probable earthquake intensity, usually from 5 to 10–12 points, over a certain period of time are highlighted in seismic zoning maps.

The destructive consequences of the intensity of earthquakes strongly depend on the engineering-geological and hydrogeological conditions of a particular site and on the ratio of the natural periods of structure vibrations to resonant ground vibrations at the base. These features cannot be taken into account on small-scale maps of general seismic zoning. Therefore, for cities and individual construction sites of critical facilities, maps of seismic micro-zoning are compiled and amendments are introduced to increase or decrease the estimated points, depending on the ground conditions.

The science of seismology today cannot predict with 100% accuracy the time of occurrence of a strong earthquake. Therefore, the most reliable way to resist earthquakes is to build reliable seismically stable buildings and structures.

Test questions to chapter 2.3. Seismic phenomena

1. Definition of seismic phenomena.
2. Types of earthquakes.
3. causes and mechanism of occurrence of earthquakes.
4. Tectonic earthquakes.
5. Types of seismic waves.
6. The causes of the tsunami.
7. Earthquake intensity scales.
8. The ratio of magnitudes and earthquake scores.
9. Volcanic earthquakes.
10. Technogenic (anthropogenic) earthquakes.
11. The principles of general seismic zoning.

PART III.

EXOGENOUS PROCESSES AND ENGINEERING GEODYNAMICS

Exogenous processes are geological processes that occur due to external sources of energy relative to the Earth, which primarily include solar radiation in combination with gravitational forces. Exogenous processes occur on the surface of the earth's crust and near it in the form of mechanical and physic-chemical interaction of rocks with the hydrosphere and atmosphere. The main natural exogenous processes include:

- weathering of rocks and soils;
- groundwater activity: suffusion and karst processes;
- slope processes: landslides, scree, mudflows, avalanches, etc.;
- wind activity (corrosion, deflation, dust storms);
- activity of flowing surface water (flat, ravine, river erosion and sediment accumulation);
- the activity of the waters of the seas and oceans (abrasion), glaciers (exazation);
- processes occurring in soils with special properties (movement of quicksand, subsidence of losses, swelling of clay soils).

The main forms of manifestation of exogenous processes on the surface of the Earth are the destruction of rocks during physical, chemical and organic weathering; the transfer of loose and dissolved products of rock destruction by gravitational forces, water, wind and glaciers; deposition and accumulation of these products in the form of precipitation on land or at the bottom of water bodies. Under the combined action of exogenous and endogenous processes, the Earth's relief is formed.

In addition to natural processes, in the formation, and more precisely in the change in the earth's crust and relief, people are more and more actively participating. Technogenic processes are especially vividly observed with open mining in quarries, hydraulic engineering and road construction, in the life of cities and industrial centers, and in agricultural and land reclamation works.

Engineering geodynamics is a branch of engineering geology that studies the mechanism, stages of development, local patterns of the formation of

natural and anthropogenic geological (engineering-geological) processes in the upper horizons of the earth's crust on its surface in connection with human engineering activities. The main attention in engineering geodynamics is given to the study of geological processes that occur or may occur in the uppermost near-surface horizons of the earth's crust both in the natural environment in the form of natural geological processes and in the territories developed by man, as geotechnical anthropogenic processes.

This section provides information on the main natural and technogenic engineering-geological processes that have a direct impact on territories, buildings, structures, utilities, and often can be a danger to human life and health. The characteristic is given and examples of these processes in various regions are given.

Thus, the section discusses in more detail: suffusion, karst, slope processes, wind and water erosion, abrasion, quicksand, processes in the developed areas, seismic phenomena, flooding of territories with groundwater and flooding with surface waters, subsidence and swelling of soils.

Chapter 3.1. SOIL SUFFUSION

Soil suffusion (from Latin *suffusio* – dripping) is the process of washing and removal of fine mineral particles from the dispersed soil mass when water percolates through it. The smallest particles can be washed out from non-homogeneous sands and other coarse-grained soils (gravelly soils). Clay fractions less than 0.002 mm in size, silt (0.002–0.05 mm) and even sands (0.05–2 mm) may be washed away by a stream of groundwater and separated or completely removed from the soil mass. Suffusion is often observed in fossil soils, where the movement of water occurs through macropores and moving animals.

The process of suffusion is close to the karst process, but the difference is that suffusion is mainly the mechanical removal of soil particles without their physical alteration. Chemical suffusion is less commonly observed, where water dissolves certain salts contained in the soil (NaCl , CaSO_4) and removes the soluble components. Mixed chemical and physical processes may sometimes be observed, mainly in loess soils. These processes cause deformation of the earth surface by formation of smooth settling troughs, funnels and collapse of existing irregular shapes.

Suffusion processes are most often observed on steep slopes of river valleys, ravines, on coastal slopes, sides of construction dredges, irrigated territories, that is in places with high hydraulic gradients in moving groundwater.

Under natural conditions, suffusion is a relatively slow process and its effects can manifest after several years. Suffusion funnels are clearly visible in aerial photographs, observed on dusty country roads and suffusion cavities can even be seen during digging of ditches (Fig. 3.1.1).



Fig. 3.1.1. Natural suffusion cavity

<http://present5.com/disciplina-geologiya-lekciya-7-tema-7-prodolzhenie/>



Fig. 3.1.2. Mechanical suffusion of clayey sand when groundwater arrives through the gaps in the sheet pile wall enclosure

http://st2.stpulsken.ru/images/product/043/522/490_big.jpg

Under the influence of man-made factors, natural suffusion processes can increase intensively. Technogenic suffusion may occur with leaks and damages in water supply and sewage systems; in backfills without adequate compaction when laying pipelines and cables; in case of uncontrolled drainage of groundwater into sewer system (Fig. 3.1.2).

Suffocation phenomena represent a serious hazard to sites located near dams and reservoirs as shown in Fig. 3.1.3.

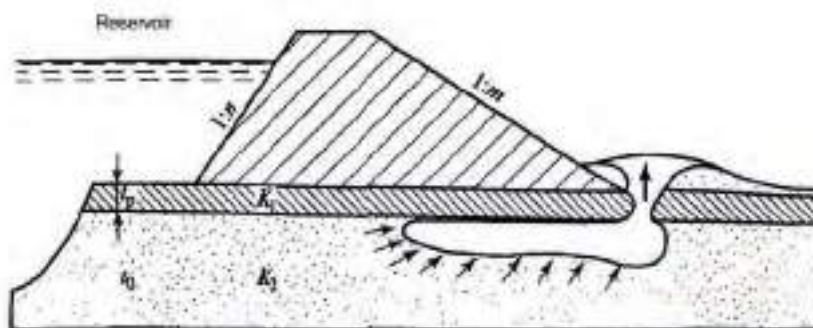


Fig. 3.1.3. Scheme of formation of the suffusion cavity under an earth dam

Geological Engineering: Textbook for building special universities / V. P. Ananyev, A. D. Potapov. – Moscow: Higher. school, 2005. – 575 p.

Adverse effects can occur with the construction of drainage wells (Fig. 3.1.4 a) during pumping of groundwater from open mining quarries and also from underground mines, tunnels and wells. Surface settlements may occur in the vicinity of sewer and observation wells under the influence of suffusion (Fig. 3.1.4 b).

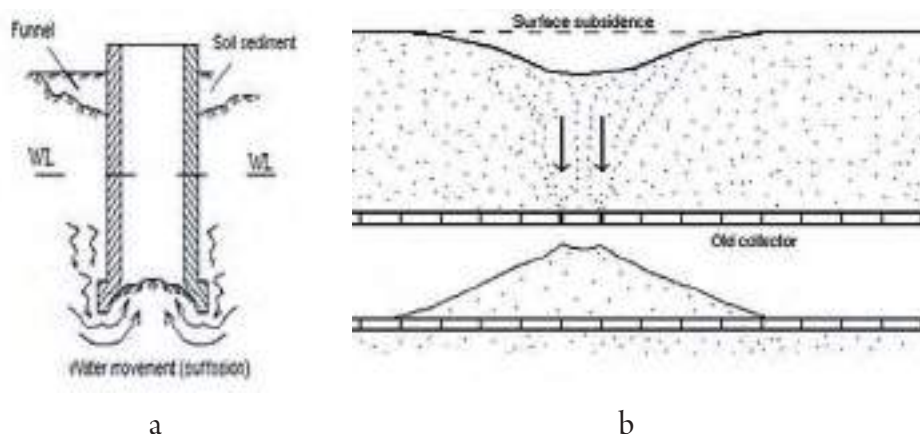


Fig 3.1.4. Suffusion removal of soil particles up through the bottom of the lower well (a) and down through the openings in the manifold (b)

High heterogeneity in the particle size distribution of soils, increase of groundwater velocity and filtration transition from laminar to turbulent regime, which occurs at hydraulic gradient $I > 5$ are favorable factors for suffusion.

The coefficient of heterogeneity of the particle size distribution, determined by the formula $C_u = d_{60} / d_{10}$, where d_{60} and d_{10} – diameters corresponding to 60 and 10% content of fractions respectively can be used to assess the likelihood of suffusion. Sandy soils are classified in three categories according to C_u value as follows: suffusive – $C_u > 20$, transitional – $C_u = 10-20$ and non-suffusive – $C_u < 10$.

Suffusion leads to weakening of soils and settling of the overlying soil thickness with formation on the surface of suffusion funnels, saucers, hollows, dips with diameters from one meter up to 100 meters and more; sometimes even the formation of large underground cavities and caves is possible.

Temporary or permanent washing of the soil near the surface of the ground can also cause suffusion as shown in Fig. 3.1.5.



Fig 3.1.5. Deformation of the pavement surface caused by suffusion and movement of soil into the manhole
Photo by A. Zhezhera

Suffusion of sub-base materials underneath roads may be a very dangerous for motor vehicles (Fig. 3.1.6).



a

b

Fig. 3.1.6 a, b. Suffusion cavities due to groundwater ruptures

<http://newtimes.kz/eshche/regiony/90822-avtobus-provalilsya-v-yamu-na-doroge-v-ust-kamenogorske-video>

<http://rossija.info/dorogami-rossii/kogda-zemlya-uhodit-iz-pod-nog.htm>

<http://rossija.info/dorogami-rossii/kogda-zemlya-uhodit-iz-pod-nog.htm>

Within the soil masses, suffusion can develop at the contact area of two layers made of different soils, often comprising rocks of different lithological composition (Fig. 3.1.7) or native soil and backfill (possibly hosting structures).

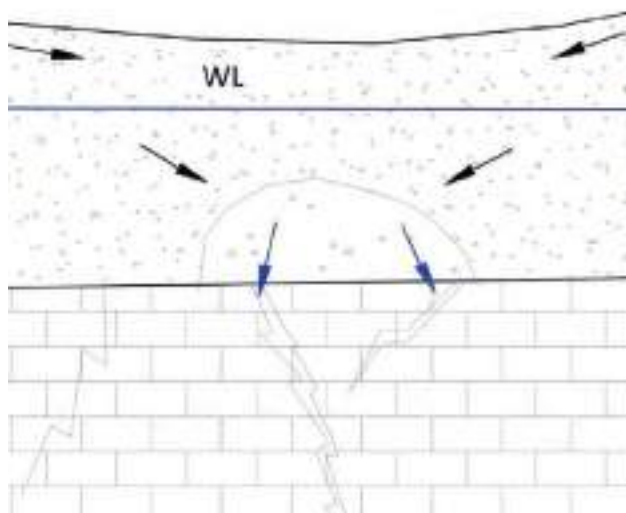


Fig. 3.1.7. Scheme of the development of the suffusion process in the depth of the array due to the leaching of particles from the overlying dispersed soil into the cracks of the underlying rock/soil stratum

http://sprosigeologa.ru/attachments/Image/Shema-razvitiya-suffozii_4.jpg?template=generic

Precautions to avoid suffusion:

1. the cessation of movement of water by waterproofing the surface and drainage of surface runoff water;
2. reduction of groundwater movement speed to value of lower critical filtration rate by means of anti-filtration loops and screens;
3. backfilling of groundwater discharge sites on the surface of the earth (sand is most often used for this purpose);
4. artificial stabilisation of soils, weakened by suffusion using ground improvement techniques (impregnation with cement, lime, fly ash and clay solutions, bituminization, etc.).

Since water filtration plays a leading role in the process of suffusion, the main engineering means to protect territories and structures against suffusion is a sound drainage system for groundwater evacuation. Traditional drainage solutions often used are the horizontal, vertical and combined (combining elements of horizontal and vertical drainage) systems. Drainage is realized using the system of horizontal drains or wells, preferably gravity drainage. If that's not possible, forced evacuation by pumping is recommended. In conditions of dense urban development, the use of special types of drainage like radiation and ventilation may be effective.

Test Questions for Chapter 3.1 Suffusion

1. Definition of suffusion.
2. Mechanisms of mechanical and chemical suffusion.
3. What is the danger of suffusion processes?
4. The reasons for the development of suffusion near the surface and in the depths of the soil mass.
5. The principles of anti-suffusion measures.

Chapter 3.2. KARST

Karst (also spelled *Carst*) is a combination of processes and phenomena associated with the activities of surface and underground waters, expressed in terms of erosion, dissolution of rocks, the formation of voids of various sizes and often negative forms of relief on ground surface. The word *karst* comes from the German word *Karst*, Sloven. *Kras* – the name of the limestone plateau of the north-west of the Balkan Peninsula on the border of Slovenia and Italy (Fig. 3.2.1).



Fig 3.2.1. *Karst Plateau, Slovenia, giving the name to all karst processes*
[http://ru.wikipedia.org/wiki/%D0%9A%D0%B0%D1%80%D1%81%D1%82_\(%D0%BF%D0%BB%D0%B0%D1%82%D0%BE\)/#/media/%D0%A4%D0%B0%D0%B9%D0%BB:Karst_under_Skocjan.jpg](http://ru.wikipedia.org/wiki/%D0%9A%D0%B0%D1%80%D1%81%D1%82_(%D0%BF%D0%BB%D0%B0%D1%82%D0%BE)/#/media/%D0%A4%D0%B0%D0%B9%D0%BB:Karst_under_Skocjan.jpg)

Karst processes will only develop with the presence a powerful stratum of water-soluble rocks and a low groundwater level. The main lithological types of rocks in which such processes develop are the following: 1) limestones; 2) dolomites; 3) marble; 4) chalk and chalky marls; 5) gypsum-anhydrite strata; 6) rock and potassium salts.

Open and buried carbonate rocks in all continents, within regions subject to karst occupy an area of about 40 million km² (Fig. 3.2.2) with gypsum and anhydrite – about 7 million km² and rock salt – up to only 4 million km².

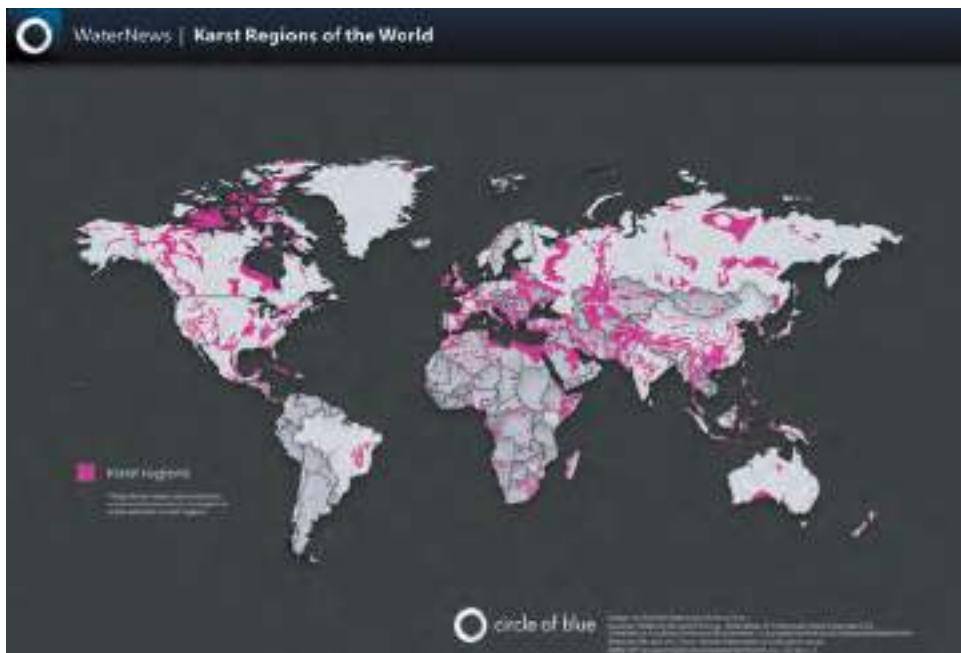


Fig 3.2.2. Map of the distribution of karst in carbonate rocks

<http://www.circleofblue.org/2010/world/chinas-karst-region-infographics/attachment/world-karst-map-web-1-12/>

The earth's surface in formations subject to karst has a specific appearance – these are the various characteristic landforms, mainly: shallow (from a few centimeters to two meters deep) furrows and indentations – *carras* (Fig. 3.2.3); closed depressions – *funnels and saucers* (Fig. 3.2.4), *natural wells and mines, polia* (hollows with an area of up to several tens and even hundreds of km², with waterways going underground), "*blind*" *ravines and valleys, niches in cliffs*.

Areas composed of soluble rocks are remarkable not only by specific reliefs of the earth's surface, but also by unique natural underground formations associated with them (Fig. 3.2.5).

Funnels are typical forms of karst (cones, cauldrons or saucers, or irregularly shaped pits) reaching diameter up to two hundred meters and a depth of 0.5 to 50 m. At the bottom of such funnels and other depressions, there are vertical holes that absorb water – *ponors*, which are often mouths of mines and wells, reaching a depth of more than 1000 m.



Fig. 3.2.3. Carras on Karabi-yayla plateau, Crimea
http://crimea.nezabarom.ua/alushta/Dostoprimechatelnosti/karabi_yayla/



Fig. 3.2.4. Cratered landscape in South Canterbury, New Zealand
<http://www.sciencelearn.org.nz/images/498-dolines>

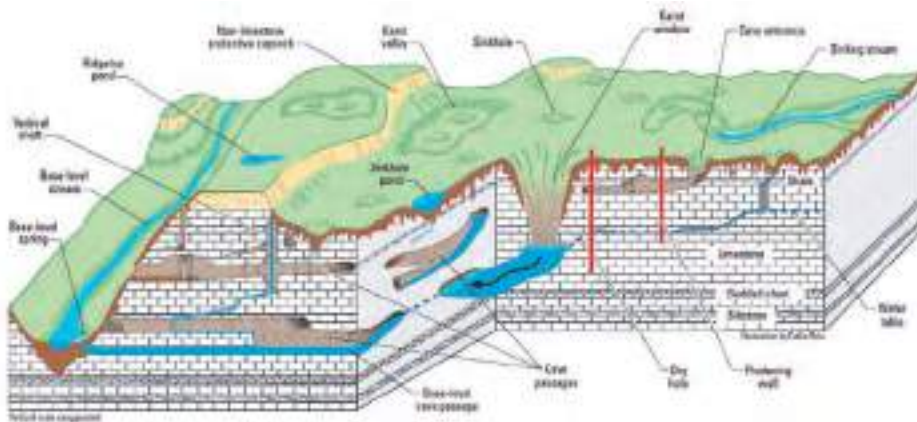


Fig. 3.2.5. Scheme of the development of karst processes on the surface and in the depths of mountain ranges
<http://en.wikipedia.org/wiki/Karst#/media/File:KarstterrainUSGS.jpg>

Hollows and funnels can be filled with water which may drain with drought season, forming dry lakes. Sometimes such lakes are significant in size, such as Slika Cerknisko Jezero in Slovenia (Fig. 3.2.6).



a



b

Fig. 3.2.6. Seasonal Lake Slika Cerknisko Jezero, Slovenia
<http://de.m.wikipedia.org/wiki/Datei:SlikaCerkniskoJezeroPolno.jpg>

Two types of karst can be distinguished depending on the type of cover deposits over the karst rocks: *open* (bare, Mediterranean, Crimean) – devoid of top organic soils and vegetation, (Fig. 3.2.7 a) and *closed* (Central European or Uralian) – with a cover from Quaternary sediments and soil (Fig. 3.2.7b).

The karst process contributes to the emergence of unique natural objects and whole complexes such as, “stone forests” (Fig. 3.2.8) and huge dips (Fig. 3.2.9).



a



b

Fig. 3.2.7. Karst relief:

a – closed type of karst, Moravian Karst reserve, Czech Republic
<http://czech-rurepublic-gb.ru/sights/peshhery/zapovednik-moravskij-karst/>

b – open type of karst – highlands of Karabi-Yail, Crimea
<http://goru.travel/place/plato-korabi-yayla>



Fig. 3.2.8. Stone forest Tsingy_de_Bemaraha, Madagascar

<http://reserves-park.ru/natsionalnye-parki-madagaskara/723-tsinzhi-dyu-bemarakha.html>



Fig. 3.2.9. Sima Humboldt is a funnel in Venezuela

At a depth of approximately 314 m with almost vertical walls, the volume of the funnel is 18 million m³. The upper edge of the dip has a width of 352 m, and below it reaches 502 m. Thanks to the vertical walls, at the bottom of the funnel has developed its own unique ecosystem, with species of plants and animals that are not found anywhere else on Earth

<http://travelask.ru/blog/posts/2858-6-samyh-vpechatlyayuschih-karstovyh-voronok-mira>

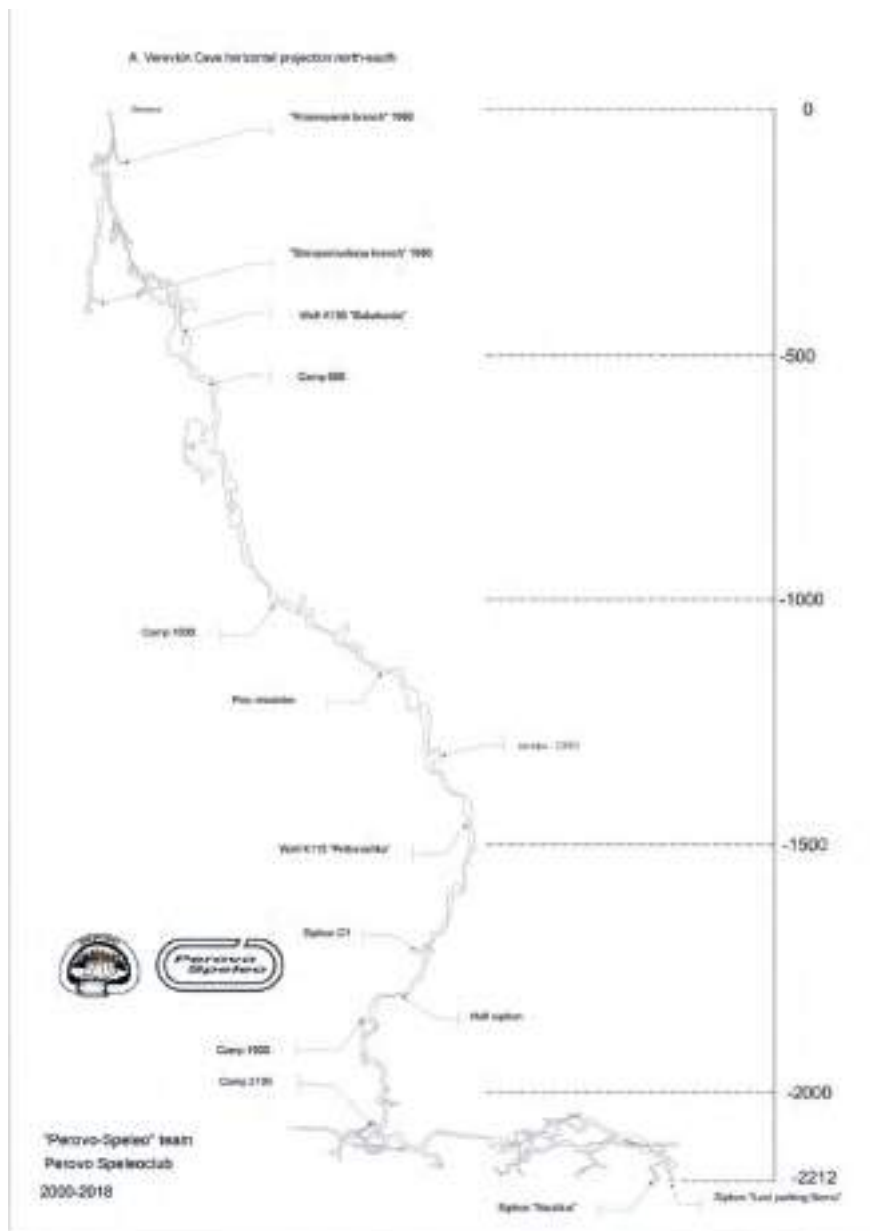
Natural Karst Caves

Fig. 3.2.10. The scheme of the deepest cave in the world named after Verevkin
https://en.wikipedia.org/wiki/%D0%A4%D0%B0%D0%B9%D0%BB:%D0%9F%D1%80%D0%BE%D0%B5%D0%BA%D1%86%D0%B8%D1%8F_%D0%BD%D0%B0_%D0%BF%D0%BB%D0%BE%D1%81%D0%BA%D0%BE%D1%81%D1%82%D1%8C_%D1%81%D0%B5%D0%B2%D0%B5%D1%80-%D0%AE%D0%B3.jpg

The most famous and voluminous underground karst forms are caves; the largest of them are formed in carbonate rocks, most often in limestones, which are overlain from above by solid insoluble rocks.

The longest in the world today is the Flint Ridge cave system with the Mammoth Cave in Kentucky, USA. Cave explorers mapped 587 km of underground passages and the Mamontov's cave is considered as the longest in the world. Professional researchers continue to find more and more inaccessible corridors, draw up new maps and, as they often say, «the end of the land is not visible».

According to the topographic survey of 2017, the deepest in the world are caves Verevkina (2212 m) and Krubera-Voronya (2199 m) in Abkhazia. Typical caves are subvertical karst and their lower part is composed of black limestones (Fig. 3.2.10). The caves are located in the Arabica mountains of the Gagra Range in the Western Caucasus.

From the cave on the coast at the foot of the Arabica massif flows the Reprois River, officially considered the shortest in the world and the coldest of the rivers flowing into the Black Sea. Reprois is a powerful outlet for underground karst waters, which after 18 meters flow into the Black Sea. An underground stream originates on a glacier on the high plateau of Arabica at an altitude of 2500 m, 12–15 km from the sea coast.

Numerous amazing natural formations can be found in karst caves: giant and very tiny stalactites, stalagmites and crystals covering the walls of huge halls, “bottomless” dips, underground waterfalls, lakes and rivers, stone “mushrooms, flowers”, etc. (Fig. 3.2.11).

The discovery of new caves is a continuing process, despite many years of research by cavers. In 1991, a cave was discovered in Vietnam, and was examined by cavers in 2007. The Son Doong Cave (Cave of a mountain river) is unique even on a global scale. Today it is the largest in the world in terms of internal spaces (Fig. 3.2.12). The dimensions of the cave are impressive: with a length of 9 kilometers, in some places its width is more than 200 meters, and its height is about 150 meters. Son Doong Cave is part of an extensive, unexplored cave system, which includes 150 caves, and possibly more.



a



b



c

Fig. 3.2.11. a, b, c Various karst forms in the cave of Lechugia, USA
<http://www.besttourism.com/medias/dfp/1146>



a

<http://www.wantseeproject.com/wp-content/uploads/2015/10/son-doong-cave-nature.jpg>



b

<http://thekievtimes.ua/wp-content/uploads/2015/03/2015.jpg>

*Fig. 3.2.12. The cave of the mountain river, Vietnam – the largest in the world in terms of internal volumes: **a** – the entrance to the cave; **b** – giant stalagmites*

In the Ternopil region of Ukraine there is a gypsum cave “Optimistic” – the longest in Eurasia. With a maximum depth of only 20 meters, it extends over 216 km and is a complex labyrinth of passages, galleries and grottoes of various shapes and sizes. The cave was formed as a result of the dissolution of gypsum deposits of the Neogene age by underground waters. The walls of many underground passages are covered with a continuous carpet of gypsum

plaster, as well as coral-like formations that have been forming for thousands of years. Often, gypsum is observed in the form of drusen of large snow-white and transparent crystals (Fig. 3.2.13).



a



b

Fig. 3.2.13. **a, b** Optimistic Cave, Ukraine –
the longest gypsum cave on the Eurasian continent
[http://myplanet.com.ua/wp-content/uploads/2014/09/
Peshhery-Ternopolya-peshhera-kryshtaleva.jpg](http://myplanet.com.ua/wp-content/uploads/2014/09/Peshhery-Ternopolya-peshhera-kryshtaleva.jpg)

Negative manifestations of karst processes. Man-made karst

According to the regulatory documents (DBNV.1.1-24: 2009 «*Protection against dangerous geological processes*»), karst is a complex geological process associated with the dissolution of surface and (or) underground rock waters, with their weakening, destruction, formation of cavities, change in the stress state of the rocks, the chemical composition and regime of groundwater, suffusion (mechanical and chemical), erosion, sediment, collapse of soil mass on the earth's surface.

Karst regions, which are known to occupy a significant part of the Earth's land, may become a cause of damage and destruction to buildings and structures from karst deformations. Particularly dangerous are areas of open and developing karsts, where there are failures which can result in collapse of surface and become severe hazard to buildings and roads.

In some territories, karst processes began exclusively under the influence of human activities (man-made karst). Material loss associated with the activation of karst processes as a result of anthropogenic impact, significantly exceed loss from natural karst. The development of anthropogenic karst, often with catastrophic manifestations, is observed in areas of underground mining and similar anthropogenic activities. This process is common in areas of extraction of salt minerals, sulfur deposits, development of flux-dolomite raw materials and in areas of coal mining.

A typical example is the New Carthage brine field in the Donetsk region, where rock salt was mined from a depth of about 200 m by underground dissolution with pumping brine through boreholes. Twenty years after the start of operation of the site, gradual smooth subsidence of the earth's surface began (Fig. 3.2.14) and brine solution flowing from wells occasionally occurred.



Fig. 3.2.14. Earth surface subsidence on brine field New Carthage, Donetsk region, Ukraine. Photo by A. Ubivovk

The maximum depth of subsidence, as at date, is 25 m. Fresh rainwater accumulates at the bottom and the area is not suitable for economic use.

In the Transcarpathian region, as a result of mine flooding with groundwater, dips occur on the surface of the earth, which is a great hazard to people (Fig. 3.2.15).



a

http://zaholovok.com.ua/sites/default/files/1973339_943581412340285_4593587793710818369_o_0.jpg



c



b

http://www.tyachivnews.in.ua/uploads/posts/2015-09/1441958441_53a586e-1432391278-provallya-solotvino.jpg
http://compas.ucoz.com/_ph/14/747558527.jpg

Fig. 3.2.15. Technogenic karst dips in Solotvino village, Transcarpathia: **a** – funnel, which appeared on April 16, 2015; **b, c** – dips threatening buildings

Some modern examples of karst dips in built-up territories are shown in Figs. 3.2.16, 3.2.17.



a

[http://www.rferl.org/
a/russia-s-uralkali-
says-nine-miners-trapped-
inside-solikamsk-mine/
29671038.html](http://www.rferl.org/a/russia-s-uralkali-says-nine-miners-trapped-inside-solikamsk-mine/29671038.html)



b



c

[http://blakenet.org.ru/
solikamsk-proval-foto.html](http://blakenet.org.ru/solikamsk-proval-foto.html)

Fig. 3.2.16. Technogenic karst failure in the territory of suburban areas, Solikamsk, Russia:
a – 2014; **b** – 2016; **c** – 2018



Fig. 3.2.17. Technological karst failure in Berezniki, Russia, which occurred in December 2011. Since then, the funnel has swallowed up several industrial buildings of the mine-building department
<http://earth-chronicles.ru/news/2014-07-25-68765>

Karst construction

The main danger of karst to buildings and engineering structures is the occurrence of unexpected and poorly predictable failures of the earth's surface, the main reasons for which in most cases are the collapse of the roof of underground karst cavities. Therefore, the prediction of failures consists mainly in the detection of voids in the rock mass, determining their spatial characteristics, assessing the possibility of deformations of the earth's surface, their probable sizes as well as in predicting the service life of the structure under these conditions.

To calculate the safety and sustainability of buildings and structures under construction, as well as design measures for their engineering protection, information on the karst process prevailing on the construction site is needed. Contouring of all karst voids, dips, underground passages, rather accurate for engineering purposes, is required.

The most effective protection of buildings and structures against karst is the provision of information during the process of engineering surveys which will help to implement a series of anti-karst measures. In areas with increased

karst danger, it is especially important to rationally place objects outside the zone of possible failures.

Deformations of the foundations of buildings and structures of karst-suffosive origin occur according to the law of rare events (Poisson distribution), that is, the time of dangerous manifestation of karst and its location are probabilistic in nature. Therefore, the main objective of constructive protection against karst is to prevent the catastrophic destruction of buildings and structures against possible deformations during a certain duration, allowing enough time for the evacuation of people and valuable equipment as well as to stop the progression of destruction.

The main precautionary measures may be summarized as follows:

- assessment of the possibility of development in karst-hazardous territories in various environmental conditions;
- protection against storm and surface runoff, household and industrial water from infiltration into karst rocks;
- technical reclamation of rocks subject to karst-suffosion processes, including filling karst cavities with cement, silicate, bitumen filler, taking into account the effect on neighboring areas;
- modeling and design of buildings and structures with consideration of the appropriate foundations and ground structures;
- reliable maintenance of buildings and structures in the event of the formation of karst deformations at base level.

Test questions for chapter 3.2. Karst

1. What is a karst process? In what breeds does it develop?
2. The main territories of karst development in the world.
3. What are the main surface and underground forms formed during the development of karst?
4. The main conditions for the development of karst.
5. Where does technogenic karst develop?
6. Fundamentals of engineering and geological study of karst.
7. Assessment of the degree of karst and the stability of the territory in karst areas.
8. Speed estimation and prediction of karst processes, their significance for different structures.
9. Measures to combat karst processes.

Chapter 3.3. SLOPES AND TYPES OF SLOPE PROCESSES

Slopes are inclined areas of the earth's surface with positive slopes – rising above the earth's surface and negative slopes – located below the earth's surface. Slopes are formed as a result of natural endogenous and exogenous processes or human engineering activities. On land, slopes occupy up to 75% of the Earth's surface and can have different shapes – straight, hilly, convex, concave, stepped, among others. The relief of the earth's surface as a whole consists of a combination of horizontal surfaces and slopes.

Slopes are classified as follows: very steep – $> 35^\circ$; steep – $15\text{--}35^\circ$; moderately steep – $8\text{--}15^\circ$; slightly steep – $4\text{--}8^\circ$; very slightly steep – $2\text{--}4^\circ$. The length of the slopes is divided into: long > 500 m; moderate – $500\text{--}50$ m; short < 50 m. The surface of each of the listed slopes can be complicated by steps of various heights, irregular shapes and so on. According to the relief surface of the slopes, considerable information about the processes occurring on the slopes can be obtained and conclusions about the nature of the interaction of endogenous and exogenous phenomena can be drawn.

Natural slopes can be endogenous or exogenous at origin. Slopes of endogenous origin are formed as a result of tectonic movements of the earth's crust, earthquakes, igneous and volcanic processes including mud volcanism. Among the slopes of exogenous origin, slopes created by the action of surface waters, the activity of seas, lakes, glaciers, wind, groundwater and permafrost processes can be distinguished. Slopes created as a result of the activity of organisms, such as the slopes of coral reefs are also exogenous. Often, slopes can be created as a result of the combined action of two or more of both endogenous and exogenous factors.

According to morphometric characteristics (height, steepness, configuration), as well as the geological structure, composition and properties of the constituent rocks, hydrogeological and hydrological conditions, nature, strength, intensity of external influences, three main groups of natural slopes are identified:

- coastal slopes, that is, along the seas and oceans;
- slopes in river valleys;
- slopes in mountainous areas.

Slopes experience permanent change under the influence of a number of processes and as such, “slope transformation” or “gravitational transformation” can be identified. These include landslides, rockfalls, mudflows, avalanches

and other natural events. For ease of study, information on these processes is described in three chapters 3.3, 3.4, 3.5.

According to the prevailing nature of the slope processes, four types of natural slopes can be identified:

1. *Gravitational* with a significant angle of inclination of the surface – $35\text{--}40^\circ$ or more, where fragments of rocks formed as a result of weathering of bedrock slide to the toe of the slopes under the action of gravity. Varieties are: landslide, talus and avalanche slopes (Fig. 3.3.1, 3.3.2).



Fig. 3.3.1. Scree slopes of the high mountains of the Carpathians, Ukraine. Photo by A. Yegupov

2. Slopes of *block displacements* are formed when rock blocks moving down the slope are predominantly large in size. Groundwater contributes significantly to such movements, but the role of gravity remains decisive. The steepness of these slopes is usually in the range of $20\text{--}40^\circ$. These include slopes with various types of landslides (Fig. 3.3.3).

3. Slopes of *plastic displacement* of the soil. The nature of the movement of soil depends primarily on its consistency and occurs on fairly gentle slopes (with an angle of inclination of the order of 3° ; Fig. 3.3.4).

4. *Diluvial* slopes (planar flushing). Diluvial deposits on slopes are very widespread; they are formed as a result of the transfer of rock weathering products

by shallow temporary rain water (or melting of snow). Gravity, which contributes to the movement of soil particles, plays an important role in this process. Due to diluvial processes, the rocks in the upper part of the slope undergo weathering and debris accumulates at the toe. The intensity of the diluvial processes depends on a number of factors, but primarily on the state of the surface of the slopes. They occur both on steep and very gentle ($2-3^\circ$) slopes (Fig. 3.3.5).



a



b



c



d



e

*Fig. 3.3.2. Slopes of various types:
a – landslide, China; **b** – avalanche, Alps;
c – talus, the main Caucasian ridge;
d – topple, coast of Thailand; **e** – slope with
 block movements, Siberia*

a <http://imagens.publico.pt/imagens.aspx/452814?tp=KM&db=IMAGENS>

b <http://ru.tokkoro.com/%D0%93%D0%BE%D1%80%D0%B0-1332983.html>

c Photo by V. Derkach

d Photo by V. Benko

e http://images.myshared.ru/6/779576/slide_4.jpg



Fig. 3.3.3. Landslide, Canada

<http://eco-intelligent.com/2016/06/02/landslides-all-you-need-to-know/>



Fig. 3.3.4. Rock formations on the slopes of Talgar settlement, Kazakhstan

<http://nazarovilya.alnaz.ru/images/talgar4.jpg>



Fig. 3.3.5. Diluvial slope

<http://900igr.net/datai/geografija/Ekzogennye-protsessy/0055-031-Osnovnym-soderzhanie-sklonovykh-protsessov-javljaetsja-transportirovka.png>



Fig. 3.3.6. The largest and deepest open pit mine in the world, Utah, USA. This giant quarry has a width of 4 kilometers and a depth of 1200 meters. It was discovered back in 1848 for the extraction of copper ore, and since then it has used for extraction of large quantities of copper, gold, silver and molybdenum

<http://enki.ua/news/10-samyh-bolshih-otkrytyh-karerov-mira-4379>

In addition to the natural slopes created by endogenous and exogenous natural processes, there are currently a large number of man-made artificial slopes, arising as a result of *human engineering activities*. The largest of them are confined to negative landforms – mines and quarries for the extraction of various minerals (Fig. 3.3.6, 3.3.7).



Fig. 3.3.7. Kryvyi Rih iron ore quarries, Ukraine
http://g.io.ua/img_aa/large/1831/54/18315466.jpg

Most of the artificial positive relief forms created by man are mainly the various industrial waste from the mining industry in the form of waste heaps, dumps, artificial mountains, sludge collectors, among others (Fig. 3.3.8). These formations often pose a serious environmental threat. For example, there are 61 heaps of waste in the city of Donetsk (Ukraine) alone, which annually emit about 70 tons of harmful substances into the atmosphere in the form of gases and dust. Among them, a whole complex of chemical elements and compounds hazardous to health: sulfur, cobalt, arsenic, lead and nitrates.



a

<http://fototerra.ru/image.html?id=71183&size=medium>

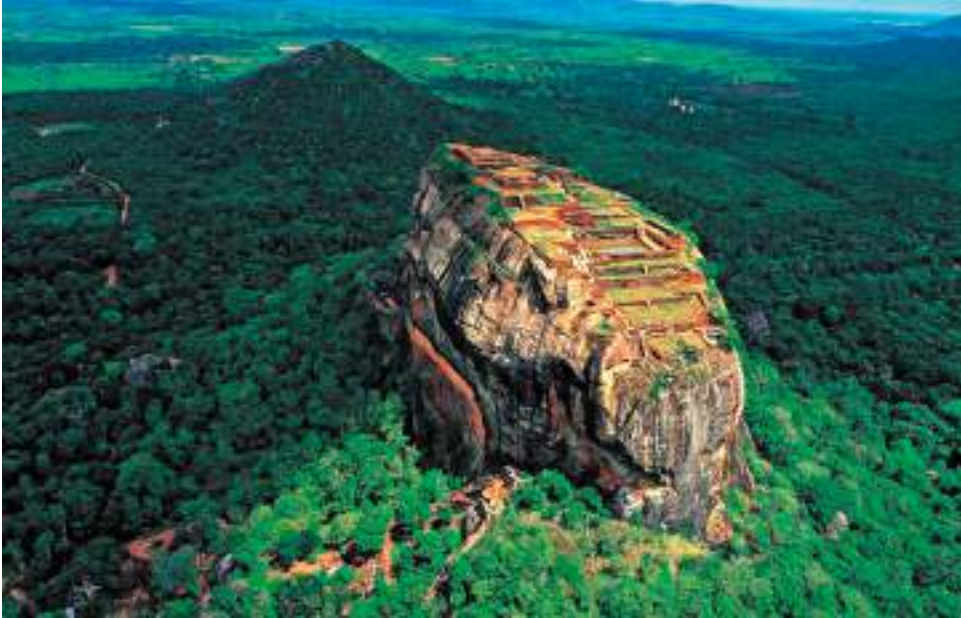


b

<http://lh5.googleusercontent.com/-spY9CNT-jZI/UzPDqZpf2oI/AAAAAAAAAMrg/ql7efUxtBW0/w700-h467-no/CMOL8349.jpg>

*Fig. 3.3.8. Man-made mountains in Ukraine: **a** – terrikon, Donbass; **b** – slag dumps, Zaporozje*

In many parts of the world, natural slopes, even on the most remote and steepest cliffs, have been transformed by human being for the purpose of creating horizontal habitable terraces. Such areas serve various purposes, formerly military, and nowadays, primarily agricultural (Fig. 3.3.9, 3.3.10).



<http://tripland.info/2016/02/15-neoficialnyx-chudes-sveta-kotorye-nuzhno-obyazatelno-uvidet/>
Fig 3.3.9. Sigiriya, Sri Lanka – also known as the “lion rock” – the ruins of an old fortress, which is located on a huge granite rock (approximately 180 m high), rising above the surrounding plain and is visible for far away,



Fig. 3.3.10. Agricultural Terraces, Vietnam

http://twitter.com/mien_tay/status/1068106141413056512

Slope processes

Hazardous engineering and geological processes can occur on both natural and artificial slopes, often associated with hydrometeorological phenomena that have a negative effect on territories, national premises, and people's livelihoods (topple, landslides, earthflows, debris flows and snow avalanches) and substantial expenses are required to prevent their occurrence or protective measures.

Schemes of various types of gravitational displacements of soils on the slopes are shown in Figure 3.3.11.

A *collapse (or topple)* is the rapid movement of soil masses under the influence of gravity: dislocation of a rock mass from a steep slope and its rapid movement downwards with falling, tipping over and crushing along its way down (Fig. 3.3.12). Most often, landslides occur on the slopes of mountains, on the steep banks of river valleys and seashores, as well as in construction pits, trenches, and quarries. Schemes of the main types, by the mechanism of movement, are shown in Fig. 3.3.13. A common cause of collapse is loss of equilibrium: the excess of shear force component of gravity over forces required to keep the rocks of the slope intact.

Collapse occur on steep slopes (more than 45°) due to loss of adhesion of part of the soil to the main massif as a result of crack development due to weathering, causing instability at the toe of the slope, for example, due to abrasion or river. The largest landslides on the planet are associated primarily with earthquakes. The movement of large rock masses over considerable distances (up to 7–12 km), sometimes even moving upwards on slopes, is explained by the enormous kinetic energy accumulated by the landslide masses and the low friction of moving rocks. Such a decrease in friction is caused by the frontal compressed air, turning into a form of air cushion. Compressed air with large collapses can create a powerful shock wave, the destructive effect of which is sometimes even stronger than the direct action of the collapse masses.

Collapse, rockfalls, debris flows and avalanches produce the main degradation (destructive) in mountainous areas.



a

http://www.theoaklandpress.com/news/colorado-rock-slide-rains-boulders-on-bridge-highway/article_a5ceab00-3482-50bd-870c-a3868710111d.html



b

<http://www.dailymail.co.uk/news/article-2156465/They-don-t-things-half-China-lucky-drivers-escape-TWO-runaway-boulders-flattening-cars.html>

*Fig. 3.3.12. Collapse of blocks on highways in the mountains: **a** – Colorado, USA; **b** – China*

Dislocation and downward movement of small volumes of rocks, consisting of fragments smaller than 1 m^3 , is called rockfall. The collapse of a single block from a very steep or steep slope is quite common in many areas (Fig. 3.3.13). The block falls freely and does not slip along the slope. Most often, outfalls occur in layered rocks of sedimentary origin (sandstones, marls and limestones).



Fig. 3.3.13. Rock outcrop

http://fs.nashauche.ru/tw_files2/urls_3/1202/d-1201054/img8.jpg

Giant landslides sometimes occur in mountainous regions, with volumes of rocks of the order of hundreds of millions of cubic meters. For example, as a result of the earthquake of February 18, 1911, the largest landslide with a volume of 2.2 billion m^3 and a mass of 6 billion tons occurred in the Pamirs in the Bartang River Valley, Tajikistan. Nowadays called the Usoi Dam, it is the largest in modern history. The 567 m high natural stone dam blocked the river valley and the modern Sarez Lake was filled with water for several years. At present, the length of the lake is about 70 km, the maximum depth is 500 m and the capacity of water storage is more than 17 km^3 (Fig. 3.3.14).



Fig. 3.3.14. Sarez lake, formed as a result of a catastrophic gravitational displacement of rocks that blocked the river valley
<http://ozerra.ru/zavalnye-ozera/31-sarezskoe.html>

Important landslides occurred in the Alps, according to A. Gerhard, the largest volume displaced amounted to 15 km^3 . Mountain landslides often block river beds and river valleys, which leads to the formation of lakes in alpine regions around the world.

Protective measures against collapse. The prevention of especially large collapses in the vast majority of cases is technically impossible; engineering protection against them is also not realistic and these areas normally do not accommodate any structure or building.

For small scale collapse protective measures can be taken to prevent their occurrence. A widespread methodology is the removal of overhanging blocks by means of low-power explosions or by driving wedges into rock cracks (wedging). The wedging is safer than the explosive method because it allows to stabilize individual rocks and on the other hand, an incorrect explosion may cause a major collapse.

Most often roads and railways may be protected from small collapse disasters by building protective and auxiliary structures, which include:

- anti-rock walls capable of withstanding the impact of large debris, with ditches on the slope and near the roadway to accumulate rolling material;

- shafts and walls of various designs, directing the gathering of rock masses in a safe direction;
- making the surface of the slope and the device of the shafts in an appropriate form to ensure the transfer of rock masses safely over the roadbed;
- reinforced concrete powerful walls with buttresses to support potentially dangerous rock blocks in combination with their strengthening with anchors or iron brackets;
- protective galleries with reliable ceilings, which are most often arranged in the form of semi-open structures (Fig. 3.3.15);
- shotcrete consisting of concreting the surface of weathered rocks of a crumbling slope;
- installation of metal nets to protect against rockfalls and shedding debris on the road;
- regular removal of large loose blocks from the slopes;
- groundwater drainage facilities to prevent uncontrolled discharge on the slope.



Fig. 3.3.15. Protective anti-rockfalling gallery
http://otktravels.narod.ru/travels/more2/more2_38.htm

In order to prevent rock fall in construction pits, the slope angles are reduced, retaining shields and temporary sheet pile walls are installed. *It is strictly not recommended to overload the edges of the excavations with heavy vehicles or heavy building structures nor to cut the toes of the slopes.* Pits with rainwater must not be left open for a long time and removal of rain water must be carried out.

Screes or Talus are formed by the process of displacement (mainly rolling down from mountain slopes) of stone fragments formed as a result of weathering of rocks and their accumulation in the lower part of steep slopes. Screes are most characteristic to growing mountain systems, young in terms of their geological age, for example, the Pamirs, the Alps, the Himalayas, on which the process of rock weathering is particularly intense.

They occur on steep slopes composed of rocky and semi-rocky soils which are mainly affected by processes of physical weathering. Fragments of various sizes, broken off from the main massif, slide down to places with a flatter slope of the relief and accumulate materials at the toe of slopes comprising weakly rounded blocks, gravels and wood. The volumes of scree are different, the thickness of the scattering layer can be from several to tens of meters (Fig. 3.3.16). The size of the fragments is determined by the *petrographic composition* and the *degree of weathering* of the rocks of the slope: slightly weathered igneous rocks often form coarse materials; less strong sedimentary and highly weathered rocks form medium to fine clastic (gravelly) material. Various types of metamorphic schists (crystalline, mica, etc.) and layered sedimentary rocks (sandstones, marls) often form scree, consisting of fragments of a certain shape, such as slabs.

From an engineering and construction point of view, the most important characteristic of talus is their ability to move. On this basis, talus is characterized as active (being in the stage of active movement), decaying (the processes of moving talus material gradually stop), and motionless (at rest).

There is almost no vegetation on the active scree. The mass of debris is in a loose, very unstable state and can begin to move due to an increase in the total weight of the talus upon receipt of new material, high moisture, cuts at the toe of the talus and traffic movement.

The angle of repose of the scree material primarily depends on its particle size distribution. In a low-moisture state, large and medium clastic, loose talus soils have an average angle of repose $\varphi = 35-37^\circ$ and small clastic $\varphi = 30-32^\circ$. The slope value of each particular scree is also associated with the slope angle

and roughness of the slopes, the amount of material coming from above and its saturation with water.

Scree is characterized by the *coefficient of scree or talus mobility*: $K = \alpha / \varphi$ where α is the inclination of the talus and φ – the angle of repose (internal friction) of clastic talus material.

Talus are classified with respect to K value as follows:

- mobile, $K \geq 1.0$;
- moderately mobile, without signs of attenuation, $K = 0.7–1.0$;
- inactive, with a weak supply of new incoming material, $K = 0.5–0.7$;
- relatively motionless, where the receipt of new material does not occur, $K < 0.5$.

Mobile talus is characteristic of steep slopes with an angle of more than 65° , moderately mobile one has less steepness – from 45 to 65° . Vegetation (shrubs and trees) is often observed on decaying scree.

Another type of scree occurs when the slope and the debris located on it are saturated with water which leads to a decrease in the angle of repose of the talus material and an increase in its total weight. Also, sliding frictional resistance on the wet stationary surface of the slope is reduced, and as a result, the mass of talus begins to slide. The movement of talus of this type can be caused even by the most insignificant fluctuations, for example, even by a passing pedestrian. It is deemed dangerous to walk on scree slopes, for example, mountaineering tourists, especially in wet and rainy weather.

Protection against talus. In areas prone to talus, construction is significantly complicated. Clastic talus material can periodically fill roads, damage structures, and occupy useful areas. When designing the engineering protection of structures and communications from scree, it is very important to reliably know the speed of falling clastic material, which can be determined by long-term field observations.

With small gravel scree, the protection is relatively simple and may be reduced to the removal of debris material located higher up the slope from the protected structure. This method is very time-consuming and is used in case of special significance of structures.

Examples of constructions of engineering protective structures against talus instability are trenches that catch crumbling debris, retaining walls, concrete peaks or metal nets over roads. In dangerous places where large volumes of scree are observed, reinforced concrete galleries and tunnels for roads protection are erected. Groundwater drainage and surface water drainage will also reduce talus instability.



http://bigpicture.ru/wp-content/uploads/2010/06/h30_dsc0.jpg



<http://bigpicture.ru/wp-content/uploads/2011/06/0313.jpg>

Fig. 3.3.16. Scree of various types: **a** – in Pakistan; **b** – in China

A special form of talus (*kurums*) may be powerful deposits of rocky soils, consisting of large boulders that accumulate at the foot of gentle slopes, in troughs and valleys of watercourses (Fig. 3.3.17). The steepness of the slopes is less than the angle of repose of coarse clastic material (from 3° to $35\text{--}40^{\circ}$). Sometimes a single mass of coarse clastic material can form from the top of the hill to the bottom of the slope.

The thickness of the layer naturally decreases from 1–2 meters in the upper part of the slopes to 10–15 meters at the bottom of the valleys.



Fig. 3.3.17. Kurum – a slowly moving stone river from blocks
<http://eco-turizm.net/uploads/2013/05/kurumyi-na-Urale.jpg>

Earthflow is the displacement down the slope of clayey soils under the action of gravity. Loess soils are especially susceptible to earthflows (Fig. 3.3.18).



Fig. 3.3.18. Sweeping of a slope composed of loesslike loams
http://dumskaya.net/pics/b4/picturepicture_34393742121553_80297.jpg

Solifluction (from Lat. Solum – soil and fluctio – flow) is a visco – plastic displacement of soil saturated with water along the underlying frozen surface of a slope cemented by ice. Solifluction is widespread in permafrost zones or in territories with long and severely freezing soils (Siberia, Canada, high mountains of the Himalayas, Alps, etc.). The soil cover, saturated with moisture from melting snow or rains, significantly increases its weight, becoming viscous-plastic and begins to move along the slippery surface of the frozen underlying layer, even with very small slopes of $2-3^\circ$; as slopes increase, the speed of movement increases. As a result, low ridges and sometimes entire solifluction terraces may be observed (Fig. 3.3.19).



Fig. 3.3.19. *Solifluction – viscoplastic soil flow*

<http://foto-traveller.ru/en/foto/kirgizstan/kirgizstan2008/173.jpg>

Measures to prevent the occurrence of solifluction are similar to those for earthflow.

Chapter 3.4. LANDSLIDES

A landslide is a sliding displacement of ground masses down a slope without loss of contact between a shifting sliding mass and a stable non-moving part of the slope, which occurs under the influence of gravitational forces and, as a rule, with the participation of underground or surface waters.

Landslides are widespread throughout the world: on mountains slopes (mainly at altitudes of 1000–1700 m), on river banks, on the sides of ravines, earthen structures (dams) and also in coastal regions. They also occur in series of artificial excavations – construction pits, mines and quarries. Landslides can have a huge negative impact as they often cause destruction of buildings, structures, railways and roads, accidents during the construction of excavation pits and quarrying of mineral resources. For example, in the highlands of Central Asia, most of the territories are at risk of landslides or collapse.

Many catastrophic landslides are known with a huge number of victims and material destruction. Throughout the history of mankind, protection against landslides has been among the most serious problems at par with earthquakes, floods and hurricanes.

Landslides have played an important role in the formation of relief in the past and continue to influence the modern relief of the Earth's surface land, as well as the floors of the oceans. The largest landslides on Earth occur under water and are much larger than those occurring on land. They are formed by the sliding of large masses of sedimentary rocks from the edges of continental shelves, for example, the landslide of «Sturegga» occurred about 8,200 years ago and as a result of which a segment of the coast, with 3,000 km³ of materials, detached from Norway mainland. The landslide area was about 3900 km² and the range of movement of landslide masses reaches 500 km. The descent of this landslide in the North Sea caused a tsunami, 5-meter-high, which flooded the coasts in northern Europe. In the mountains of Scotland, traces of the impact of this tsunami at a distance of 80 km from the coast were discovered.

In 2010, NASA released a global catalog of landslides that have occurred on Earth. It is an extensive scientific database with detailed reports of all landslides that occurred in different parts of the world including their locations, causes and the death tolls among the population (Fig. 3.4.1, 3.4.2).



Fig. 3.4.1. Using the Global Landslide Catalog, a map has been produced to show the location of 5741 rainfall-triggered landslides from 2007 till 2013
<http://www.nasa.gov/feature/goddard/2016/using-nasa-data-to-detect-potential-landslides>



Fig. 3.4.2. Using the Global Landslide Catalog, a map, including a legend, has been produced to show the distribution and number of reported fatalities, associated with approximately 10,804 rainfall-triggered landslides between 2007 and 2017. Out of the 10,804 reported rainfall-triggered landslides, 8,369 incidents had zero fatalities. White dots represent incidents with zero reported fatalities. Dots in the color scale from pink to red represent incidents with fatalities in the range of 1–5000
<http://svs.gsfc.nasa.gov/4632>

As evidenced by the above maps, the largest number of large and dangerous landslides occur in Central and Southeast Asia.

In Ukraine, the most landslide hazardous areas are located on the shores of the Black and Azov Seas (Fig. 3.4.3), as well as on the banks of large rivers.



Fig. 3.4.3. Landslide massifs in the region of Sevastopol, Crimea
<http://www.studmed.ru/docs/static/3/b/2/c/a/3b2caa8b6ec.jpg>

The surfaces of landslide slopes can be inclined both at large and at small angles, for example, on clay soils, landslides occur even with very low slope angles – only $5-7^\circ$, if the flow of surface or ground waters are significant to cause the movement. In general, the steeper the slope, the more significant is the component of the driving shear forces, which tend to overcome the resistive cohesive force of the rock/soil particles and eventually cause a downward movement. This movement is facilitated or counteracted by the characteristics of the of slope soil mass: nature of the layers forming the slope, composition and strength of the material, ground and surface waters and weakening cohesive forces. Sliding is more likely, if the direction of the angle of incidence of the overlying soil mass (most often clays) coincides with the direction of the slope. The top layer in

this case serves as a sliding surface along which a significant block of overlying material slides down the slope.

Landslide-hazardous slopes have a specific external appearance with a number of characteristic features which help to recognize the unstable slopes:

1. Series of cracks on the surface of the earth in the upper part of the slope oriented along the slope (Fig. 3.4.4).
2. Landslide circus (amphitheater) – a rounded or flat surface on a slope, which is formed as a result of the separation of the landslide body from stationary soils (Fig. 3.4.5 a).
3. Small landslide ledges or large terraces in the sliding massif (Fig. 3.4.5 b).
4. The surface of the slope is tuberos – the number of hillocks and their height increase towards the bottom of the slope due to the pressure of the sliding material.



Fig. 3.4.4. Typical cracks on the upper part of the landslide slope
Photo by G. Strizhelchik

5. Waterlogging of the slope surface (water outcrops, the appearance of hygrophilous vegetation) arising due to the fact that the occurrence of aquifers and water-resistant rocks is disturbed and new places of groundwater discharge are formed (Fig. 3.4.6).

6. An important sign of landslide movements is the so-called “drunken forest” – trees tilted in different directions (Fig. 3.4.7 a), as well as torn, twisted, saber-like tree trunks (Fig. 3.4.7 b), which are formed from damage to the root system.

7. Telephone poles, power lines, walls and fences go off their vertical position as well.

8. On landslide slopes, deformations of buildings and structures often occur: cracks appear in buildings, some of may even completely collapse (Fig. 3.4.8 a, b).



*Fig. 3.4.5 **a** – landslide amphitheatre, **b** – landslide ledges*
Photo by V. legupov



Fig. 3.4.6. Landslide Terraces, Groundwater Outcrops
<http://image.slidesharecdn.com/las30imgenesmasincrebles-090629204056-phpapp01/95/slide-18-728.jpg?1246326100>



a

b

Fig. 3.4.7. Vegetation on a landslide slope: **a** – “drunken forest” – trees are tilted at different angles; **b** – saber-shaped curvature of tree trunks

a http://iknowit.ru/image_base/2013/pimg_2367_1586.jpg

b http://paranormal-news.ru/_nw/98/s27373736.jpg a b



a

b

Fig. 3.4.8 **a, b** – Stages of destruction of a residential building during the slow movement of a landslide

Photo by G. Strizhelchik

The main elements of the landslide

When a landslide occurs, a number of characteristic geomorphological elements are observed on the slope (Fig. 3.4.9):

- landslide body – the entire shifted soil massif;
- sliding surface – the boundary between the landslide body and the stationary part of the soil massif, along which the displacement and sliding of the landslide body occurs; this surface may have a flat, rounded, cylindrical or undulating shape;

- stall edge – a line on the surface at the top of the slope, where the landslide body detached from the main fixed mass of soil;
- terrace-like ledges or landslide terraces, which are formed during the stepwise movement of the landslide mass and are often tilted in the direction opposite to the fall of the slope;
- an extrusion shaft at the bottom of the slope, on which cracks sometimes appear;
- landslide sole – the place of intersection of the sliding surface and the earth's surface, which is usually located at the level of the sole of the slope, but may be higher or lower.

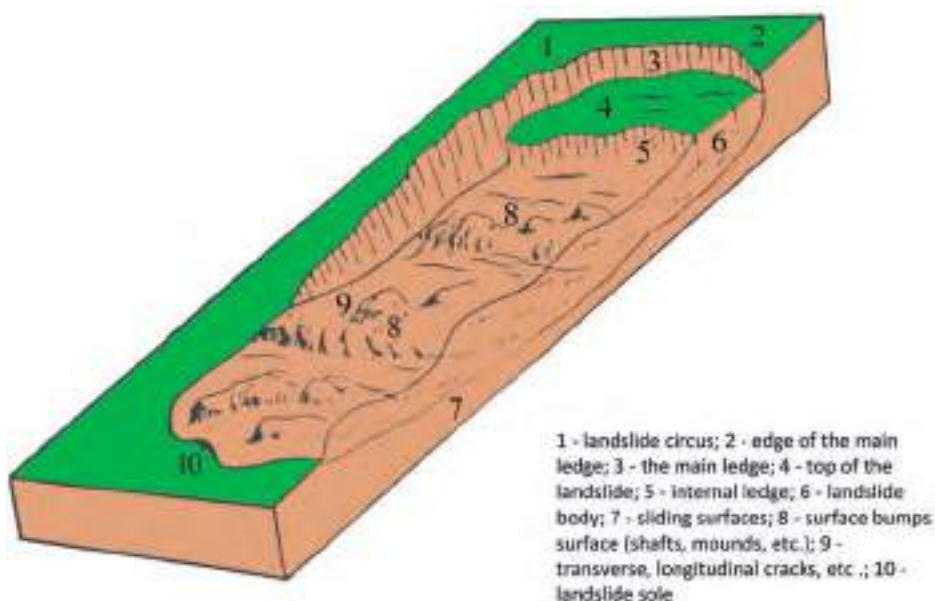


Fig. 3.4.9. Landslide Elements

http://zilant.kpfu.ru/kek/gidrogeo/Fig_1_2.jpg

Due to their characteristic forms, landslides are usually clearly visible on the terrain. The upper part of the landslide body lies under the upper ledge below the sharp separation edge. However, there are exceptions, especially for ductile clay rocks, when this boundary is practically unremarkable. In homogeneous rocks, for example, loess-like loams and similar soils, rounded landslide circuses are widespread and if several adjacent landslide circuses are sloped, then inter landslide ridges may appear between them.

Classification of landslides. There is no unique universal classification of landslides because of the large variety of relevant landslide parameters which can be used for their classification.

One of the simple classification methods, based on the structure of landslides (proposed by F. P. Savarensky), identifies 3 types of landslides as follows:

- *asequent* – landslides develop in homogeneous non-layered silty clay soils; the sliding surface has a curved shape, depending on the angle of internal friction and cohesion of sliding soils;
- *consequent* – the sliding surface coincides with the inclined surface of the bedding soils, zones of their weakening or cracks of various origin;
- *insequent* – the sliding surface intersects layers of various lithological composition with an uneven or concave shape.

Volumes of displaced soil masses can fluctuate over a very wide range and according to this criterion, landslides may be further classified in accordance with DBN B.1.1-46, Ukraine: 2017 (Tab. 3.4.1).

Table 3.4.1

Classification of landslides by the amount of soil displaced

Classification	Volume of soil displaced, m ³
Slight (Insignificant)	Few thousands
Moderate	Tens of thousands
Severe	Hundreds of thousands
Very severe	Millions
Extremely severe	Tens of millions and more

The types of slope processes may also be classified by the mechanism of rock displacement (Russian classification according to SP 11.105-97, part 2), the conditions of their occurrence, and the nature of their manifestation (Tab. 3.4.2). In this classification, apart from landslides, scree and talus are also listed (which are not landslides).

Table 3.4.2

Classification of landslides by the mechanism of rock displacement

Classification	Subtypes	Characterization of rocks of the main deformable horizon (ODG)	Nature of manifestation
Shear landslides (slip)	Insecure (cutting)	Clay (weathered rocks) rocks, massive or layered, with a slight or backward slope.	Separation and displacement of rock blocks along a concave curved surface with their simultaneous tipping.
–	Consequential (sliding)	Interlayers of clayey plastic soils in the matrix of stronger soils and a weakening surface, inclined towards the slope.	Offset of massif or blocks of rocks along weakening surfaces.
Extrusion landslides	–	Clay, mostly plastic.	Squeezing the soil from underneath the edge of the slope and its displacement together with landslide accumulations previously formed on the slope.
Viscoplastic landslides	Flowing landslides	Clay, slightly compacted and slightly lithified to plastic.	Visco-plastic flow of soil mass: within the zone of seasonal freezing during thawing – mudslides.
Landslides of hydrodynamic destruction	Suffusive. Hydrodynamic pressure	Water saturated sand and silty clay soils.	Separation of a landslide body or collapse of a suffusion niche with subsequent spreading of a displaced water-saturated mass.
Landslides of sudden liquefaction	Non-seismogenic liquefaction, Seismogenic liquefaction	Loose compacted clay and sandy water-saturated soils subject to rapid softening under dynamic impacts.	Liquefaction under dynamic action (man-made or seismic shocks) and fast viscous flow of liquefied soil along the slope of the relief.
Collapses and falls	–	Rocky, semi-rocky and clayey solid fractured rocks.	Separation from steep slopes of large blocks (landslides) or individual blocks of soil (falls) with subsequent rapid displacement (free fall or rolling).
Scree	–	Rocky and weathered semi-rock, sandy and hard clay rocks.	Separation from the exposed surface of the ledge (slope) and rolling small fragments of rock to its base.

The speed of landslides varies significantly from a few centimeters per year to several meters per second (Tab. 3.4.3).

Table 3.4.3

Characteristics of landslides in terms of speed

Classification	Speed
Extremely fast	3 m/s
Very fast	0.3 m/min
Fast	1.5 m/day
Moderate	1.5 m/month
Very slow	1.5 m/year
Extremely slow	0.06 m/year

By the nature of the movement of landslide masses, landslides can further be classified as: sliding and gradually sliding. During sliding, the entire body of the landslide moves at one time and at high speed. Such landslides are extremely dangerous and often lead to disasters and casualties (Fig. 3.4.10).



Fig. 3.4.10. A huge landslide (sliding type) descended in Afghanistan to the village of Khobo Barik on May 5, 2014, causing about 300 deaths

http://rusevik.ru/uploads/posts/2014-05/thumbs/ogromnyy-opolzen-v-afganistane_7.jpeg

Factors triggering landslides.

Landslides can be caused by diverse natural and technogenic processes and phenomena among which three main groups are distinguished:

1. *A change in the shape or height of the slope*, which may be associated with an increase or decrease in the erosion basis of rivers and ravines located at the foot of the slope; the abrasive effect of sea waves eroding the bottom of slopes; slope cutting during the construction of roads and artificial excavations.

2. *Loss of the strength characteristics of soils comprising the slope, due to weathering* – waterlogging of soils by underground, surface and domestic waters; dissolution and removal of salts from the soil, as well as suffusion (mechanical removal of particles by a stream of underground water with the formation of voids in the underlying material).

3. *Processes favouring additional shear force in the soil mass*: an increase in the hydrostatic pressure of water in the cracks and pores of the rock/soil material and an increase in mass with an increase in the level of ground water; hydrodynamic pressure of groundwater flow during water infiltration towards the slope; artificial static and dynamic loads on the slope and seismic vibrations.

With a variety of significant factors and causes of landslides in each case, several factors can be simultaneously involved.

For reliable prediction of the danger of landslides on specific slopes, an analysis of the development history and determination of the age of prior landslides across the territory are of great importance. Landslides are divided into modern and ancient.

Modern landslides can be in three stages: 1) stages of readiness to move, 2) stages of active landslide, or 3) in the process of completing the movement (Fig. 3.4.11). Many modern landslides are shifting gradually and relatively slowly, albeit at different speeds. Observations of the movement of slow landslides are carried out by geodetic reference points installed in the body of the landslide and on fixed sections of the slope. For modern slow landslides, engineering measures can be taken to protect against the negative consequences of their development.

On *ancient inactive landslides*, no signs of movement are observed. The landslide body is gradually covered by vegetation and smoothed out by weathering processes. An example of an ancient landslide is shown in Fig. 3.4.12.



Fig. 3.4.11. Modern landslide on an artificial dam, Kharkiv, Ukraine
Photo by G. Strizhelchik



Fig. 3.4.12. Ancient large landslide-stream, which filled the entire valley and is overgrown with forest, Colorado, USA

<http://coloradogeologicalsurvey.org/wp-content/uploads/2013/08/slumgullion%20usgs.jpg>

Methods of protection against landslides.

Protection against landslides is a real challenge, expensive and in many cases may not be effective. Successful application of landslide mitigation measures requires highly professional engineering and geological surveys and forecasts with an assessment of the actual degree of slope stability. These surveys must be carried out in accordance with the requirements of regulatory documents.

Passive measures are precautionary. These include prohibition of:

1. Trimming the bottom of the slopes during construction of roads and trenches.
2. Any construction and soil movement/transportation in the landslide zone.
3. Blasting, driving piles and other vibratory works near landslide slopes.
4. The movement of heavy vehicles and limiting the speed of trains near the landslide zone.
5. Discharge onto the slope surface, irrigation and any other waters.
6. Removal of trees and shrubs (vegetation) from the slope.

Active measures consist of engineering protective measures and are divided into four groups.

1. *Prevention of landslide-causing processes*, for example, elimination of the abrasive effect of sea waves and river erosion, associated with the soaking of slopes with surface and underground waters. As such, shore protection works need to be carried out, surface waters are redirected by digging ditches and groundwater drainage systems. Terracing of slopes help to increase their stability.

2. *Anchoring of soil masses prone to landslide*. This includes the device of reinforced concrete or metal piles, which are anchored, through the landslide body, into a stable part of the slope. In order not to compromise the stability of the slope during driving, bored piles are used, usually in a checkerboard pattern. The construction of retaining walls at the bottom of the slope, the base of which must be soundly anchored below the sliding surface. The loading of the bottom of the slope with massive concrete counter-banquets.

3. *Technical stabilisation of soil slopes*. These include silicification, cementation, freezing and other methods to increase the mechanical strength of soils. Due to the high cost of labour and materials, these methods are used relatively rarely.

4. *Removal of landslide soil masses* is often the most effective. The method is very laborious and therefore is usually used for small landslides or in special cases.

When constructing and operating quarries for mining, including natural building materials (sand, clay, gravel, etc.), it is necessary to ensure the creation

of stable and safe walls and slopes. Landslides and collapses in large quarries can lead to disastrous consequences (Fig. 3.4.13).



(Photo: AP Photo / The Deseret News, Ravell Call)

<http://mirfactov.com/v-ssha-na-mednom-karere-proizoshel-gigantskiy-opolzen/>



<http://fishki.net/picsw/062013/20/post/opolzen/opolzen-0003.jpg>

Fig. 3.4.13 **a, b**: A landslide in the world's largest copper ore quarry, Bingham Canyon, Utah, USA. This copper ore quarry has been operating since 1863. The quarry was closed due to a giant landslide on April 11, 2014

Installation of quarry walls in non-rocky soils.

It is strictly not recommended to extract building materials with the formation of overhanging sections of walls. When designing a quarry development, it is necessary to provide a safe profile of walls, resistant to landslides and collapses. Steps or terraces are provided on the slopes of quarries – intermediate horizontal platforms, ditches and drains are arranged to divert surface and groundwater away from the slopes. The slope angles are taken in accordance with table. 3.4.4.

Table 3.4.4

Characteristics of steady slopes in dispersed soils

Soils	Dry		Water saturated	
	Angle of slope stability	Gradient	Angle of slope stability	Gradient
Pebble and gravel	35–40°	1:1½ 1:2¼	35°	1:2¼
Sand	30°	1:1¾	25°	1:2¾
Silty clay	40–45°	1:1½ 1:1	20–25°	1:2¾

Test questions to chapter 3.4. Landslides

1. Definition of landslides and their distribution on Earth.
2. The most landslide hazardous areas in the world.
3. What are the slopes with the likelihood of landslides?
4. The main elements in the structure of the landslide.
5. The dependence of the shape of the sliding surface on the geological structure of the slope.
6. Classification of landslides according to F. P. Savarensky.
7. Modern classification of landslides.
8. Characteristics of the movement of landslides and its speed.
9. The main causes of landslides.
10. Passive measures to combat landslides.
11. Active measures to combat landslides.
12. Rules for the construction of quarry walls in dispersed soils.

Chapter 3.5. MUDFLOWS, LAHARS AND AVALANCHES

Mudflow (often called “seil” from Arabic Sayl – rapid flow) is a water stream with a very high content of clay and sand particles, stones and larger fragments of rocks, up to 50–60% of the volume of the stream, which suddenly occurs in small mountain valleys, generally caused by intense downflow of debris (Fig.3.5.1). The characteristic mud-forming valleys are located on small mountain streams up to 25–30 km long with a catchment area of up to 50–100 km². The mudflow becomes a combination of water and solid mud-stone with the size of individual boulders and debris in the stream reaching up to 3–4 m in diameter. The movement of mudflows occurs quickly and relatively briefly: the duration of the intensive phase is from ten minutes to several hours. Mudflows move as large waves, compared to a water stream which moves in a single continuous flow.



Fig. 3.5.1. Mudflow

<http://territoryengineering.ru/wp-content/uploads/2014/09/Seli.jpg>

Along with the main causes of mudflows (intense and prolonged downpours, rapid melting of snow or glaciers), sometimes mudflow can form as a result of the collapse of a large amount of loose soil into the river channel. Mudflows

simultaneously carry thousands, and sometimes millions cubic meters of viscous water-saturated mass. Obstacles, like dams and bridges, are often demolished by mudflows which continue to move with an increasing kinetic energy.

Having a large mass and high speed, up to 15 km/h, mudflows destroy buildings, roads, public transport, demolish towers and other structures, disable communication and power lines, destroy agricultural lands and kill people and animals.

On 23/07/2015, mudflow in city of Almaty in Kazakhstan almost completely affected the city bringing huge amount of dirt and stone material, destroying houses, roads, vehicles and agricultural land (Fig. 3.5.2).



a http://vlast.kz/media/upload/images/ATN_6754.JPG



b http://titus.kz/load_theme/files/2015072309331755b0607d3d42c.jpg



c http://mix.tn.kz/userdata/images/23.07_sel/2565.jpg

*Fig. 3.5.2. The consequences of mudflow on 23.07.2015 in the city of Almaty, Kazakhstan: **a, b** – houses flooded with mud-stone material; **c** – blocks taken out by mudflow to the streets*

Other examples of mudflow consequences are shown in fig. 3.5.3.



a <http://ua-reporter.com/sites/default/files/219311/2015/11/21/dr3.jpg>



b http://lh6.googleusercontent.com/GPw4lMd4sznbBHqOqrck_Pyrvh_kC33dwZn_HHrt32ODP_zdGWgVNs9SjRPWsViy7SYrTw=w1200-h630-p

*Fig. 3.5.3 **a** – the road washed out by mudflow in the Carpathians;
b – the consequences of mudflows*

The type of mudflow is determined by the composition and content of rocks in the mudflow. The main types of mudflows:

- *water-stone* – a mixture of water mainly with large stones and rock fragments (bulk density $\gamma = 1.1–1.5 \text{ t/m}^3$);
- *mud* – a mixture of water and clay particles with occasional stones ($\gamma = 1.5–2 \text{ t/m}^3$);
- *mud-stone* – a mixture of water, clay, sand, gravel, pebbles and cobbles ($\gamma = 2.1–2.5 \text{ t/m}^3$).

In mountainous regions, the solid mass content predominates in the composition of mudflows. Classification of mudflows by the solid content in the stream is given in table. 3.5.1 and their names, depending on the causes of occurrence – in table. 3.5.2.

Table 3.5.1

Classification of types of general flows according to DBN B.1.1-24: 2009

Ratio of the volume of solids to the volume of the mixture	Size of predominant fragments (> 50% of the total volume of the solid phase)	
	> 1mm	< 1mm
>0,5	Mudstone	Mud
<0,5	Nanosized	

Table 3.5.2

Classification of mudflows by the reasons for their occurrence

Types	Causes	Propagation and Origin
1. Rain	Showers, heavy rains	The most massive type of mudflow on Earth; formed as a result of erosion of slopes and soil movement
2. Snow	Intense snowmelt	Occurs in subarctic mountains as a result of waterlogging and disruption of snow masses
3. Glacial	Intensive melting of snow and ice	It is observed in high mountain regions. The origin is associated with the accumulation and breakthrough of thawed glacial waters
4. Volcanogenic	Volcanic eruptions	In areas of active volcanoes. The largest mudflows occur during violent snowmelt and breakthrough of crater lakes
5. Seismogenic	Strong earthquakes	In areas of high seismicity. Formed upon the disruption of soil masses from slopes of river beds
6. Limnogenic	The destruction of lake dams	In high mountain areas during the destruction of dams holding lakes
7. Technogenic (direct exposure)	Accumulation of man-made rocks (soil dams)	In areas of waste storage of mining industry, dumps. The erosion and sliding of man-made rocks. Dam destruction
8. Anthropogenic (indirect impact)	Removal of vegetation	In forests areas. The erosion of slopes and channels of watercourses

The engineering and technical measures for protection against mudflows aim to stop a moving mudflow or to limit the zone of its harmful effects. In the channels of mountain rivers, along which mudflow is possible, structures are built to prevent deep and lateral erosion of the channel – bank walls, gutters, and bottom dams. Mudflow protective structures are divided into three classes depending on their main purpose: regulatory, stabilizing and delaying.

Regulatory structures – mudflow dams and channels which serve to divert to a safe place, change the direction of movement, localize or pass the mudflow above or below the protected zone.

Stabilizing structures – a system of low retaining dams along the mudflow channel, transforming its longitudinal profile into a stepped one with smaller slopes which prevent the passage of mudflows. Cellular anti-mudflow dams and dams serve to delay coarse material but allow passage of a mixture of water and small rock fraction (Fig. 3.5.4).



Fig 3.5.4. Gabion Type Mudguard Dam

<http://www.drs-engineering.com/slope-stabilization?lightbox=dataItem-ji2enbs1>

Deterrent structures are massive mudflow-holding dams and reservoirs that are designed to stop the entire mudflow or most of the solid component of the stream. A famous example of a large dam built specifically to protect against mudflows is the Medeo Dam in Kazakhstan (Fig. 3.5.5).



Fig. 3.5.5. Anti-mudflow dam in the Medeo tract, Kazakhstan

http://zateevo.ru/userfiles/image/Zarubezhie%20nashe/Kazakhstan/kazah_plotina01.jpg

Engineering structures are most effective when they also serve for land reclamation of mudflow basins. To prevent mudflows, vegetation is very important on mountain slopes, especially in the places of mudflow formation. Plants regulate water levels in mountain lakes and reservoirs. However, when maximum level of water is exceeded, periodically pumping is done to regulate the latter. Digging trenches and spillway ditches to divert the drain into the nearest waterways and construction of drainage channels are also effective measures against mudflow.

For reliable protection of populated areas from mudflows and timely adoption of measures, the organization of an operational and effective warning system is of utmost importance. In areas threatened by mudflows, an anti-mudflow service is set up with aim to forecast the occurrence of mudflow and its intensity, informing the population about the time of its occurrence and, if necessary, planning for evacuation.

Lahar (from Indonesian *Lahar* – mud volcanic stream, mud-ash lava) – a mud-stream that occurs on the slopes of the volcano. Lahar is formed by

the mixing of cold or hot volcanic material with the waters of crater lakes, rivers, glaciers or rainwater and carries volcanic ash, small solid fragments, sometimes angular blocks of rocks of effusive origin, lying on a volcanic slope (Fig. 3.5.6).

Hot Lahar (boiling river) is a stream formed by hot ash with a large amount of other pyroclastic material mixed with water. Most often, it occurs during the eruption of volcanoes with crater lakes. *Cold Lahar* (cold lava) is normally formed during heavy rain and snowmelt on the slopes of the volcano.

Like mudflow, lahar moves under the influence of gravity with high energy and is highly mobile. Having a high speed and intensity, the lahar flow may be fatal. The consistency, viscosity and density of lahar is approximately the same as that of concrete. It is liquid when moving, and at rest it turns into a dense mass due to its high viscosity.



Fig. 3.5.6. Lahar at St. Helens volcano, Cascade Mountains, USA, resulting from the 1980 eruption

<http://busy.org/@sooflauschig/geology-of-iceland-part-7-eruption-styles>

The flow velocity may reach 100 km/h, and the distance over which the lahar travels can reach hundreds of kilometres (according to some reports, up to 300 km), causing catastrophic destruction on its way (Fig. 3.5.7, 3.5 .8).



Fig. 3.5.7. Cold lahar from the volcano Merapi, Indonesia
<http://arifberbagi.wordpress.com/2011/01/15/ancaman-banjir-lahar-merapi/>



Fig. 3.5.8. Houses completely absorbed by the lahar during the eruption of the Galunggung volcano in Indonesia, 1982
http://1.bp.blogspot.com/-Rn28A9fwuO8/TevSA1IcyhI/AAAAAAAAFFQ/4FoOClzFOSs/s1600/Galunggung_lahar.jpg

In the Cascade Mountains on the western coast of the United States, after the eruption of the St. Helens volcano in 1980, several lahars occurred on the slopes, flowing up to a distance of 80 km.

One of the largest lahars descended from the top of the Cloud volcano on the island of Java, Indonesia in 1919. It covered an area of 132 km², while more than 100 villages were destroyed and 5110 people died.

The deadliest lahar in history is considered to be the huge mud-ash stream which completely destroyed the city of Armero in Colombia and led to the death of 23,000 inhabitants (Fig. 3.5.9). Similar, but not so destructive, lahars occurred in this area back in the years 1595 and 1845. However, the relatively small eruption of the Nevado del Ruiz volcano in 1985 after a 150-year hibernation period caused a severe destructive lahar. Currently, up to half a million people living in the areas adjacent to the volcano are constantly threatened by the emergence of lahars, which can flow on the slopes of this volcano.



Fig. 3.5.9. Lahar, which destroyed the city of Armero, Colombia, 1985
http://dic.academic.ru/pictures/wiki/files/65/Armero_aftermath_Marso.jpg

A snow avalanche or just an avalanche (German Lawine, from the Late Latin Labina – landslide) is a snowfall, a glide of suddenly massed snow on a mountain slope. Avalanches are possible in all mountainous regions with stable snow cover, and large avalanches occur on slopes with an angle of inclination of 25–60°. The avalanche speed is on average 20–30 m/s.

Most often, an avalanche is a mixture of snow mass with air. Its movement is usually accompanied by a unique low tone whistling sound if it consists of dry snow, a rattle (in the case of movement of wet snow and stones) or deafening noise in the event of an air shock from the movement of a powerful avalanche.

According to the composition of the moving mass, the following avalanches can be identified: a snow avalanche, consisting only of *snow* – this is the most

common type (Fig. 3.5.10); *snow-ice*, including debris in addition to snow mass; *crushed-snowy*, capturing motion of underlying dispersed fragments, usually scree slope deposits.



Fig. 3.5.10. Descent of an avalanche, Alps
<http://snowavalanche.ru/images/media/foto/46.jpg>

Three types of avalanches are distinguished depending on the nature of the movement of the avalanche mass on the slope:

“*Snow slide*” – a stepwise sliding snow landslide that slides along a relatively flat surface of a steep or grassy slope outside the channels of watercourses; Wasps often occur during partial thawing of snow and are therefore observed on the southern slopes of the mountains (Fig. 3.5.11 a);

“*Channel avalanches*” – moving along ravines, channels and rivers; after the descent of such avalanches, a large drift cone is formed at their toe (Fig. 3.5.11 b).

“*Jumping avalanches*” – arising high in the mountains, and then freely falling down from the mountain ledges, sometimes directly into the underlying valley (Fig. 3.5.11 c).



a



b

[http://www.mountain.ru/img.php?src=/article/](http://www.mountain.ru/img.php?src=/article/article_img/3556/f_9.jpg&gif=0&width=310&height=0)

[article_img/3556/f_9.jpg&gif=0&width=310&height=0](http://www.mountain.ru/img.php?src=/article/article_img/3556/f_9.jpg&gif=0&width=310&height=0)

<http://www.mexat.com/vb/attachment.php?attachmentid=1658910&stc=1&d=1333722725>



c

http://blankonthemap.free.fr/95_update/pic_infos/info038/Avalanche1.JPG

*Fig. 3.5.11 **a** – snow slide; **b** – channel avalanche; **c** – jumping avalanche*

Avalanches, like mudflows and lahars, are capable of causing great damage, destroying buildings and structures, filling roads and often lead to human casualties. One of the tragedies of mountaineering was associated with the descent of a large snow avalanche on the slope of Lenin Peak in the Pamirs, which on July 13, 1990 demolished the climbers' camp, located at an altitude of 5300 m and 40 people were killed. In Nepal, on April 25, 2015, 65 people died in an international camp of climbers, preparing to climb the Everest. Examples of the consequences of avalanches are shown in Fig. 3.5.12.



a



b

a [http://static.euronews.com/articles/304876/](http://static.euronews.com/articles/304876/1200x630_304876_nepal-earthquake-survivors-tell-o.jpg?1430128260)

[1200x630_304876_nepal-earthquake-survivors-tell-o.jpg?1430128260](http://static.euronews.com/articles/304876/1200x630_304876_nepal-earthquake-survivors-tell-o.jpg?1430128260)

b <http://upload.wikimedia.org/wikipedia/commons/e/e7/Lanches250295-4.JPG>



c



d

c <http://www.tz.de/welt/galtuer-zehn-jahre-nach-der-todeslawine-95980.html>

d <http://img.gawkerassets.com/img/19ezv1posc61kjpg/original.jpg>

Fig. 3.5.12. Consequences of avalanches: **a** – international climbers camp at the foot of Everest; **b, c, d** – snow-covered buildings and cars

Special maps are compiled for areas exposed to avalanche, indicating areas with high, moderate and low threats. Areas with low avalanche threat may

become area of potential avalanche hazard with deforestation and excavation on slopes. Depending on the conditions of their formation and descent, avalanches can be divided into natural and man-made. The following complex of factors belongs to *natural*:

Geomorphological conditions – the exposure of the slope with respect to cardinal points, angle of inclination, structure of the valley and slope, the presence of vegetation which trap snow on the slope and steepness of the slope (α). The movement of avalanches with different snow composition occurs at the following angles: for wet snow $\alpha = 15^\circ$ and less; dry snow $\alpha = 15-22^\circ$; firn $\alpha = 30-55^\circ$ and more.

Climatic and weather conditions – the amount of snowfall, intensity and duration, the direction of the wind during snowfall, the temperature of the air and the surface of the snow cover, recrystallization and thawing of the lower layer of snow in the mass, which reduces the cohesion and frictional forces.

Seismic conditions – the possibility of weak seismic shocks or strong earthquakes.

Technogenic (anthropogenic) factors of avalanches are the following:



Artificial vibration-dynamic impacts on the slope – blasting operations during the extraction of minerals, the work of powerful mechanisms and heavy vehicles.; These effects are deemed most dangerous;

Destruction of trees and shrubs – deforestation on the slopes, the creation of open spaces;

The direct impact of people on the avalanche-hazardous snow cover: skiers, snowboarders and others (Fig. 3.5.13).

Fig. 3.5.13. Skier on an avalanche slope
<https://www.gore-ljudje.net/novosti/63546/>

Improper development of slopes, leading to local accumulation of avalanche hazardous snow masses to a critical level; construction in avalanche-hazardous areas should be carried out according to special standards with a set of measures to prevent avalanches.

The most reliable way to protect against avalanches is to place construction objects outside the zone of avalanche hazardous areas. But if this is not possible, protective measures should be provided in accordance with prevailing regulatory requirements, for example DBN V.1.1-24: 2009.

Anti-avalanche measures are divided into three groups: preventive, warning and avalanche-protective (Tab. 3.5.3).

Table 3.5.3

Types of anti-avalanche measures and facilities (DBN B.1.1-24: 2009)

Types of events and facilities	Purpose of structures and events, conditions for their use
<i>I. Preventive:</i> Organization of a monitoring, forecast and alert service. Artificially adjustable avalanche discharge	The forecast avalanches. Termination of work and access of people to avalanche-hazardous areas during avalanches and evacuation of people from the danger zone. Adjustable descent of avalanches and unloading of unstable masses of snow by shelling, explosions, etc. Based on the forecast of stability of snow masses on a slope
<i>II. Warning:</i> Snow-holding systems (fences, walls, shields, gratings, grids), terracing of slopes, agroforestry Snow Barrier Systems and Shields: Snow-blown panels (nozzles), Kolktafels	Ensuring the stability of the snow cover in areas of avalanche origin, including combination with terracing of slopes, agroforestry, regulation of snow accumulation. Prevention of snow accumulation in areas where avalanches occur by retaining precipitation on the windward slopes and plateaus. Regulation, redistribution and consolidation of snow in the zone of avalanche origin Change of direction of the avalanche. Avalanche flow around an object
<i>III. Avalanche protection:</i> Guiding structures: walls, artificial channels, avalanche cutters, wedges. Braking and stopping structures: gouges and hills, trenches and barriers. Permeable structures: canopies, galleries, overpasses	Change of direction of the avalanche. Avalanche flow around an object. Braking or stopping the avalanche. Avalanche passage above or below the object

Some examples of avalanche facilities are shown in Fig. 3.5.14, 3.5.15.



Fig. 3.5.14. Snow retention nets

http://hgex.univie.ac.at/uploads/media/Loigge_091209_Text.pdf



Fig. 3.5.15. Anti-avalanche gallery

<http://www.tuvaonline.ru/2018/01/12/glavnaya-trassa-tuvy-m-54-smenila-nazvanie-na-r-257-enisey.html>

Modern avalanche protective measures can be divided into two main groups – passive (means of protection) and active (means of influencing snow cover).

Passive (protective equipment) – these are avalanche-removing dams and avalanche cutters, as well as snow-holding nets.

One of the reliable ways to protect against avalanches is to artificially change the path of their movement in order to divert the snow-avalanche stream away from the protected object or direct it along a strictly fixed channel – build cutters, snow dams and guide walls (Fig. 3.5.16).

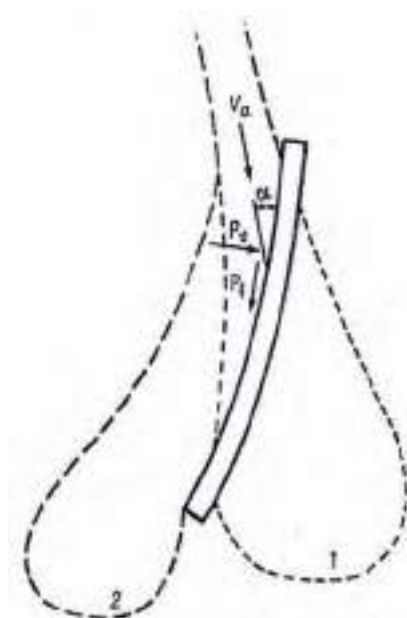


Рис. 11.9. Действие отводящей стенки.

1 – лавина при отсутствии стены,
2 – отведенная лавина.

Fig 3.5.16. Scheme of the guide wall:

1 – avalanche in the absence of a wall; 2 – allotted avalanche

<http://ok-t.ru/helpiksorg/baza4/110136650454.files/image018.gif>

Avalanches are wedge-shaped structures in plan, the tip of which is directed against the movement of the avalanche. They are built to divide the avalanche stream in two to bypass any structure or site, for example, to protect the supports of cable cars. When the avalanche cutter is located at an angle to the avalanche stream, it changes the direction of the avalanche, taking it away from the protected zone.

Active methods are engineering systems that directly affect the snow cover for timely artificial dumping of avalanches. For example, used to protect objects in avalanche-hazardous areas, “Gazex” system and air gun.

In 1989, after many years of testing and experimentation in avalanche management, the French company T.A.S. (Alpine Safety Technologies) created the Gazex system, which initiates forced avalanches, using an active mechanism based on a mixture of oxygen and propane (Fig. 3.5.17).



Fig. 3.5.17. The main part of the GazexExploder system is the installation of an active impact. It is a system of metal pipes for supplying the gas mixture directly to the collection, to which the gas pipes from the tanks located in the command post are connected. Inside the explorer, oxygen and propane gases are mixed in the ratio of 1 : 6

<http://territoryengineering.ru/wp-content/uploads/2014/05/P1000435.jpg>

Similar installations are used all over the world, both to protect the slopes of ski resorts, roads, tunnels and residential complexes. The system initiating avalanche descent has a threefold effect:

- shift of snow down before the installation of an active impact initiating an avalanche, using the products of combustion of a mixture of gases;

- compaction of snow cover;
- the seismic shock wave after the start of the installation of the active impact increases the capture area of the snow cover.

Test questions for chapter 3.5. Mudflows. Lahars. Snow avalanches

1. What is mudflow?
2. Why do mudflows occur?
3. Types and features of mudflows.
4. Classification of mudflows for reasons of their occurrence.
5. Distribution of mudflows.
6. Protection measures from mudflows.
7. Definition of lahars, their speed.
8. Definition of avalanches, their speed.
9. Varieties of avalanches in the composition and nature of the movement.
10. Avalanche-hazardous areas in the world.
11. Natural and technogenic factors of avalanches.
12. Avalanche activities.
13. Engineering methods of protection against avalanches.

Chapter 3.6. EROSION OF ROCKS AND SOILS. WIND EROSION AND DESERTIFICATION

Erosion (from Latin *erosion* – erosion) is a complex of natural, as well as anthropogenic or technogenic processes, which causes the degradation of the earth's surface (rocks and soils). Erosion is a destructive process that occurs on the surface of the Earth under the influence of wind, flowing water (river, rain and snow melt water), glaciers, sea surf (*abrasion*), gravity slope and other factors that move rock fragments and soil particles. The processes of erosion of the earth's surface occur everywhere and they are sometimes considered in a broader sense, as weathering or denudation of rocks. Land surface water and ocean waves are normally the most common factors that change the topography of the Earth. Wind erosion prevails in arid climates and water erosion in humid climates.

The degradation of rocks on the earth's surface is often observed in the form of corrasion. *Corrasion* (from Latin: *corrado* – *scrape*) is the mechanical erosion of soils and rocks by the abrasive action of particles set in motion by running water, wind, glacial ice and gravity. In deserts, corrasion is produced by wind carrying the sand particles, in the bed of glaciers – by moving ice and rock fragments, in river beds – by boulders, pebbles and gravels carried by water, on the slopes – as a result of the movement of rock fragments down the slope. The blowing and transfer of fine materials (sand, silt and clay particles) by air during corrasion is called *deflation*.

The hardness of rocks, their structure, texture, degree of weathering and other factors affects the intensity of erosion processes. The processes of physical, chemical and biological weathering lead to more intense degradation of rocks under the simultaneous actions of corrosion and the associated deflation. As a result of predominating erosion, various characteristic rock forms and reliefs are formed in certain areas (Fig. 3.6.1, 3.6.2).

Wind erosion (corrasion and deflation)

Wind erosion is developed mainly in areas with very low to low moisture content, with insignificant amount of precipitation and where groundwater is either absent or is located very deep from the surface – in deserts and steppes. In such areas, the main contributing factor to rock erosion is the wind.

Corrasion of collapsing rocks is accompanied by blowing and moving of small fragments (sand and dust particles) which are obtained in the process of degradation. These particles, picked up by the wind, produce further corrosion

of the rocks during their movement. The air-sand flow corrodes all rocky ledges falling in its path and the weakly cemented sections of rock masses decompose faster than the stronger ones (Fig. 3.6.3).



Fig. 3.6.1. Weathering columns in the Monument Valley National Park is a unique geological site located on the border of the states of Arizona and Utah, one of the national symbols of the United States. Photo by Iu. Iegupov



Fig. 3.6.2. Bryce Canyon, USA. This is a giant natural amphitheater along the eastern side of the Paunsaugunt Plateau. Bryce Canyon is widely known for its unique geological objects, called hoods, formed during erosion of alluvial and lake deposits as a result of exposure to wind, water and ice. Photo by Iu. Iegupov



a

<https://upload.wikimedia.org/wikipedia/commons/thumb/f/fe/WaveRock.jpg/1280px-WaveRock.jpg>



b

https://all-free-download.com/free-photos/fire-hdr_sort_by_newest_page_3.html



c

https://uk.wikipedia.org/wiki/%D0%95%D0%BE%D0%BB%D0%BE%D0%B2%D1%96_%D0%BF%D1%80%D0%BE%D1%86%D0%B5%D1%81%D0%B8

Fig. 3.6.3. Geological objects formed as a result of corrosion: **a** – Wave-Rock (Australia); **b** – corrasion niches; **c** – a grotto made by the wind, Utah, USA

The denser and more stable sections of rocks become convex with time under the influence of corrosion. This is because sandy materials, transported by the wind and exerting a corrosive effect, moves above the surface of the earth, usually not higher than two meters, normally up to half a meter and as such, alteration is more intense in the lower part of the rocky ledges. Therefore, quite often various rocks of an exotic kind are formed naturally: “stone obelisks”, “stone mushrooms”, shapes with a thin “neck” at the base and extension at the top. Sometimes rocking (moving) and balancing stones are formed when only one small contact surface remains between the stone blocks and its base (Fig. 3.6.4, 3.6.5, 3.6.6, 3.6.7).



<http://mytour.agency/%D0%B1%D0%B5%D0%BB%D0%B0%D1%8F-%D0%BF%D1%83%D1%81%D1%82%D1%8B%D0%BD%D1%8F-%D0%B2-%D0%B5%D0%B3%D0%B8%D0%BF%D1%82%D0%B5/>



Fig. 3.6.4. Stone mushrooms and obelisks in the White Desert, Egypt



Fig 3.6.5. Corrosion-Deflation Hoodies, BryceCanyon, USA
Photo by Iu. Iegupov



a



b

Fig 3.6.6 Balancing multi-ton block – “Golden Rock” in Myanmar: **a** – modern photo; **b** – photo of 1900. A balancing block defies gravity, as it constantly seems to be on the verge of rolling down a hill. It is a famous pilgrimage site for Buddhists. On the top of a granite boulder covered with gold leaves, a small pagoda 7.3 meters high was built.

According to legend, the Golden Rock itself is held on a strand of Buddha’s hair

<https://www.travelstories.it/2015/11/si-va-in-birmania.html><http://www.bl.uk/onlinegallery/onlineex/apac/photocoll/k/019pho000000180u00035000.html>

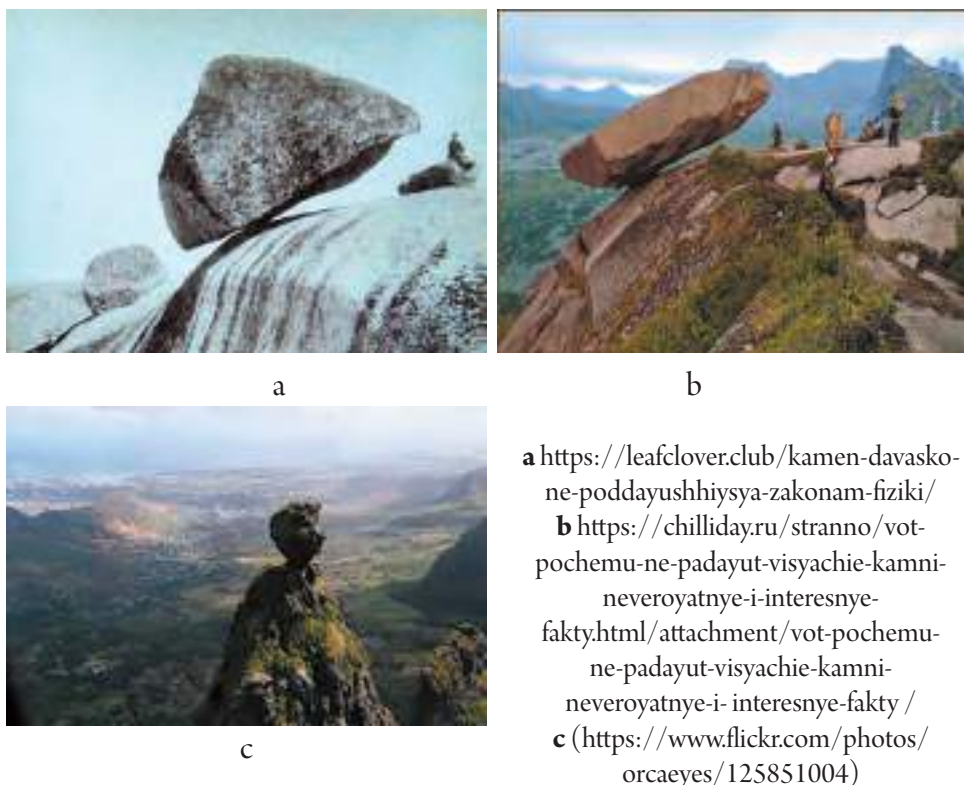


Fig. 3.6.7. Balancing stones: **a** – “Davasco stone”, Argentina, **b** – stone in the mountains of Ergaki, Altai, **c** – Peter Both Mountain tip, considered as one of the legendary attractions in Mauritius

he most popular manifestations of deflation are observed in deserts, where strong winds blow the surface layers of dry loose sandy or dusty deposits, which lie above rock massifs or above soft but moist formations. Long-term blowing of soil from the surface leads to the formation of vast and deep depressions. For example, in the Libyan Desert, the Qattara basin, with an area of about 18,000 km², is located at a depth of 134 m below sea level. Deflation troughs and basins of a similar type are characteristic to many deserts throughout the Earth.

Due to the fact that the wind constantly blows sand and other small particles from all rock cracks and other depressions, deflation can further deepen any artificial excavations, for example trenches, ruts from cars, tractors, etc. Loess rocks are easily blown, forming sometimes, 20–30 m deep deflationary notches (Fig. 3.6.8). In northeastern China, on territories underlain by thick loess strata, ordinary earth roads under the influence of deflation deepen over time and turn



Fig. 3.6.8. Wind erosion of loessal rocks

<http://www.geonature.ru/geophoto/35tun/05.jpg>



Fig. 3.6.9. Masonry Corrosion,
Gozo Island, Malta

https://uk.wikipedia.org/wiki/%D0%92%D0%B8%D0%B2%D1%96%D1%82%D1%80%D1%8E%D0%B2%D0%B0%D0%BD%D0%BD%D1%8F#/media/%D0%A4%D0%B0%D0%B9%D0%BB:Salt_weathering_in_gozo.jpg

into gorges. In deserts and steppes, there is an intensive degeneration of brickwork (Fig. 3.6.9) and concrete structures.

Corrosion and deflationary effects on buildings and structures must be taken into account when building in areas where strong winds prevail. Intense deflation processes can also contribute to the occurrence of sand and dust storms.

Dust storms and soil deflation

A sand or dust storm is a weather phenomenon that has been threatening life in the steppes and desert areas from ancient generation times. Such storms can damage buildings, completely fill roads and cause large-scale disruptions in aviation and road transport communications, both of local importance and between large cities (Fig. 3.6.10).

Dust storms occur with strong dry and hot winds and have various names in different countries: samum, sirocco, hamsin, so on, blowing and transporting sand (sandstorm) and millions of tons of dust and fine soil particles (black storms) over huge distances. They cause great damage, sharply worsening visibility and polluting the atmosphere, threaten the health of people breathing heavily polluted air; covering the fertile layer of soil, crops and ponds.

Small sand and dust particles with a size of 0.5–0.1 mm or less, at wind speeds of 3.8–6.6 m/s break away from the surface, come into motion and can move to very far distances.

Small silty-clay particles (<0.01 mm) are able to cover distances of hundreds, and sometimes thousands of kilometers. The material of dust storms from the Sahara easily flies over the Mediterranean Sea and is often traced over the Atlantic Ocean up to North America. Dust storms often occur in large deserts – the Sahara, the Arabian Desert, the Near and Middle East, in Mongolia, China, the central parts of the USA, the pampas of South America and in Australia. In Eurasia, the northern border of dust storms passes along a conditional line through the cities of Kharkov, Saratov, Ufa, and Barnaul.

Soil deflation

Wind erosion in the form of deflation has a particularly negative effect on the topsoil, which is responsible for their fertility. The amount of soil substrate blown away by the wind in some cases can reach 100 tons per 1 hectare and even more. The degree of impact of wind erosion depends on the strength and speed of the wind, the particle size distribution of the surface soil layer, the presence and type of vegetation and other factors. So, on light sandy to silty soils, even with a light wind, blowing of particles begins and eventually, their transfer over great distances with dust storms. The first phase of deflation begins at a wind speed of around 5 m/s, when smaller particles of soil (0.1 – 0.5 mm in size) are raised by turbulent air flows and move abruptly above the surface of the earth, and larger ones (0.5 – 3.0 mm) roll or slide over the surface.

In steppe regions where arable lands occupy large areas, wind erosion of soils usually begins at wind speeds of 10 – 15 m/s. The beginning of a dust storm is associated with a relatively high wind speed. However, the flying particles hit the ground and cause a “chain reaction” of separation of new particles which ends up at lower wind speeds (Fig. 3.6.11).



a



b



c



d

*Fig. 3.6.10. Dust and sand storms have different colors depending on the composition of the blown mountain rocks and soils: **a** – Kuwait; **b** – Sydney, Australia; **c** – Phoenix, USA; **d** – red dust storm over the ocean ahead of a cyclone approaching Onslow, Western Australia, 2013. Photo: AFP*

a http://www.coolwebmasters.com/uploads/posts/2013-04/thumbs/1364806914_sandstorm-01.jpg; **b** http://www.coolwebmasters.com/uploads/posts/2013-04/thumbs/1364806882_sandstorm-24.jpg; **c** http://www.coolwebmasters.com/uploads/posts/2013-04/thumbs/1364806915_sandstorm-08.jpg; **d** <https://mostbeautifulpicture.com/2019/07/17/dust-storm-australia/>



Fig. 3.6.11. Wind erosion (deflation) of the topsoil

http://2.bp.blogspot.com/_qudJsVkpBs/S-YRWtQhaI/AAAAAAAAABAg/Fsl-CbMxYmg/w1200-h630-p-nu/wind_erosion_BGR_big.jpg

The main factors causing soil deflation are strong winds in the conditions of arid climate and the absence of vegetation. Deflation occurs mainly on light carbonate dusty-loamy, loamy and sandy soils, especially in winter and early spring, when they are not yet covered by vegetation. Due to its granulomeres composition, heavy loamy and clay soils comprising particles larger than 1 mm are practically not deflated.

Soil wind erosion occurs in all forms of terrain. When the relief is dissected, elevated surface areas and leeward slopes are most prone to erosion and increases with the steepness of slopes. The destructive effects of the wind are much more intensive on hills and in basins than in flat territories.

Water and wind erosion develop in zones with low moisture and alternating wet and drought seasons according to the following scheme: flush – drainage of the soil – blowing – water saturation – flush. The simultaneous effect of water and wind erosion causes a particularly strong degradation of the overlying top soil.

Along with weather and climatic conditions, soil erosion is also promoted by a low level of agriculture and especially cattle breeding. Deep ploughing and grazing by cattle expose the soil and makes the upper soil layer vulnerable to both wind and water. As a result of mechanical action on the upper fertile humus-accumulative horizon of the soil, its degradation and even complete degeneration occurs, and its restoration may require hundreds of years. Uncontrolled grazing by herds of domestic sheep and goats led to the disappearance of meadows and even forests in North Africa, the Middle East and many other parts of the world. Small ungulates with extraordinary speed exterminated all wood and grass vegetation and literally “kicked out” the entire surface soil layer, turning steppe and forest-steppe landscapes into desert ones. On mountain and hill slopes without a protective soil horizon, erosion processes can sharply intensify with the degradation of plant ecosystems. To protect the natural environment in some countries (New Zealand, Cyprus), special legislation has been adopted.

Dust storms, most often occurring in early spring and summer, cause enormous damage to agriculture and the environment as a whole, but there are cases where such storms, during slightly snowy windy winters lead to the destruction of crops, lower soil fertility, pollute and introduce dust and sand into forest belts and reclaimed areas. Very often, dust storms are associated with irrational agricultural activities of people, primarily – massive ploughing of land without soil protection measures. Examples of the most powerful anthropogenic dust storms are the “Dust Bowl (dust boiler)” in the USA during the 1930s

(Fig. 3.6.12) and “black storms” in the USSR in the late 1960s that appeared after “development of virgin and fallow lands” in Kazakhstan.



a

http://blogimg.goo.ne.jp/user_image/43/e5/e485a4066c1b8a687300e826ad5b3ecf.jpg



b

Fig. 3.6.12. Dust storm, Texas, South Dakota, USA (1936):

a – dust front; **b** – filled up equipment

https://en.wikipedia.org/wiki/Wikipedia:Featured_picture_candidates/Dust_Bowl_-_Dallas,_South_Dakota_1936.jpg#/media/File:Dust_Bowl_-_Dallas,_South_Dakota_1936.jpg

Desert development

Due to the global climate changes that are currently observed on Earth, there is a gradual increase in average annual temperatures in various climatic zones and, as a result, the setting up of deserts. So, for example, the Asian Gobi Desert (from Mongolian translates as “waterless place”) is constantly growing and now covers an area of more than 1,3 million km², stretching over 1,600 km from the southwest to the northeast and 800 km from the north South. To prevent desert expansion, China is implementing a very expensive Green Wall project.

Many oases, along with the people living there, are exposed to dangers in the desert. An example is a fantastically beautiful oasis near the Yueyaquan Lake in China. The shape of this lake really looks like a growing crescent, which can be seen from the air (Fig. 3.6.13).



Fig 3.6.13. Oasis with Yueyaquan Lake, Gansu Province, China
<http://www.archimir.ru/blog/arhimir/6522.html>

This oasis, hosting one of the most important desert biogeocenosis, may disappear with time. The volume of water in Yueyatsuan Lake is rapidly decreasing due to pumping of significant volume of underground water. In the early 60s of the twentieth century, the average depth of the lake was 4–5 meters, the maximum depth – 7.5 meters. Over time, the area and depth of the lake was constantly decreasing, and now the average depth of the lake is 0.9 meters (maximum 1.3 meters).

An increase in the area of sand in some coastal areas is also observed in much colder Europe. For example, the Rubjerg Knude lighthouse in Denmark was built on the shores of the North Sea and lit its first signal lights on December 27, 1900. Its elevation above sea level was 60 meters and height – 23 meters. During the twentieth century, the level of the earth's surface near the lighthouse steadily increased due to the movement of sandy coastal dunes and the sand constantly showered on Rubjerg Knude and the adjacent buildings. Unsuccessful attempts to fix the moving sands around the lighthouse have been repeatedly made (Fig. 3.6.14).



Fig. 3.6.14. Lighthouse of Rubjer Knude, Denmark, covered in sand
<http://mossiso.com/wp-content/uploads/2009/04/8663586.jpg>

Global climate change poses a real danger to agricultural areas in the steppe zones worldwide. In Ukraine, for example, repeated droughts can lead to the transformation of the steppes of southern region into a desert with the loss of more than half of the country's vegetable land. In recent decades, both maximum and average summer temperatures have risen significantly. The observed rate of temperature rise in this area is significantly ahead of the average planet. This tendency is especially evident in the south of the steppe zone, and over the past decades, the actual shift of the boundaries of natural climatic zones by

100–150 km to the north has been observed. The vegetation conditions of plants in the traditional subzone of the Northern Steppe (Dnepr and surrounding regions) in recent years have actually met the conditions of the subzone of the Southern Steppe, similar to the Kalahari Desert of South-West Africa. If the observed climate change trends continue over the next 20 years, it can lead to unsuitability of the territory for agricultural activities over 15 to 21 million hectares of arable land.

Desertification processes also often occur in areas with intense anthropogenic stress that causes destruction of the soil layer. Territories with many features of the desert often arise around military training grounds, regardless of their geographical location. The territory around the Kherson region is the largest desert in Europe and during the times of the USSR it was used as an aviation training ground for bombing (Fig. 3.6.15, 3.6.16).

To prevent all types of soil erosion and desertification, rational land use should be organized in order to prevent exposure of soils and subsoils. For example, vegetation, especially perennial grasses, effectively contribute to a decrease in wind speed on the land surface and the roots bind the soil particles. Protective measures against wind erosion is largely aimed at reducing wind speed by creating forest shelterbelts around fields and increasing the resistance of deflation of soils by sowing perennial grasses.



*Fig. 3.6.15. Desert “Oleshkovsky Sands”, Kherson region, Ukraine.
The air temperature here can reach 45°, and the sand heats up to unbearable 75 °C*

https://24tv.ua/en/oleshkovskie_peski__vtoraja_po_velichine_pustynja_evropy_fantasticheskie_foto_n1188627



*Fig. 3.6.16. Territory resembling a desert near with Kitsevka,
Pechenezhsky district, Kharkiv region, Ukraine*
[http://ua.igotoworld.com/frontend/webcontent/
websites/1/images/1036108_800x600_harkov_6.jpg](http://ua.igotoworld.com/frontend/webcontent/websites/1/images/1036108_800x600_harkov_6.jpg)

Prior to the start of any construction, the top humified and vegetable layer must be cut off in order to preserve it and further use it in land reclamation after the completion of works, for agricultural purposes or decorative needs (flower beds, parks, etc).

Test questions to chapter 3.6.

Erosion of rocks and soils. Wind erosion and desertification

1. Determination of erosion of rocks and soils.
2. Mechanisms of action of wind erosion.
3. What is corrosion and deflation?
4. Dust storms, their distribution.
5. Soil deflation and its factors.
6. Anthropogenic causes of soil degradation.
7. Features of soil erosion.
8. The development of desertification and its factors.
9. Measures to combat wind erosion.

Chapter 3.7. WATER EROSION. RAVINES

Water erosion is the process of degradation of the upper soil horizons of the earth's crust – usually the organic vegetable layer, underlying soil strata or rock outcrops by atmospheric precipitation, surface runoff, temporary water flows, streams or rivers. This natural process results in the degeneration of soil layers by predominantly intense downpours with further flushing of the material, usually arriving from the upper soil horizons (Fig. 3.7.1).



Fig. 3.7.1. Slope destruction by water erosion, Thailand. Photo by V. Benko

With anthropogenic impact in areas primarily associated with intensive agricultural production, erosion increases sharply, and it becomes the largest factor in the degradation of arable and pasture lands. On Earth, water erosion is observed in areas covering up to 31% of land.

Water erosion is especially active in mountainous regions, where sometimes all the soil is washed away from steep slopes, turning the slopes into barren soils or bare rocks. Especially susceptible to water erosion is the soil cover in the tropical and subtropical wet forests due to the rainstorms. Heavy rain showers cause flat flushing of the upper soil horizons, destroy the entire soil stratum and underlying rocks, and lead to the formation of ravines and potholes (Fig. 3.7.2).



Fig. 3.7.2. Lavaka, Madagascar. Actual water erosion is observed on the right side of the slope, and the left notch is the old part of the eroded land
<https://de.wikipedia.org/wiki/Lavaka>

Lavaka (from Malagasy – pit) is a form of erosion of soils and soils, characteristic especially for Madagascar. Typical dimensions of lavaka are: length 80–100 m, width 40–50 m and depth 15–18 m, and a very narrow area of the discharge area. They are formed on steep convex slopes with the sudden emergence of groundwater to the surface caused by weak earthquakes, and the accompanying liquefaction of soils. In the highlands of Madagascar, up to 25 such manifestations per km² are noted. Prerequisites for the formation of lavaka are seasonal tropical showers, deep weathering of rocks (up to 100 m) and rare grassy vegetation. Damage to the vegetation cover by cattle and earth roads contribute to the formation of lavaka.

Water erosion affects directly the crops, and significant areas of valuable agricultural lands are destroyed or degraded, their fertility sharply decreases, and the moisture supply is greatly reduced (Fig. 3.7.3). The washing out and removal of underlying soil particles, siltation of rivers, ponds and reservoirs occur. The fragmentation of the territory due to increases of ravines and the hydrological

regime of the terrain as a whole deteriorates. Erosion of riverbanks and streams threatens buildings and structures located near these watercourses.



Fig 3.7.3. Water erosion threatens crops

<https://timesofindia.indiatimes.com/home/environment/global-warming/mountain-erosion-may-add-co2-to-atmosphere-study/articleshow/63748136.cms>

Among modern environmental threats, water erosion, even in developed countries with a high crop culture, remains a potential threat. In the United States until recently, annual losses of arable land from erosion amounted to 200 thousand hectares, and over the past 180 years arable land equivalent to about 100 million hectares has been destroyed by water erosion. The extent of erosion in southern developing countries is particularly impressive: if on average up to 10 tons of fertile substrate are washed off from 1 hectare of arable land in the USA, then in India ~ 75 tons from 1 hectare, in China – up to 250 tons, and in the mountainous regions of Ecuador – up to 560 tons.

According to their influence on soils and rocks, water erosion is divided into drip, flat (or surface), linear – ravine and river (deep and lateral). Depending on the nature of the surface runoff, water erosion is also divided into erosion due to the action of snow melt, rain or irrigation water.

Drip erosion is the deterioration of the soil layer or exposed rocks under the impact of raindrops. Soil structures on the surface of the earth are destroyed under the influence of the kinetic energy of the impacts of raindrops or sprinklers, and the lumps of soil knocked out by drops are scattered to the sides. Then the soil particles fall on the water film on the surface of the earth, on the leaves of plants or in temporary streams of water which contributes to their transportation. On slopes, ground particles can move down over long distances. The drip variety of water erosion is mainly spread in the humid tropics and subtropics.

Flat (surface) erosion is a uniform flushing of soil material from the slopes, as a result of which the slopes become gentler. In arid areas, where this type of erosion is more often observed, even minor precipitation can have significant consequences. After sustained heavy rainfall, the upper soil layer is saturated with water and excess water flows in an almost continuous shallow stream down the slopes, dragging away soil particles. The process of such flushing, which does not form noticeable gaps on the surface of the earth, is called planar erosion. It is conventionally believed that this process is carried out by a continuous moving layer of water, although a network of shallow temporary water flow produces planar erosion. Surface erosion leads to the formation of washed-out (bare) soil slopes and these washed-up soils accumulate at the toes of slopes to form the diluvial deposits. If water flows in extended streams, then ravines are likely to form on the slopes.

Linear erosion, unlike surface erosion, occurs on relatively narrow sections of the earth's surface and leads to its separation with the formation of various depressions (erosion forms) – ravines, logs and valleys (Fig. 3.7.4 a). Linear erosion proceeds more intensively than planar erosion: as soon as even a shallow ravine network is formed, active dissection of the earth's surface begins. Small temporary and sometimes permanent streams form in the ravines, which ultimately merge and gradually transfer solid sediments to larger rivers. The linear form is sometimes also attributed to deep and lateral erosion produced by constant watercourses.

Deep (bottom) erosion is the erosion and constant deepening of the floors of channels of watercourses. Bottom erosion is directed upstream from the mouth and continuously continues until the bottom of the stream reaches the level of erosion basis. The basis of erosion is the level of the longitudinal profile of the water stream (or river) below which water loses its energy and it cannot erode the floor anymore.

Lateral erosion is a washout of the banks of watercourses with their subsequent collapse (Fig. 3.7.4 b). In each permanent and temporary watercourse (ravine, stream, river), both forms of erosion are always present, but in the first

stages of the development of the watercourse, the deep one prevails, and in the subsequent stages it becomes lateral.



Fig 3.7.4. Water linear erosion: **a** – deep, **b** – lateral

a <http://2.bp.blogspot.com/-ZVB34TYI1IA/URXHWSi-btI/AAAAAAAAACVQ/NURcYBnFSwY/s1600/A+gully+in+Kharkov+oblast,+Ukraine.jpg>

b <http://историческая-самара.рф/i/priroda/Samara-Pochva/10.jpg>

There are two main types of water erosion of soils and rocks, depending on the causes of their occurrence: natural (or geological) and accelerated (anthropogenic). Natural erosion occurs slowly and, compared to large areas, is not accompanied by a remarkable decrease in the fertility of natural soils or rapid relief transformations; anthropogenic water erosion proceeds intensively and is primarily caused by irrational human economic activity.

Factors causing water erosion of rocks and soils

The characteristics and intensity of water erosion of various types depend on a number of factors, mainly: the micro climate, the nature of the relief, granulometric and mineral composition, structure of surface and underlying soils, the presence of vegetation and anthropogenic (technogenic) impact.

The climate and weather conditions of the area have direct influence on the development of erosion processes. These are the amount and intensity of rainfall, size of the raindrops, thickness of the snow cover in winter and the snow melting rate in spring, daily and seasonal fluctuations in air temperature, strength and prevailing wind directions.

The topography is another significant factor in the development of water erosion. The length and steepness of the slopes, size of the catchment area, shape of the surface

of the slope determine the degree of development of erosion processes. The longer the slope and the greater its steepness, the more erosion develops over a larger area. The amount of soil washed out by water depends on the shape of the slopes: on convex ones it is more, on concave ones it is less. If the slopes have a complex shape: in one place – convex, in another – straight or concave, then, respectively, both erosion of the surface and deposition of material can occur simultaneously.

The intensity of water erosion also depends on the condition and structure of the top soil. Well-structured soils of light and medium loamy composition are characterized by friability and good water permeability; therefore, their washing out and erosion are sharply reduced. On the contrary, on non-structured and compacted soils with heavy clay composition, water is absorbed slowly, lingers on the surface and quickly drains to lower places of the relief, causing erosion of the soil.

Grass cover, trees and shrubs protect the earth from water erosion and their removal has an adverse effect.

During water erosion of sedimentary rocks containing soluble salts, the soluble components fall into the water and cause salination of surface and underground waters. Water erosion primarily threatens agricultural lands and protective measures are important to mitigate its development. Protective measures are divided into three main groups: soil protection, agricultural and forest reclamation.

Protective measures. They consist in the correct distribution of types of cultivated crops, their seasonal rotation every year (crop rotation) and the corresponding methods of tillage. In case of soil-protective crop rotation, it is important to note that row crops do not protect the soil from erosion and washing off, especially in spring and early summer. An increase the area under perennial grass cultivation very well protects the soil during erosion-hazardous periods.

Agrotechnical anti-erosion measures. A fairly simple but effective way to slow down the speed of surface runoff is ploughing, cultivating and sowing crops across the slope, if possible parallel to the main direction of the horizontal contours of the terrain.

Reclamation measures include planting and growing protective forest belts for various purposes: windbreaks located along the perimeter of fields; field protection, designed to delay surface runoff in the fields, and therefore they are laid across the slopes; ravine forest stands on the slopes and bottoms of ravines; water-protective forest stands, which are arranged around ponds, lakes and canals. On lands unsuitable for agricultural production, forest stands for general environmental purposes are organized.

Engineering anti-erosion measures. When designing anti-erosion structures to protect against the growth of ravines, compliance with regulatory documents is important.

First of all, it is necessary to determine the stage of development of the ravine. There are several stages of the emergence, growth and transformation of ravines:

1 – the formation of small holes on the surface of the earth, their gradual deepening (Fig. 3.7.5 a, b);

2 – ravine formed from larger ravine; there is an active growth, inset of the top of the ravine, its deepening, the development of side branches (Fig. 3.7.5 c, d);

3 – development of the equilibrium profile of the ravine, the termination of its deepening (Fig. 3.7.6);

4 – attenuation of erosion processes, overgrowing of the ravine with grass, trees and shrubs (Fig. 3.7.7)

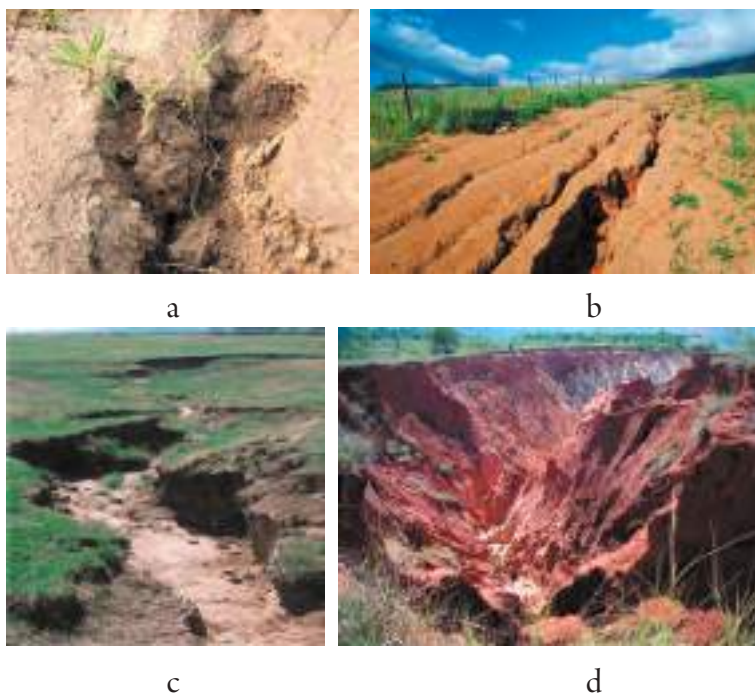


Fig. 3.7.5. Initial stages of ravine development: **a** – small gullies; **b** – deep ravines, with erosion of earth road; **c** – a small ravine; **d** – deep, intensively growing ravine
a http://www.agweek.com/sites/default/files/styles/full_1000/public/field/image/Soil_Erosion_With_Roots.JPG?itok=CPepYKet; **b** <http://lachachara.org/chachawp/wp-content/uploads/2015/05/Fenómeno-del-Niño.jpg>; **c** <https://classconnection.s3.amazonaws.com/357/flashcards/969357/jpg/gullyerosionpasture-nrcs-lg1323193190637.jpg>; **d** https://parquetierra.files.wordpress.com/2014/10/madagascar_erosion.jpg

There is an intense deepening of ravines at growth stage and, as a rule, they have a V-shaped profile with very steep, often almost vertical slopes. Over time, the amount of material washed out of the ravine decreases, stabilization occurs, and the slope angles decrease, the ravine profile becomes U-shaped and trough-like. With the gradual transformation of the ravine, the slopes become more gentle (Fig. 3.7.6, 3.7.7).



a b
Fig 3.7.6. Gullies of the V – shaped (a) and U-shaped (b) profile
a http://static.iloveukraine.com.ua/p/0/96/96265/61100a409a20afd92e1227de5e24717f_600x1000.jpg
b <https://docplayer.ru/64660959-Degradaciya-pochv-ekologiya-11-klass-urok-7-potapova-g-i.html>



Fig 3.7.7. Clough with gentle slopes, Kaniv Nature Reserve, Ukraine
<https://www.photoukraine.com/i/articles/Kanevskiy%20Zapovednik%20Photos/011.jpg>

It should be emphasized that the frequent intense growth of ravines is not always limited to degradation of agricultural and undeveloped lands, but sometimes it can take a catastrophic character, with the destruction of roads,



a



b



c

buildings, structures and may require the evacuation of people (Fig. 3.7.8).

A giant ravine, caused by land erosion after nine days of sustained heavy rainfall, rapidly developed near the village of San Antonio in the municipality of Comasagua, the Libertad department in El Salvador. The depth of the ravine was about 100 meters with a length of 500 meters (Fig. 3.7.8 a). People who lived near the place (196 people) where the land opened up were immediately evacuated due to the high risk of land erosion due to oversaturation of the soil.

Fig. 3.7.8 a, b, c – the negative consequences of the development of ravines

a <https://poleshift.ning.com/profiles/blogs/el-salvador-ravine-depth-of-100-meters-and-length-500-meters>

b <http://168.ru/files/news/full/1376471669.jpg>

c http://www.maipark.com/assets/uploads/Erly_1.pdf

Anti-erosion measures should include the prevention of planar flushing of the soil, stabilization of slopes, a decrease in the active erosion of ravines and in some cases, the elimination of ravines.

Engineering structures for the protection of territories and construction objects from erosion processes, including the formation of ravines, include: water retention, waterways and bottom structures.

Water-retaining structures must ensure the drainage of snow melt and rainwater, interception and deceleration of surface runoff. To reduce erosion, terracing of slopes is carried out. Terraces are arranged on slopes with steepness from 7° to 35° , while to ensure low speeds of surface runoff, the surface of the terraces should not have a longitudinal slope more than 3° . On slopes with steepness up to 10° above the peaks, ravines are equipped with water retention shafts.

Waterways are structures made for drainage and distribution of surface and ground waters on the slopes, in ravines, gullies and basins. These include water-guiding shafts and distribution ditches, which have a generally trapezoidal cross section.

Spillway structures are used to quickly discharge melt and storm water from the undisturbed earth's surface to the bottom of ravines and basins. They also serve to strengthen the tops of ravines and together with strengthening their bottom, they can delay the development of linear erosion and stabilize the lower slope of the ravines. Spillway constructions can be: open, in the form of channels – rapid currents, drops, gutters and closed – mine, tubular spillways. In the downstream spills of the spillways, water flow energy dampers are installed – water wells and walls.

Bottom structures are designed to reduce the intensity of erosion processes in ravines: to prevent erosion of the bottom, to delay the removal of material and to increase the basis of erosion of the ravine. The bottom engineering structures include the following engineering structures: continuous dams; bottom structures; staggered piling in dams.

Agroforestry. Agro- and forest-reclamation measures include the arrangement of forest stands on the lower parts of the slopes and at the edge of gullies and ravines, as well as in open areas adjacent to the slopes; trees and shrubs are planted along river banks, around ponds and other water bodies. Sowing perennial grasses or herbs is used on natural and artificial slopes with a steepness of up to 35° , and with a greater steepness (up to 45°) the soil is stabilized with cementitious materials.

Elimination of ravines. Partial or complete elimination of ravines or their closure is used together with other types of land reclamation. The filling of ravines with soil should be limited to those with a depth, down to 15 m. Washing of ravines with the use of hydromechanical means should be used for depths up to 25 m.

When eliminating ravines, as part of the design and survey work, forecast for possible changes in the groundwater level in the territories adjacent to the ravine should be made. Gullies are often natural drains for groundwater and after their elimination, there will be a likely rise in groundwater level and flooding of neighboring territories and construction sites. As preventive measure, it is necessary to provide facilities for the removal of surface water (uphill ditches and storm sewers) and groundwater (linear tubular drains).

Test questions to chapter 3.7. Water erosion. Ravines

1. What is water erosion and where is it common?
2. Water erosion in the world and its varieties.
3. Definitions of drip, planar and linear erosion.
4. Factors of water erosion.
5. Soil protection against erosion.
6. The stages of development of ravines.
7. Engineering anti-erosion measures.

Chapter 3.8. RIVER EROSION

Rivers are permanent watercourses that flow along channels developed by them and exist only under the condition of their continuous water supply, which is carried out due to precipitation, melt water of glaciers and snows, lakes, swamps or groundwater. The amount of precipitation in the river basin is usually greater than evaporation. The most important river networks are located in areas of humid climate, less often in the arid zone – steppes, with fewer rivers in the semi-desert areas. Rivers do not originate in the deserts. In some cases, rivers can exist in deserts, only if the feeding area is located outside the desert zone. Thus, the largest African river Nile, flowing through the Sahara, has its feeding area in the tropical rainforests.

Erosion of rivers takes place in river valleys, created by the rivers' activities. River water flows are the most dynamic and efficient systems that transform the reliefs of the earth's surface. Powerful river currents divide huge terrestrial spaces, significantly affects the global erosion of the earth's crust, transfer and accumulation of eroded material. River erosion gave rise to one of the most impressive geological sites of our planet – the Grand Canyon in Arizona, USA (Fig. 3.8.1).



Fig. 3.8.1. Grand Canyon, Arizona, USA. It is one of the deepest and most extensive canyons in the world. Photo by Iu. Iegupov

Located on the territory of the Grand Canyon National Park, it is a system of gigantic precipices on the Colorado Plateau, which arose due to the erosion activity of the Colorado River. With an average depth of the canyon – 1300 m, the greatest depth is 1857 m, length is about 446 km. The canyon began to form about 65 million years ago when the Colorado plateau began to rise up as a result of tectonic movements of the earth's crust. As a result of the elevation of the territory, the angle of inclination of the Colorado river channel changed, and as a result, the flow velocity and the intensity of erosion of rocks in the river valley increased. First, the overlying limestones were washed away, and then, the more ancient sandstones and slates that lie deeper. So about 5.5 million years ago, the modern form of the Grand Canyon was formed. The canyon continues to deepen now due to the uninterrupted processes of river erosion.

There are three (sometimes four) stages distinguished in river development: youth, maturity and old age.

During their youth, rivers flow along uneven mountainous terrain. The flow rate in different parts of rivers as a whole is quite high, rapid and even waterfalls are often encountered (Fig. 3.8.2, 3.8.3).



Fig. 3.8.2. Thresholds on the Keret River, Karelia. Photo by V. Iegupov



Fig. 3.8.3 a – Waterfall on the Grand River South East, Mauritius – a tourist attraction
<https://www.google.com/search?q=grand+river+south+east+waterfall>



Fig. 3.8.3 b – Waterfall on the Dzhurin River, Ternopil region, Ukraine. At a height of 16 meters it is the largest waterfall in Europe plains.
 Photo by V. Iegupov

Rivers intensively erode the rocks lying on the floor of the channel, converting them to boulders and cobbles (Fig. 3.8.4 a). These fragments, when transported downstream, are increasingly reduced and transformed into gravels and coarse sand. At this stage of river development, intensified processes of bottom erosion occur, which lead to intensive deepening of the channel. Lateral erosion at this time is almost absent and weakly manifested; the flow energy is mainly directed to erosion of the bed and transfer of erosion products. The tortuosity coefficient of the river (K) at this stage is minimal (K is the ratio of the length between two points

along the river channel to the distance between the same points in a straight line). Rapid deepening of the channel leads to the formation of valleys having a V-shaped transverse profile (Fig. 3.8.4 b). Gradually, the water flow rate decreases, along with the appearance of bottom erosion, and eventually lateral erosion begins to prevail, i.e. erosion of the coast. In the middle and lower reaches of the river, as a rule, deep erosion is completely replaced by lateral erosion, which leads to the expansion of its valley making a U or trapezoidal shape and riverbanks are formed on the river (Fig. 3.8.4 c). The river passes into the maturity stage, which is characterized by a slower flow, the width and depth of the river increase. On large rivers, there is an opportunity for shipping (Fig. 3.8.4 d).

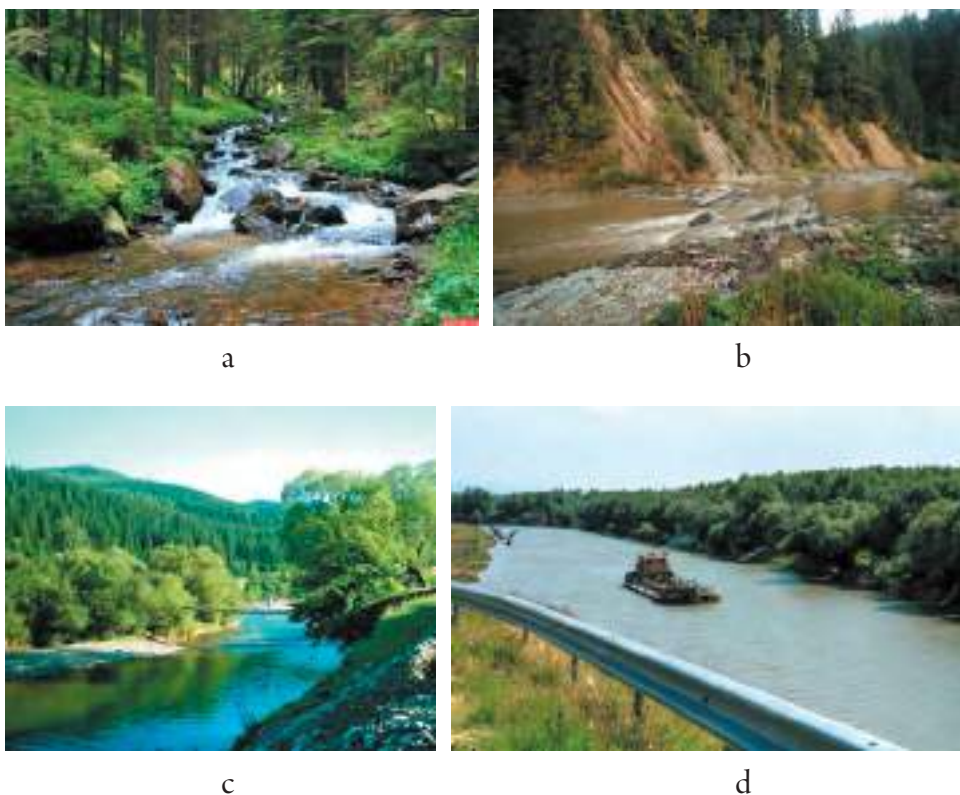


Fig. 3.8.4. Development stages of the Prut River, Ukraine-Moldova: **a** – near the source; **b** – the upper reaches; **c** – a river in the middle course; **d** – lower reaches

a – <http://rasfokus.ru/images/photos/medium/a00be5eb6f95153b64212831fe5150d3.jpg>; **b** – Photo by V. Novgorodov; **c** – <http://www.zamky.com.ua/wp-content/uploads/2015/04/PCDV0082.jpg>; **d** – http://www.moldovenii.md/resources/files/images/natura/68_Prut_Giurciulesti_Cahul_290711_02.JPG

The asymmetric form of river valleys is characteristic of the stage of river maturity, the occurrence of which is due to the uneven activity of lateral erosion. Large rivers flowing in the meridional direction from north to south wash the right shore, i.e. the one on the west, which becomes steep, and the eastern, as a rule, low and gentle, consists of several terraces and horizontal platforms. During the ripening period of the river, a wide floodplain (floodplain terrace) is formed in its valley – part of the valley, subject to flooding during floods and elevation above the water level in the river during low tide. Several floodplain terraces are also formed, which during specific high-rain seasons may become prone to temporary flooding.



*Fig 3.8.5. The Dniester River in the middle course:
the west bank is steep, the eastern one is gentle. Photo by V. Iegupov*

At the maturity stage, many meanders (bends) appear on the rivers, arising due to the fact that the water at the turning points erodes the concave shore and deposits clastic material on the convex, creating shallows and braids (Fig. 3.8.6). The transverse profile of the valley is transformed into a trapezoid with a wide and flat bottom. The channel gradually moves between the sides of the river valley, leaving secondary river channels, branches and oxbows and isolated meanders (Fig. 3.8.7).



Fig. 3.8.6. Rivers at maturity: **a** – meanders of the Seversky Donets River (Photo by V. Novgorodov), **b** – erosion and redeposition of sandy alluvium by the Dnieper River
<http://komanda-k.ru/category/%D1%82%D1%8D%D0%B3%D0%B8/%D0%B1%D0%B5%D0%BB%D0%BE%D1%80%D1%83%D1%81%D1%81%D0%B8%D1%8F>



Fig. 3.8.7. River bed and oxbows – former meanders, Estonia
http://balticguide.ee/wp-content/uploads/2014/09/bg0914_45_pic_emajogi_jaanus_jarva.jpg

The final stage in the development of the river is the stage of old age. The river flow rate gradually decreases, begins to loop increasingly and the tortuosity coefficient K increases significantly. The river valley is filled with thick layers of sandy-clay alluvial deposits (Fig. 3.8.8). The slopes of the water surface of the river bed are significantly reduced, compared with the previous stages, and reaches

minimum necessary to maintain its movement. Near the mouth of the river delta, numerous arms and channels arise, along which water flows parallel or at small angles to the main channel. Extensive alluvial plains appear in the delta (Fig. 3.8.9).



Fig. 3.8.8. River in the period of old age: p. Mackenzie, Canada
<http://nextews.com/1a2e1472/>



Fig. 3.8.9. The mouth of the Dnieper, Ukraine

https://www.google.com.ua/imgres?imgurl=https%3A%2F%2Flookaside.fbsbx.com%2Flookaside%2Fcrawler%2Fmedia%2F%3Fmedia_id%3D248965468468459&imgrefurl=https%3A%2Fbook2ww.com%2Ftavriyaks%2F&tbnid=BGTNI5-4-qb9WM&vet=12ahUKEwjxpp2rvqrmAhUC8KYKHZFPCRwQMygAegQIARAW.i&dclid=tIPq-t_klvsUtM&w=807&h=426&q=aerial%20photography&hl=ru-UA&ved=2ahUKEwjxpp2rvqrmAhUC8KYKHZFPCRwQMygAegQIARAW

Rock fragments are transported by the river in four ways: by dragging those along the bottom, abruptly above the bottom, suspended in the water column and in dissolved form (in the case of solubility of eroded rocks). Moving fragments hit the bottom and against each other – as a result they are crushed and rolled, and they are also sorted by size and weight – larger ones (boulders and cobbles) remain in areas with a fast flow, and finely fragmented ones (sand, silt and clay particles) are deposited where the flow slows down. The detrital material brought by the river and deposited in the river valley is called alluvium. The alluvial deposits that make up river terraces and floodplains are classified according to the size of the debris: boulders, cobbles are characteristic of fast mountain rivers; gravel, sand – for beds of flat rivers; loamy, peaty and silty sediments – for channels and branches with a slow current, as well as for floodplain lakes without current (Fig. 3.8.10).

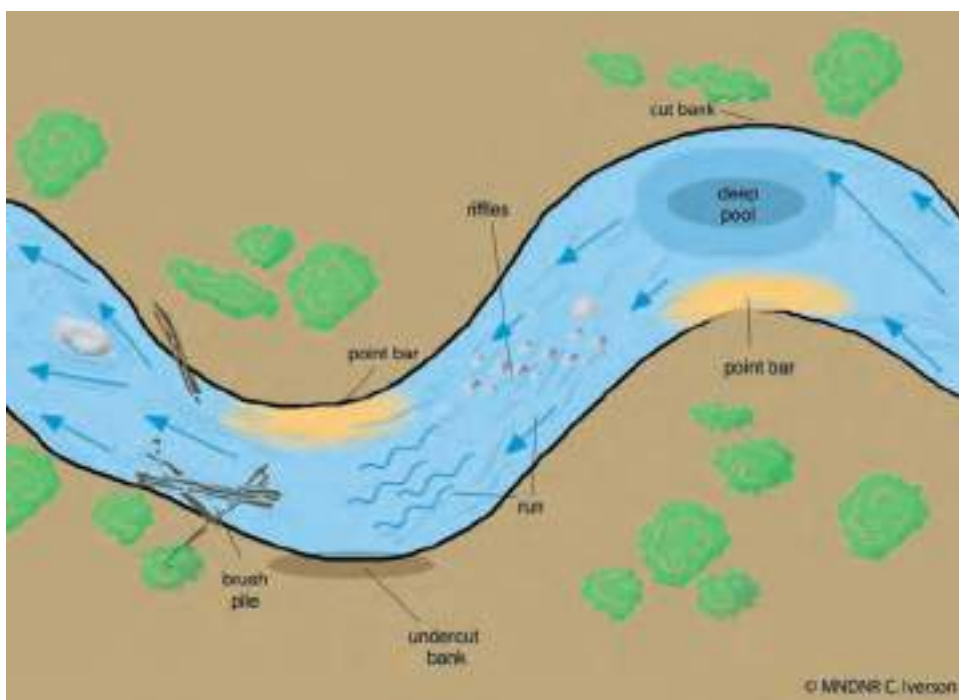


Fig. 3.8.10. Scheme of the formation of alluvial deposits

http://www.geol.science.cmu.ac.th/gs/courseware/205103/pisanu/10_runwater-S_2561.pdf

When engineering and geological assessment of river valleys are carried out for construction purposes, it is important to have a sound understanding of the geomorphological structure and their lithological conditions (Fig. 3.8.11).

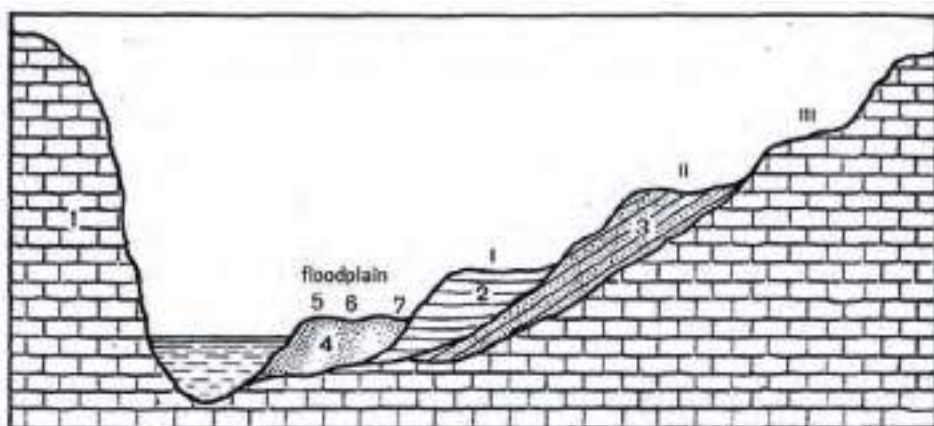


Fig. 3.8.11. The construction of the valley of the plain river: **1** – bedrock; **2** – alluvium of the first floodplain terrace; **3** – alluvium of the second floodplain terraces; **4** – alluvium floodplains; **5** – a river-side shaft; **6** – horizontal part of the floodplain; **7** – terraced lowering. **I** – first and **II** – second accumulative terraces, **III** – third erosion terrace
http://physiography.ru/picture_library/rechnaya-dolina.jpg

The most favorable deposits for construction purposes are the bedrock and the erosion terraces. It is not recommended to use accumulative floodplain deposits as bases for buildings and structures because they often contain a large amount of organic matter in the form of silt and plant debris.

Protection against river erosion

Measures to combat river erosion are divided into preventive and engineering. Preventive measures include various methods of preventing the negative consequences of dangerous erosion processes: the establishment of a prohibited strip within the zone of intensive erosion; the prohibition of the extraction of building materials from river channels, sharply activating deep erosion; regular monitoring of the intensity of lateral erosion.

Engineering shore protection measures include the construction of coastal structures and fortifications: gabions (strong wire cage filled with stone cobbles), installation of embankments, protective walls, laying of concrete slabs, sheet piling, among others (Fig. 3.8.12). To protect the territory from floods, earthen dams, regulating dams and reservoirs are built.



Fig. 3.8.12. Options for strengthening the coast: **a** – concrete slabs;
b – stone blind area; **c** – sheet piles; **d** – geogrids

a – <http://www.mikron-ugzbn.ru/assets/images/beregoukreplenie/3-2.jpg>;

b – <http://www.zaorec.ru/userfiles/155.jpeg>;

c – <http://www.rosbereg.ru/shpuntovye-svai-v-ukreplenii-beregov-foto/>;

d – http://www.vashsad.ua/plants/interesting_plants/show/8932/

Strengthening the coast is a high budget major work and it mainly serves to reinforce the coastline and prevent water erosion. As the construction industry develops, construction technologies and methods improve, shore protection also goes to a new level and uses more modern building materials and structures, which, for example, include geogrid and geotextiles.

Engineering constructions from box gabions and gabion mats have been widely used for over a hundred years. The main area of their application is the protection against water erosion of soils (not only river, but also landslide, mudflow, ravine, slope, etc.). The first hydraulic structure using gabions was built

in Italy (1894) on the Reno River and is still functioning. Currently, several types of such structures are spread all across the world (Fig. 3.8.13).

Gabions are massive structures in the form of parallelepipeds, sometimes cylinders, which are made of double-torsion metal mesh and filled with stone. They are used to protect against erosion of any type as reliable engineering structures: retaining walls, sea and river shore fortifications, so on.

Renault mattresses are flat structures of double torsion in the form of a parallelepiped of small height and large area, filled with stone. They are used for lining the sides of canals and dams, reinforcing bridge supports and protecting pipelines, and are used in landscape design.

Terra-mesh systems: soil reinforcement systems which consist of the front surface and double torsion panels lay on the body of the embankment.



a

b

Fig. 3.8.13. Designs to strengthen the coast: **a** – gabions of various shapes

a <https://consaltstroy-geo.ru/catalog/gabiony-konstrukcii/>; **b** – Renault mattresses

b http://i01.i.aliimg.com/img/pb/668/365/911/911365668_383.jpg

Designs of protective structures are realized using guidelines from regulatory documents, for example, in Ukraine – this is DBN V.1.1-24-2009 “Protection against dangerous geological processes”.

Test questions to chapter 3.8. River erosion

1. Where does river erosion occur?
2. Stages of river development.
3. What are meanders and the reasons for their formation?
4. The formation of alluvial deposits.
5. Preventive anti-erosion measures.
6. Engineering protection against river erosion.

Chapter 3.9. ABRASION. PROCESSING OF THE COAST

Abrasion (from Latin *abrasio* – scraping, shaving) is the process of physic-mechanical destruction of rocks and the transport of debris by breaking waves and currents in the coastal zone of oceans, seas, lakes and reservoirs. The main destructive work of the coast is made by the waves and to a lesser extent influenced by various currents and fluctuating tides. Abrasion changes the shape of the coastline of water bodies, gradually pushing it inland. The impact of the abrasion process on rocks in the coasts is manifested not only on the land surface but the destruction of rocks and the movement of their fragments also occurs under water in reservoirs and seas to a depth of several tens of meters and in the oceans – down to 100 m or more. The speed of abrasion and the “advance” of the sea on land depends on the geological structure of the coast and the strength of the wave which increases with the rise in sea level.

Coastal abrasion poses a serious threat to residential and industrial developments located on coastal territories (Fig. 3.9.1), for railways, roads and farmland.



Fig. 3.9.1. Abrasion on the Pacific coast of Brisbane, Australia

<http://www.7dayadventurer.com/2017/11/14/king-canute-battling-the-relentless-tide-the-dilemma-of-rampant-beach-erosion-gold-coast-and-adelaide/>

Marine abrasion reduces the useful area of many coastal cities, activates the development of dangerous geological processes, mainly landslides on the coastline (Fig. 3.9.2).



*Fig. 3.9.2. Destruction of an apartment building
as a result of a landslide caused by abrasion, Devonshire, England*
<https://www.dailymail.co.uk/news/article-2337012/Cliff-cul-sac-Britains-dangerous-street-home-collapsed-sea-evacuated-safety-fears.html>

The length of segments, subject to abrasion processes on the coasts of all reservoirs of the globe is ~ 400,000 km, which is 51% of their total length.

Morphology of the seashore

The impact of abrasion on the coast contributes to the formation of characteristic forms of coastal relief and the formation of large volumes of clastic deposits. The process of abrasion is as follows: hitting a rocky shore, the waves gradually develop a recess at its base – a wave-breaking niche over which hangs a cornice (Fig. 3.9.3).



a



b

Fig. 3.9.3. Rock bottom cornices: **a** – Jeju, Korea <https://explorejeju.wordpress.com/2012/05/>; **b** – Mauritius. Photo by V. Iegupov

As the niche size increases, the cornice under the influence of gravity does not maintain its own weight and collapses (Fig. 3.9.4). The debris appears in the surf zone and is gradually crushed and transformed into gravels and sand.



*Fig. 3.9.4. Collapse of wave-breaking cornice, Arctic coast of Alaska
The combination of mechanical and thermal erosion caused by relatively warm waves in contact with frozen sediments leads to rapid coastal erosion. Erosion rate increases with increasing intensity and frequency of storms in combination with a decrease in seasonal ice cover*

Photograph: US Geological Survey. https://www.researchgate.net/profile/Todd_Atwood/publication/279845193_Forecasting_Wildlife_Response_to_Rapid_Warming_in_the_Alaskan_Arctic/links/55aff0f208ae11d31039a946/Forecasting-Wildlife-Response-to-Rapid-Warming-in-the-Alaskan-Arctic.pdf?origin=publication_list

In a typical profile of the sea coast across the coastal slope, there is a steep coastal ledge – *cliff*, formed as a result of the collapse of the wave-breaking niche. Gradually, after erosion and movement of the debris by the waves, a new wave-breaking niche begins to form in the lower part of the ledge. At some point, overlying rocks again collapse and such cycles are constantly repeated.

As a result of these processes, the cliff gradually shifts towards the land and leaves the underwater abrasion terrace, *bench*, slightly inclined toward the sea (bench – terrace, ledge). The bench can consist entirely of rocks of the former

cliff or sometimes covered with a thin layer of clastic material from the destroyed rocks of the coast. Such terraces are present on many abrasion banks near capes, where conditions are unfavorable for sediment accumulation (Fig. 3.9.5).



Fig. 3.9.5. Cliff wave-breaking niches and benches

Located on the coast of Basque Country, Itzurun Beach is one of the most exciting areas. Its huge and the vertical cliffs and the limestone walls that reach the 150 m of slope attract visitors, where they will be able to see a geological object called flysch caused by the erosion of the sea throughout the years. Flysch is sequence of shales rhythmically interbedded with thin, hard, sandstones. The total thickness of such rock mass is commonly many thousands of metres, but the individual beds are thin, only a few centimetres somewhere to a few metres thick.

<https://www.maxpixels.net/Clouds-Beach-Sea-Cliff-Landscape-Sky-Hermitage-4365492>

A narrow strip is often formed between the cliff and bench, consisting of clastic deposits, flooded during tides and storms – the *beach* (French *plage* – gently sloping seashore). The beaches belong to the simplest forms of the accumulative coastal high relief and they are formed under the action of the forward and reverse (Ripcurrent) surf flows (Fig. 3.9.6). Part of the clastic material is carried outside the abrasion terrace or the beach, deposited on a deeper underwater slope and creates its continuation – an underwater accumulative terrace.



Fig. 3.9.6. The beach is the simplest coastal form of accumulative relief, Northern Norway. Photo by Iu. Iegupov

The most intense abrasion is manifested in the surf zone. On average, during the erosion of coastal ledges (cliffs), 3.45 billion m³/year of clastic material enters reservoirs, and when the coastal terraces (benches) are washed out, twice as much – 7.4 billion m³/year. Pebbles, gravels and sand formed during abrasion, form underwater accumulative terraces, as well as above-water and underwater landforms – spits, embankments, etc. (Fig. 3.9.7).

According to geomorphology, beaches of the full profile are distinguished in the form of a gently sloping shaft of sand and gravel, while beaches of the incomplete profile – in the form of an accumulation of thin sediments adjacent to the foot of the cliff. The strip of coastal shallow water expands with the width of the bench and the beach. The strength of the surf decreases and the abrasion gradually hinders its further development, the cliff recedes more slowly and the process of abrasion gradually stops.

Material deposited under water (sand, gravel or fragments of mollusk shells) at a depth of a few meters can form an underwater accumulative shaft. Sometimes this submarine shaft can increase its height and even rise above the surface of the sea parallel to the shore. Such shafts are called *bars* (from the French Barre – barrier, sandbar) or reef. The formation of a high barrier can lead to the separation

of the coastal part of the sea basin from the main water area – this is how lagoons are formed. The *lagoon* (from lat. Lacus – lake) is a shallow natural coastal pond, separated from the sea by the reef or barrier, often connected to the main water area by narrow straits (French: La passé).

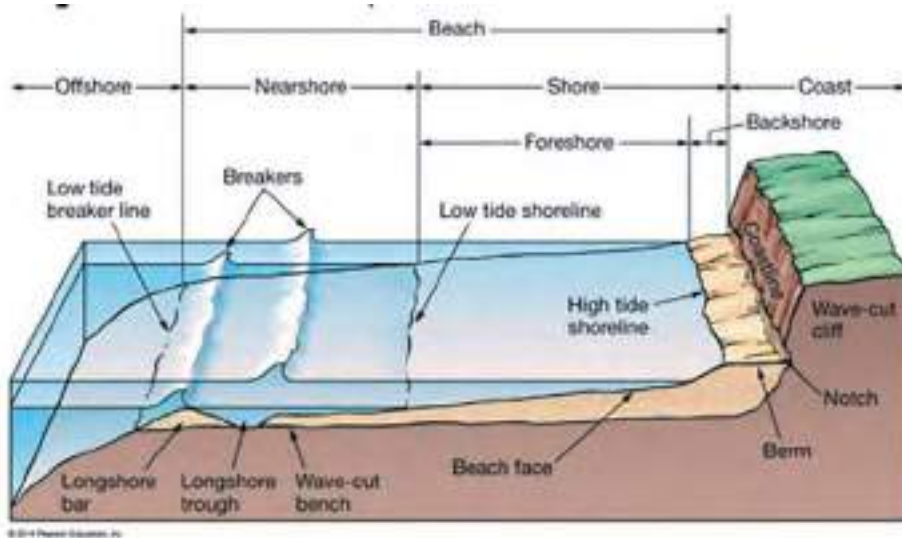


Fig. 3.9.7. Beach Formation Scheme

http://geophile.net/Lessons/coasts/coasts_01.htm

The strongest rocks of the main shore are sometimes preserved in the form of separate rocks – outliers. As a result of abrasion, sometimes unique natural objects are formed, for example, those depicted in the photo (Fig. 3.9.8, 3.9.9).



a

Fig. 3.9.8 **a** – Marble remnant on Lake General Carrera in the Patagonian Andes on the border of Chile and Argentina (Chilean Aisen region)

https://www.taringa.net/+imagenes/las-cuevas-de-marmol-hd_12yae/?commentId=1zxj0f



b

Fig 3.9.8 **b** – Le Rocher Crystal – a tourist attraction, Mauritius. Photograph: R. Goodary



Fig. 3.9.9. A unique abrasion form – “Stone Elephant” in the Hunaflowi Bay of the northern coast of Iceland. Photo by V. Novgorodov

Rock Hvitserkur is called differently – an elephant, mammoth, dinosaur or rhino. This unusual cliff looks like a huge monster eagerly drinking the water of the Greenland Sea. 15-meter Hvitserkur is all that remains after the destruction of the volcano of the same name, which over time has turned into a narrow rock from afar resembling a huge animal.

The main types of abrasion:

- *mechanical* abrasion is the destruction of coastal rocks by impacts of breaking waves, the occurrence of periodic compression and decompression of air in rock cracks when exposed to breaking waves, as well as by mutual impacts and abrasion of rocks by moving fragments;
- *chemical* abrasion – the destruction of rocks, under the influence of the dissolving ability of water in the case of solubility of rocks that make up the coast (limestone, marl, chalk, saline rocks);
- *thermal* abrasion – destruction of coasts in areas of permafrost, composed of frozen rocks or ice.

Abrasion factors

The intensity of coastal destruction of marine abrasion, as well as a similar process on large lakes and reservoirs, depends on a number of factors, among which the most important are:

- *the shock force of the waves.* During severe storms in marine areas (Fig. 3.9.10), the height of the waves in some places can reach 20 m or more, and the strength of their impact is 30–70 tf/m². Severe storms occur both in the oceans and seas and also in mainland water bodies. The height of the waves in the reservoirs is lower than that in the seas: the maximum height is often up to 4 m, often within 2–3 m, although with the same wind strength, the height of the waves in freshwater reservoirs is higher than in the sea due to the lower density of fresh water;
- *the height and steepness of the coastal slope.* The intensity of abrasion is significantly greater on high steep banks than on gentle slopes;
- *changes in sea level and currents.* Abrasion intensifies with transgressions that occur during global periodic sea level rise. Accordingly, regression – the retreat of the sea weakens abrasion. The tides, which accumulate clastic material along the coastline play a significant role in the development of marine abrasion
- *lithological composition, structure and degree of weathering of rocks.* Loose sand and clay rocks, weak semi-rock chalk and marl and also highly fractured rock are most susceptible to destruction by abrasion.



*Fig. 3.9.10. The highest regular waves in the world, Nazare, Portugal.
An underwater canyon is close to the coast on this site, which interferes with
incoming waves and significantly increases their height to 24–26 meters*
<https://cattur.ru/europa/portugal/samye-bolshie-volny-nazare.html>

Rocks according to the degree of resistance of abrasion are divided into 8 classes. The most stable rocks are class 1: strong crystalline rock – granites, quartzites, diorites, gneisses, tectonic breccias; The least stable rocks of class 8 are permafrost sedimentary clastic rocks and ice itself and class 7 are soluble chemically pure limestones, chalk, rock salt, gypsum, anhydrite, among others.

The onset of the sea (moving inland) and the retreat of the coast depends on the resistance of rocks to abrasion. The northwestern coast of France, made up mostly of weak deposits, recedes at a rate of 15 to 35 meters per year. But where the coasts are composed of very strong rocks, very ancient coastal profiles that existed even before modern times may remain intact. As such, on the Kola Peninsula between the Barents and the White Sea, granite coasts still have traces of glacier movement, i.e. over the past 10 thousand years; these slopes were practically not changed by abrasion.

Chemical abrasion is most common on shores composed of limestones and other soluble rocks. For artificial reservoirs, it is essential to predict the process of shore recession according to the salinity or components of rocks, composing the actual shores.

Protection against the negative effects of abrasion

Shores of the seas and freshwater reservoirs can be protected from abrasion by installation of passive and active types of protective engineering structures and the implementation of various existing preventive measures.

Shore protection structures that resist the impact of sea waves themselves and temporarily delay the destruction of the shore are said to belong to the passive type. These are various stones, wave-breaking walls, embankments, straight and stepped sloping structures (Fig. 3.9.11, 3.9.12, 3.9.13).



Fig. 3.9.11. Coastal protection using rock boulders in Estoril coast, Portugal
<https://geologicalintroduction.baffl.co.uk/?p=183>



Fig. 3.9.12. Protecting the embankment with the help of stable laying of blocks in Bandirma, Sea of Marmara, Turkey. Photo by V. Iegupov



*Fig. 3.9.13. Passive protection of the embankment
by the wave-breaking wall in Sevastopol, Crimea*
<http://ecodevice.com.ru/photogallery>

The main disadvantage of passive structures is their fragility, especially when built on steep banks with intense abrasion. There are known cases of destruction of expensive embankments only 8–10 years after their construction.

It is more efficient to use massive figured blocks, for example, tetrapods (Fig. 3.9.14), which are designed for coastal protection and fencing structures and are made using high strength concrete with compressive strength of at least 30 MPa. Tetrapods and similar structures (Fig. 3.9.15) must be frost and water resistant.



Fig. 3.9.14. Tetrapods are one of the most effective structures for shore protection structures.
Photo by V. Iegupov



Fig 3.9.15. The use of reinforced concrete elements of various shapes for protection against abrasion
<http://ecodevice.com.ru/photogallery>

The fundamental difference between the shore protection structures of the active type and the passive one is that they serve not only to attenuate the energy of the waves, but also to accumulate sediments that make up the beaches and at the same time, prevent them from being washed away. The main examples of structures that hold the beaches are the buns and underwater wave breakers.

Buns – these are concrete massifs, dams from concrete blocks (Fig. 3.9.16 a), stone piles, located at right angles to the shore line (Fig. 3.9.16 b). Their main purpose is to prevent the movement of sand and pebble deposits along the coast, forming a beach, wide enough to protect the coast from erosion. The distance between the buns usually depends on the length of individual buns.

Wave breakers are dams made of stone or concrete blocks, and, unlike buns, are built in parallel to the protected shore at a distance of 30–50 meters (Fig. 3.9.16 c). With strong unrest in the water area, wave breakers are arranged in several parallel rows. They contribute to both direct protection of the coast from the waves and the retention of beach sediment material.

The simultaneous construction of buns, breakwaters, wave walls and if necessary, periodically addition of sand and coarse material to beaches, proves effective. Measures for the prevention of abrasion are mandatory, for example, monitoring and regulating the flow of rivers entering the sea in order to prevent a decrease in the volume of debris carried by rivers; preservation of the natural soil and plant soil layer, trees and shrubs in the strip adjacent to the beach and shore protection structures (Fig. 3.9.17).



a



b



c

a [https://studfile.net/](https://studfile.net/preview/1867372/page:15/)

[preview/1867372/page:15/](https://studfile.net/preview/1867372/page:15/)

b <https://www.turskidki.ru/articles/tury-v-sochi-v-iyune-rascvetaem-vmeste-s-prirodoj-kavkaza/>

c <https://metro.co.uk/2012/12/20/gallery-heavy-rain-and-flooding-across-the-uk-december-20th-2012-3324972/>

*Fig. 3.9.16. The main shore protection structures:
a – a dam of tetrapods; **b** – buns; **c** – wave breaker*



*Fig. 3.9.17. The accumulation of beach sediments between the buns in Sochi, the Caucasus
<https://tvkrasnodar.ru/news/v-sochi-otkryli-goryachuyu-liniyu-dlya-zhalob-na-plyazhi/>*

The main types of measures and structures for protecting coasts from water erosion and abrasion in accordance with DBN V.1.1-24: 2009 (Ukraine) are given in table. 3.9.1.

Table 3.9.1

The main types of shore protection facilities and events

Type of facility	Purpose of the measures and conditions of use
I. Full protection. 1. Along the coast: - retaining coastal walls (embankments) of a wave breaker profile made of monolithic and precast concrete and reinforced concrete, stone, piles; - sheet pile walls reinforced concrete and metal; - step mountings with strengthening of the base of terraces; - massive breakwaters. 2. Sloping: - monolithic coatings of concrete, asphalt concrete, asphalt; - coating of prefabricated plates; - a coating of mesh blocks filled with stone (gabions); - coating of synthetic materials (geotextile) and recycled materials.	On the seas, reservoirs, lakes and rivers for the protection of buildings and structures of I and II classes, roads and railways, valuable land. Mostly on rivers and reservoirs. On the seas and reservoirs with steepness of slopes of more than 15°. On the seas and reservoirs with a stable water level. On the seas, reservoirs, rivers, slopes of retaining earthen structures with sufficient static stability. At waves up to 2.5 m high. On reservoirs, rivers, slopes of earthworks (with gentle slopes and low waves – less than 0.6 m).
II. For damping waves. 1. Along the coast: - permeable structures with a porous pressure face and chambers for damping waves. 2. Sloping: - sketches of stone or shaped blocks; - artificial free beaches.	On reservoirs, rivers, slopes of earthworks in the absence of recreational use. At seas and reservoirs in the absence of recreational use. On the seas and reservoirs at slopes (less than 10°) with a stable water level.
III. To hold the beaches. 1. Along the coast: - underwater banquets made of concrete blocks, stone; - loading with inert materials in local areas (stone banquets, sand alluviums etc.); 2. Cross: - buns, jetties, spurs (gravity, pile, from shaped blocks, etc.).	On slightly rough seas and reservoirs. In reservoirs with relatively gentle slopes. On the seas, reservoirs, rivers during the creation and consolidation of natural and artificial beaches.
IV. Special 1. Regulatory: - river flow management (regulation of water discharge, combining watercourses into one estuary); - low flooded half-dams located at an angle towards the stream; - structures imitating natural landforms; - relocation of sediments along the coast, the use of underwater quarries, etc. 2. Guiding: - dams from stone or soil; - massive directing spurs or half-dams. 3. Sloping: - artificial fixing of slope soil.	On the seas, to increase the volume of sediment, bypass areas of low output along the coastal stream. Adjustment of the bottom sediment regime and protection of the banks of the foothills of the river from erosion. At reservoirs to regulate coastal processes. On the seas and reservoirs to regulate the balance of sediment. On rivers to protect the banks of the rivers and deviate the flow from erosion of the shore. On rivers with low flow rates to divert the flow. On reservoirs, slopes of earthworks at wave heights of up to 0.5 m.

If shore protection structures also serve as landslide protection, collapse or other types of engineering protection, the requirements of the relevant sections of regulatory documents should be taken into account when determining the loads and impacts. The stability of such structures is established on the basis of the stability conditions of the entire slope as a whole, taking into account all existing loads and impacts.

Test questions to chapter 16. Abrasion, coast processing

1. What is abrasion?
2. The spread of abrasion processes and its negative consequences.
3. Causes of coastal abrasion.
4. Morphology of the sea coast.
5. Definition of cliff, bench, beach.
6. The main types of abrasion.
7. Factors causing abrasion.
8. Protection against abrasion processes.
9. The main types of shore protection facilities.

Chapter 3.10. QUICKSAND. SOIL LIQUEFACTION

Flooded loose soil, most often sand and sandy loam, capable of passing into a fluid state by water infiltration or under the influence of mechanical vibration, is called *quicksand* and the phenomenon is also known as *liquefaction*. If open soils in various mining works possess quicksand properties, then the soils are susceptible to quickly liquefy and move like a heavy viscous liquid, almost a suspension similar to very liquid dough. A quicksand is able to spread, slide along the walls of pits and move with water during opening of trenches, mines, ditches and channels located below groundwater (Fig. 3.10.1).



Fig. 3.10.1. Quicksand in the construction pit
<http://s001.radikal.ru/i193/1304/9f/5e40a1f7f302.jpg>

Quicksand properties, under certain conditions can also be manifested in gravel deposits, silty clays, loess and other soils with significant porosity and low density. As such, quicksand cannot be attributed to some specific types of soils; instead it is particular states of various disperse soils.

The main reason for the manifestation of quicksand properties in soils is a sharp drop in hydrodynamic pressure that occurs during the opening of foundation pits, trenches, underground tunnels, etc. In a quicksand state, disperse soils lose their original structural bonding between individual particles and suffer loss of stability.

Quicksand is most often encountered in river valleys, on alluvial and coastal plains, in marshy lands, among loose sedimentary rocks in the form of layers or lenses and may be located at various depths. A quicksand possesses a particular, almost hermetic volume in the thickness of the soil with an elongated form, most often in the range of 2–10 meters thick, in which fine soil particles (sand, clay and colloid), highly saturated with water are subjected to hydrostatic pressure. Quicksand is characterized by high mobility that occurs when soils are open and possess high moisture (about 50%) and porosity (40–60%).

There are two types of quicksand – pseudo (false) and true.

Pseudo-quicksand is ordinary sand of various sizes, and sometimes even gravelly soils that do not have structural bonds between particles. Such soils pass into a quick condition only under the influence of high hydrodynamic pressure of moving underground waters. Sand and smaller particles in a suspended state completely lose contact and friction between themselves. Pseudo-quicksand very easily releases free inter particle water, which may be clear or slightly cloudy. When dried, they form a loose or slightly cemented mass.

True quicksand is most often clayey soil or silty sand with special structural bonds between particles. Soils of this type are colloidal systems resembling thick jellies known as gels in physical chemistry. Structural bonds in true quicksand are caused by the presence of very small clayey particles, less than 0.001–0.0001 mm in size, and colloidal particles with high hydrophilic properties, i.e. the ability to attract water molecules. These particles are surrounded by a film of adsorbed water which decreases their adhesion and reduces their permeability. Additional mobility of true quicksand is caused by mucus, resulting from the vital activity of microorganisms, reducing friction and releasing gas bubbles, which create additional pore pressure in the quicksand. Microorganisms process organic and mineral substances, contained in ordinary water saturated sand, and transform the latter into a true quicksand.

Clay particles turn the water protruding from the quicksand into a greyish-white color, so the true quicksand can be determined by the accumulation of water in the pits in the form of “cement milk”. A hand-molded spherical lump of sand, from one of the pits may appear to be just a damp soil mass and almost does not release water, but gradually turns into dough. Slow release of water is a very characteristic sign of true quicksand. With prolonged drying, true quicksand turns into a rather strongly cemented mass.

During engineering-geological and geotechnical surveys on site, water-sand “plugs” rising to the surface during drilling of a borehole, is indicative of the soil’s possible quicksand properties.

The presence of quicksand complicates civil engineering works, especially mining works because the quicksand seeks to break through any free open space (Fig. 3.10.2, 3.10.3).

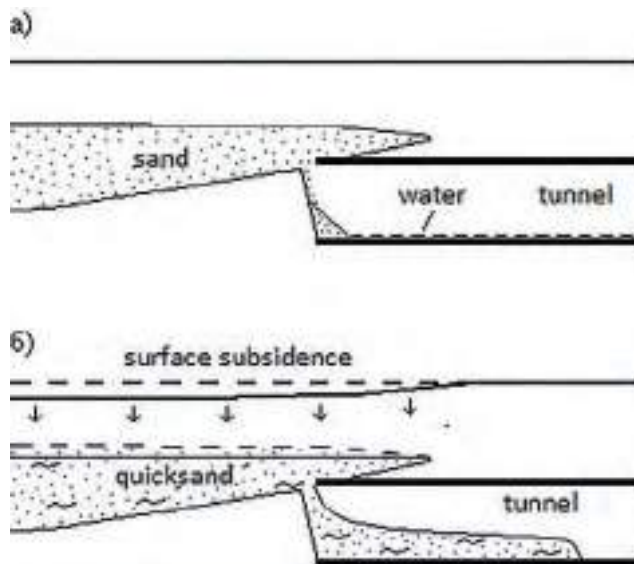


Fig. 3.10.2. Scheme of a breakthrough into the tunnel of (a) false quicksand and (b) true quicksand

<http://ok-tr.ru/studopediaru/baza5/3736518134621.files/image088.jpg>

During excavation works in quicksand, fragments of the excavated walls of the dug pit may soon after digging, begin to swell and collapse. Flooded soil gradually spreads at the bottom of the pit; the surface of this floating mass has a different slope depending on the degree of saturation with water – with an increase in natural moisture, the slope decreases.

The angle of repose of the quicksand (α) at a moisture content (w) of 12.5% is 19–37°; at $w = 13.5$ –15%, $\alpha = 4$ –5°; at $w = 17.5\%$, $\alpha = \sim 0^\circ$. True quicksand is characterized by an increased amount of deformation under load in comparison with other soils.

Movement of quicksand underneath foundations of structures built on river or sea quicksand sandy sediments may be extremely risky for the stability of such structures. The displacement of water-saturated sand masses often occurs

suddenly, and sometimes huge soil masses come into motion. Seismic tremors are extremely favourable to trigger movement of quicksand.



Fig 3.10.3. The consequences of a quicksand breakthrough in a subway tunnel under construction, Moscow, Russia
http://biryulevo.ru/_fr/46/8590220.jpg

Quicksands are also formed under the influence of rising groundwater (Fig. 3.10.4), as well as in air, supersaturated with hot water vapour, in deserts. Due to the presence of a thin film of water coating the sand particles, the adhesion and friction between them becomes extremely low, and as a result, heavy objects, vehicles, people and animals on the surface of the sand get stuck. Quicksand is found in places where there is a rising groundwater level, near the coasts, lakes and rivers. They can also be found far from the coast, mainly in sandy deserts. In accordance with the location and mechanism of action, varieties of quicksand with wet and dry surfaces are distinguished.

On some sea coasts, for example, in England (Fig. 3.10.5, 3.10.6), Denmark, and French Britain, the hydrostatic pressure of water in soils located within the tidal zone, results in the formation of quicksand, which poses a serious danger to life.

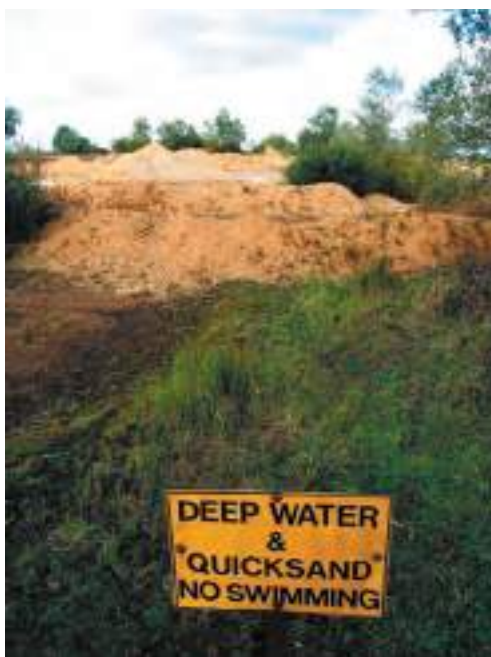


Fig. 3.10.4. Pattern of quicksand formation on river banks
<http://ribalych.ru/wp-content/uploads/2015/06/40160.jpg>



Fig. 3.10.5. Quicksand on the coast near Liverpool, England
Photo by Iu. Iegupov

In Alaska, the shores of the longest Tarnaghen Fjord extending along 150 km are a continuous strip of quicksand; they are also common on the coasts of Sable Atlantic Island near Canada, where they absorb everything that remains of shipwrecks.



a



b



c

Fig 3.10.6. Wet quicksand

a https://upload.wikimedia.org/wikipedia/commons/b/ba/Quicksand_warning.jpg

b. <http://ganbox.ru/wp-content/uploads/2011/08/02208861.jpg>

c http://mirkosmosa.ru/download/content/201511/image_563737c02c7ba6.91390198.jpg

Sable Island (Fig. 3.10.7) is one of the most dangerous for sailing among all the islands appearing on the sea navigation charts. Sable is a “wandering” island, it moves as a result of the impact on the mainland shallows of the currents occurring in this place: the cold Labrador and warm Gulf Stream. The sand from which the island is composed is constantly eroded at the western end, moves under water, and is deposited on the eastern side.



Fig 3.10.7. Sable Island

<https://commons.wikimedia.org/wiki/File:SableIsland1.jpg>

The geographical coordinates of the location of the island, as well as its shape and the dimensions on maps, quickly become obsolete. So, on French, English, Italian maps

of the 16th century, the length of the island varies from 278 to 370 km, and according to modern data, Sable is a long shallow island with a length of 44 km and a width of 1.5 km, stretching from east to west and moving eastward with an average speed of 230 m/year.

Sable Island is almost flat – its maximum height is 34 m above sea level but extremely difficult to notice from the sea during autumn and winter storms with 10–15 m high waves. Many captains of ships, even in clear weather, often failed to locate the danger until their ships got stranded. Sable's quicksand has absorbed ships sailing around and washed them away in 2–3 months (Fig. 3.10.8).



Fig. 3.10.8. Quicksand – Sable Island
https://x-files.site/articles.php?article_id=4775

It has been documented that ships up to 120 m long with a load of 5000 tons disappeared without leaving trace in the sands. The number of ships that disappeared and of people who left their lives on the shores of this small piece of land is not exactly known. The last victim was the large American steamboat Manhassent in 1947 and after that tragedy, 2 lighthouses and a radio tower was installed on the island, to avoid such events.

Quicksand in the Sahara Desert is associated with rising flows of superheated water vapor (Fig. 3.10.9). In New Zealand, quicksand is located on the sea coasts (Fig. 3.10.10).



Fig. 3.10.9. Dry Sahara quicksand

http://mirchudes.net/uploads/posts/2013-11/1384533937_zybuchie-peski.jpg



Fig. 3.10.10. New Zealand wet quicksand

<http://www.topglobus.ru/krasne-fotky/staty/253/low-tide--abel-tasman-national-park--south-island--new-zealand.jpg>

Construction in quicksand conditions

In a state of rest and natural density, quicksand has a relatively high bearing capacity, but with external interference they lose their bearing qualities and turn into a fluid state. Within a confined space, quicksand can be relatively strong, but the quality control of the boundaries of such a space is very difficult. Bulging on quicksand causes swelling of the ground surface, deformation of buildings and structures, and landslides on the slopes. Open drainage in quicksand soils can cause suffusion on the walls of the pit and eventually, their flooding (Fig. 3.10.11).



Fig. 3.10.11. Breakthrough of quicksand in an excavation in Kiev
<http://kievnews.glavcom.ua/media/o-00006717-n-00014261.jpg>

Dangerous cutting of slopes can also trigger liquefaction, since the water that saturates the quicksand is practically not compressible and very sensitive to vibration and dynamic shocks, even at far distances from the source of vibration.

The property of sands to acquire state of quicksand, and then regain stability thereafter, is exploited when driving piles. The pile is initially driven with a light gentle strike which allows its penetration in the sand. Shock-vibration impact destroys the structural bonds between particles of quicksand. After a while, in a stable state, the structural strength of the sand (which it possessed in natural conditions) is restored, and the pile acquires a sufficient bearing capacity.

To protect against quicksand, quite expensive and complex technical measures and means are required, and the measures taken do not always give the expected results. Often it becomes necessary to increase the depth of construction pits, place the base of the foundation below the layer of quicksand or opt for pile foundations and transmits the loads in underlying deep strong soils. In the choice of methods for protecting the designed buildings and structures, the type of quicksand is of utmost importance: true quicksand is much more dangerous than pseudo quicksand.

Methods of protection against

1 – artificial drainage of quicksand soils during the entire construction period by open drainage of incoming water directly from the pit and the use of needle filters for pumping ground water beyond the contour of the pit;

2 – protect pits from quicksand using metal sheet pile walls;

3 – artificial change of the structure and physical properties of quicksand with the aim of stabilization (deprivation of mobility) using cementitious additives, freezing and electrochemical methods;

4 – use of the caisson method during underground mining.

Any one of the above methods can be used for pseudo-quicksand. In the case of true quicksand, the use of only sheet piling, freezing and electrochemical stabilization is effective. The possibility of draining quicksand depends on their water permeability, characterized by a filtration coefficient (k_f). At a relatively high permeability where $k_f > 1$ m/day, water is pumped out from drainage wells; at average values of k_f in the range of 1.0–0.2 m/day, special needle-filter units should be used that allow drainage to a depth of 5–6 m, and with special-purpose needle filters – up to 12–15 m and more. At low values of $k_f < 0.2$ m/day, needle filters are used in combination with electro or vacuum drainage.

Sheet piling, driven in the underlying firm soil is used to protect construction pits from quicksand. A sheet pile wall driven through the layer of quicksand retains the lateral pressure exerted. Water penetrating the pit is pumped out, and solid soil particles are retained by the wall.

The method of stabilization using cementitious additives consists of injecting superfine cement, lime, fly ash or sodium silicate into the quicksand, if necessary, the process is followed by a hardener. The solutions react with the soil particles and gradually harden, forming a monolith. This method can be applied in the case of a sufficiently high permeability of quicksand ($k_f > 0.5$ m/day) and it requires large material and labour costs, but is proven to be very effective.

Artificial freezing is carried out by circulating a solution of CaCl_2 cooled to a temperature of minus 20–40 °C in the well system to create a zone of frozen waterproof soil around the pit. It was previously believed that freezing quicksand is a temporary and unreliable measure. However, the experience of building several underground facilities, in particular, the “Yuzhny Vokzal” station of the Kharkiv Metro, has shown high efficiency and reliability of the use of quicksand freezing during construction in dense urban areas (Fig. 3.10.12).

The freezing of soils around underground mine workings and pits was carried out continuously for five years. For this purpose, a total of 24,000 m of wells were drilled and equipped, of which about 15,000 m for station tunneling only. For the construction of the station itself, a 40x40 m pit was excavated with a depth of 13 meters, which was enclosed by a sand and ice bearing wall. This wall was buried in the underlying waterproof clay layer and consisted of 6 m thick frozen quicksand. The effectiveness of the method is evidenced by the fact that the construction project allowed the settlement of the massive building of the “South Station” to an extent of 8 mm only, compared to 100 mm allowable settlement.



Fig. 3.10.12. Freezing quicksand soils during the construction of the metro station “Yuzhny Vokzal” in Kharkov (1971)
http://www.ljplus.ru/img3/e/m/ems_viking/stroit_20yagni.jpg

For the installation of vertical and horizontal underground structures, caisson chambers with increased pressure are used to balance the water pressure of the quicksand. A caisson (from French caisson – box) is a metal enclosing structure, tight enough to create a working chamber free of water under water or in saturated soil. Water from the chamber is displaced by compressed air under pressure up to 3–3.5 atm (Fig. 3.10.13).

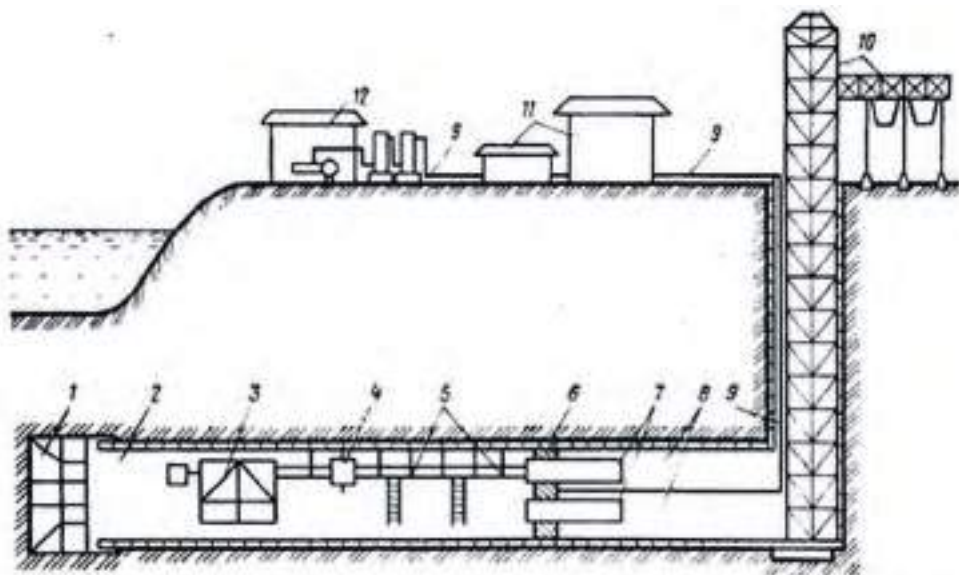


Fig. 3.10.13. Tunnel driving pattern using a horizontal caisson: **1** – tunneling shield; **2** – working area; **3** – tubing; **4** – safety screen; **5** – emergency platform; **6** – sluice partition; **7** – gateway devices; **8** – zone of normal pressure; **9** – pipelines of compressed air; **10** – mountain complex for tunneling; **11** – household premises; **12** – compressor
https://sinref.ru/000_uchebniki/03410metro/015_stroitelstvo_metro_vlasov_1987/030.htm

Liquefaction

Liquefaction of soils is the process by which the soil loses the properties of a solid and begins to behave like a dense viscous liquid (quicksand). Liquefaction is characteristic of dry-flowing soils with high water saturation, for example, these can be sands with inclusions of silty particles or clay-impermeable clay interlayers. Young Holocene sands and silts are most prone to liquefaction, with particles predominantly of the same size within a layer thickness of at least one meter. Such formations often occur near river beds, with accumulated deposits of modern alluvium.

Soil liquefaction most often occurs during earthquakes, because during the passage of seismic waves, soil particles begin to oscillate at different frequencies, and most of them lose their inter-particle contact. As a result, the soil turns into a fluid with suspended sand grains. Sandy soils have a relatively low density and have high water saturation with a high level of groundwater. In a normal stationary state, the soil is stable because the sand particles are in contact with each other, ensuring sufficient adhesion. During an earthquake, water fills the space between the particles and the distance between them increases, so the cohesion between the particles is lost.

Before the soil returns to its original stable state, buildings can be destroyed due to uneven settlement or literally completely sinking into the ground (Fig. 3.10.14).

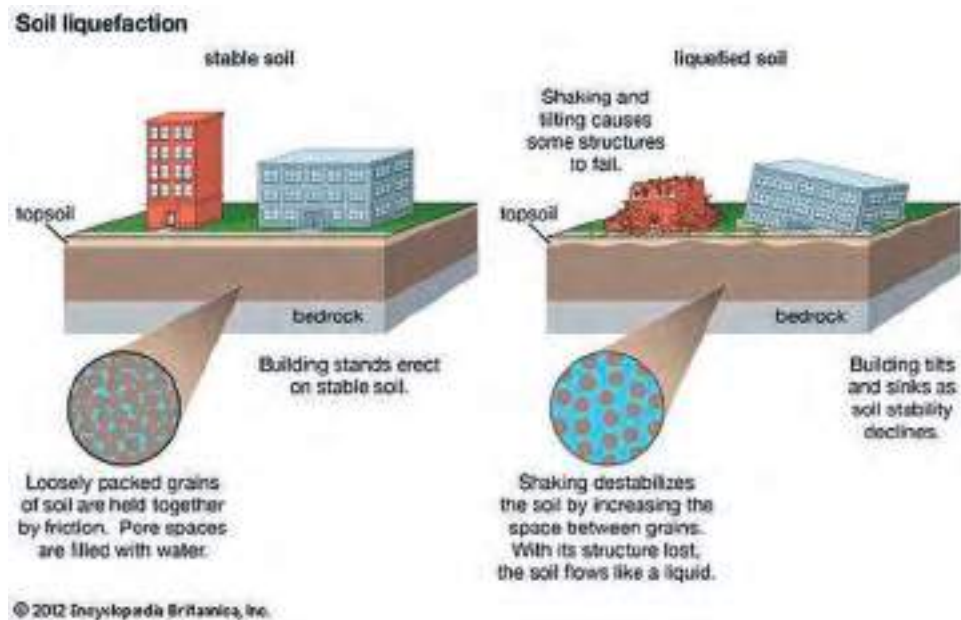


Fig. 3.10.14. Diagram of the process of liquefaction of soils and its negative consequences
<http://www.maipark.com/assets/uploads/Erly.pdf>

There are many disastrous consequences caused by the above described process. In the 17th century, sand liquefaction led to the absorption of almost the whole city of Port Royal – the famous pirate capital of the Caribbean, which was located on a 16 km sand belt on the island of Jamaica. On June 7, 1692, an earthquake occurred during which sand in the city suddenly liquefied and buildings and people began to sink in it. Over two thousand people became

victims of the disaster, several dozen ships sank in the harbor and 1800 buildings of the city sank. Historical chronicles contain descriptions of the tragedy. Some residents of the city instantly and completely fell into the ground, others stuck to their knees or to the waist. After the earthquake, which lasted six minutes, liquefied sand instantly turned into a solid cemented mass, which tightly gripped people and most of them could not get out. At the site of the buried city in the 19th century, remains of the walls of fallen buildings could still be seen. But in 1907, another earthquake occurred which swiped away all the evidence of the tragedy. A modern photo of one of the existing old buildings is shown in Fig. 3.10.15.



*Fig 3.10.15. An old building, partially submerged
in quicksand, island of Jamaica (photo 2005)*
<https://www.flickr.com/photos/muss/2049396906/>

In relatively recent times, severe damage caused by soil liquefaction during earthquakes occurred in 1964: on March 27 near Anchorage on the coast of Alaska and on June 16 in Niigata in Japan (Fig. 3.10.16).



Fig. 3.10.16. Destruction of residential buildings during liquefaction of soil 16.06.1964, Niigata, Japan
[http: //learnlearn.net/verdensrommet,jorda/Vannb.htm](http://learnlearn.net/verdensrommet,jorda/Vannb.htm)

Liquefaction mainly occurs in lowlands, on sea coasts, near rivers, lakes and bays. For example, in the San Andreas Fault and other areas of California with high seismic activity, there is a danger of liquefaction of the soil on the shores of San Francisco Bay, on the Pacific Ocean and in the vicinity of Los Angeles.

During earthquakes, water from liquefied soil tends to move towards a zone of lower pressure, that is, to the surface of the earth. The captured soil particles are also carried to the surface and the phenomenon of “sand boiling” is observed (Fig. 3.10.17)



Fig. 3.10.17. Sand Boils, Loma Prieta, SF, USA 1989
<http://www.maipark.com/assets/uploads/Erly.pd>

Lateral spreading in ground masses often leads to disruption of communication network (Fig. 3.10.18).



Fig. 3.10.18. Pipeline rush during lateral spreading, Northridge, USA, 1994
<http://www.maipark.com/assets/uploads/Erly.pdf>

Liquefaction was a major cause of damage in the Marina, San Francisco, USA area after the earthquake in Loma Prieta in 1989 and in the port of Kobe, Japan as a result of the Great Khan's earthquake in 1995. Huge damage was inflicted on housing in Christchurch, New Zealand, the earthquake in Canterbury in 2010, and especially after the aftershocks in Christchurch in early and mid-2011 (Fig. 3.10.19).



Fig. 3.10.19. Submersion of a car in liquefied sand, 22.02.2011, Christchurch, New Zealand
<http://www.maipark.com/assets/uploads/Erly.pdf>

Liquefaction control measures

To prevent the negative consequences of soil liquefaction, the following measures are used:

- identification of areas of potential soil liquefaction during geotechnical surveys;
- avoid construction in hazardous locations whenever possible;
- technical reclamation (improvement) of soils. To reduce the risk of liquefaction, three methods are used: vibroflotation (vibration with simultaneous artificial introduction of pressurized water into the soil), drainage (removal of water from the soil formation) or removal of the soil layer prone to liquefaction.
- special engineering building structures and foundations.

In various countries, normative documents have been developed for construction on liquefied soils, for example, SNI 8460: 2017 (Indonesia), containing the following recommendations:

- the use of shallow foundations is not recommended for soils with a high liquefaction potential, unless technical reclamation methods are used to eliminate the liquefaction conditions;
- when calculating pile foundations, the friction resistance in soil layers with potential liquefaction must be ignored;
- for soils with a high liquefaction potential, the use of driven piles and prestressed concrete columnar structures is not recommended;
- the use of steel supports is recommended taking into account the flexibility and ductility of the foundation system.

Test questions to chapter 3.10. Quicksand. Soil liquefaction

1. What are quicksand soils?
2. Conditions of occurrence and the reasons for the movement of quicksand.
3. What is the difference between true and pseudo quicksand?
4. What is the danger of quicksand for construction?
5. Definition and types of quicksand.
6. The causes and danger of quicksand.
7. Methods to deal with quicksand.
8. Construction in the conditions of quicksand.
9. Causes of soil liquefaction.
10. Construction in zones underlain by soils prone to liquefaction.

Chapter 3.11. UNDERMINING AREA

Undermining area is a territory on which uneven, rapid or gradual subsidence of the earth's surface and settlement of the foundations of buildings or structures can occur as a result of underground mining activities.

Underworking of territories is mostly carried out for the following types of works:

- construction of underground structures for mining and extraction of coal and minerals;
- underground tunneling, collectors, construction of subways and other underground urban infrastructure;
- gas and oil production in large volumes, intensive pumping of groundwater.

Currently, every eighth ton of coal is mined under built-up areas. For example, in Donbass region (Ukraine), 120 cities and towns are located in zones under influence of underground mining activities. As a result of underground works, smooth troughs of displacement of the earth's surface (subsidence) or sharp dips (shift trough and mining damage – collapse of plots of land under the influence of underground mining) can occur.

Trough – a depression appears on the earth's surface due to horizontal and vertical shifts (inclination, curvature due tension or compression) which occur in connection with underground mining (Fig. 3.11.1, 3.11.2). The magnitudes of the deformations depend on the depth and area of mining operations, the volume of soil extracted during tunneling or the construction of underground structures.

The trough boundary is the defined as the line connecting the points with the subsidence of the earth's surface by 10–15 mm. Within the trough, a zone of dangerous soil movement is observed, where shifts and deformations pose a direct threat to undermined territories, buildings and structures and a zone of cracks on the peripheral parts of the soil mass less actively threatening structures on the surface. The dimensions of these zones depend on the strength properties of the soil mass and the angle of incidence or dip angle of the strata (ore deposits).

Dips and troughs formed on the surface vary in shape and size. For example, round shaped failures occur after the development of medium size reservoir deposits of thickness between 1.5–3 m and larger, with horizontal or slightly inclined occurrence. With significant reservoir thickness, dips can form in the form of several separate terraces. Dips in the form of extended canyons are

formed over the developed space of thick steep deposits. For example, in Kuzbass region in Russia, tens of kilometers long failures are reported.



Fig. 3.11.1. Destruction of buildings during the subsidence of the earth's surface in the form of a trough

<http://www.charlesburrows.com/earth/animations.visuals/03SURFACE/sinkhole.jpg>

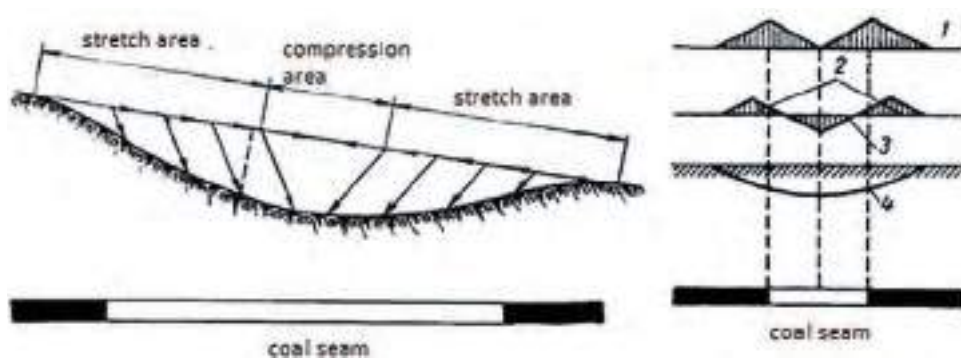


Fig. 3.11.2. The scheme of movement of the points of the earth's surface (a) and the distribution of deformations in the subsidence trough during the development of the coal seam (b): **1** – horizontal displacement; **2** – stretching areas; **3** – compression area; **4** – surface subsidence (source: Kamerstein A. G. Pipeline construction in mining areas. Moscow, Stroyizdat, 1976)

In cities, troughs of displacement and dips can occur as a result of tunneling and subway construction, large underground collectors, among others.

The surface deformation diagram in the form of a trough above the tunnel is shown in Fig. 3.11.3.

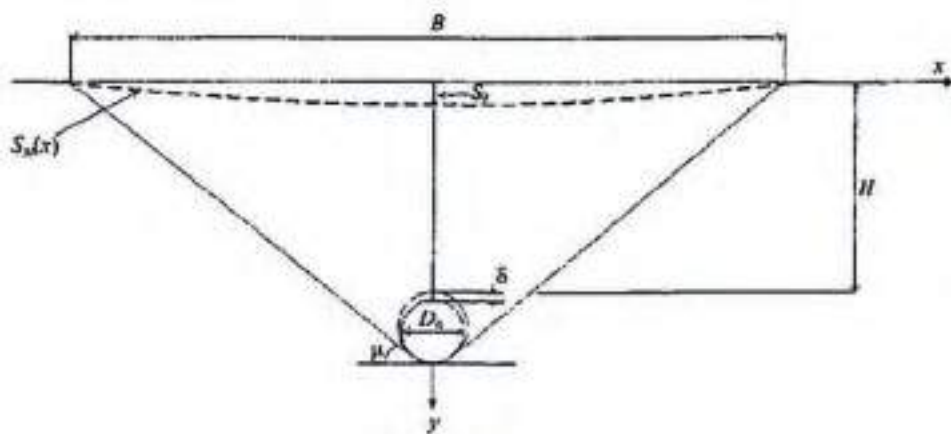


Fig. 3.11.3. Scheme of the trough of subsidence over the underground tunnel excavation (SP 21.13330.2012)
<http://files.stroyinf.ru/data2/1/4293801/4293801657.files/x023.jpg>

S_0 – the value of the maximum subsidence of the earth's surface under the influence of underground mining, which normally occurs directly above the underground cavity;

B – the width of the trough, i.e. the distance between surface points at which subsidence is zero or not more than 10–15 mm;

N – the depth of the roof of the worked-out space during the tunneling;

D_0 is the characteristic size of the underground mine;

μ – boundary angle of displacement (angle of inclination of the lines connecting the output contour with the boundary points of the displacement trough);

δ – the amount of technological exhaustion (the difference between the actual diameter of the worked output and the outer diameter of the lining of the tunnel).

An example of a failure due the construction of a subway tunnel is shown in Fig. 3.11.4, a failure within the underground mined area in Fig. 3.11.5, remediation of a failure, using concrete filling, in fig. 3.11.6.



Fig. 3.11.4. Failure in the construction of subway in Guangzhou, China
http://i.dailymail.co.uk/i/pix/2013/01/29/article-2270006-173AACAB000005DC-44_1024x615_large.jpg



Fig. 3.11.5. Failure in the mined-out space during iron ore mining (the central market of the city of Kriviy Rig)
<https://encrypted-tbn2.gstatic.com/images?q=tbn:ANd9GcQK5VKidl73zwhmGq8JUrmkSpDIHHVHlPX9TOU84w3FtP5e0Xn>



Fig. 3.11.6. Remediation of failure that occurred during the construction of a subway using concrete filling in Wuhan, China
<http://cs7054.vk.me/c7005/v7005554/2499b/TSSVvDmqhPg.jpg>

Protection measures for buildings and structures in the undermining area are carried out in accordance with regulatory documents and the following sets of measures are envisaged for the protection of buildings and structures under the influence of underground works:

- a) *geological and geotechnical*, reducing or eliminating deformations of the foundations of buildings and structures;
- b) *structural*, reducing the sensitivity of buildings and structures to deformations of their base, as well as deformations of ground structures.

Changes in the mode of operation and pre-planned repairs can also be considered as protection measures.

Geological protection measures include:

- full or partial filling of the developed underground space by borrowed material;
- development of formations within a time frame in an orderly sequence;
- do not completely extract all minerals, for stability of the area;
- preliminary strengthening and fixing of overlying formation, including the installation of advanced protective arches;

- the use of tunneling complexes with a closed face and compensating load;
- reduction of diameters and other geometric dimensions of mining areas;
- an increase in the distances between the mine works and the foundations of active buildings and structures;
- injection of cement and other hardening mortars into the space behind the lining.

Geotechnical protection measures include:

- measures to protect the soil of the base from deterioration and reduce deformation of the bases and their sensitivity to shifts;
- reinforcing the rigidity of foundations and frameworks of overlying buildings and structures;
- transfer of loads from buildings and structures to underlying soil layers which are not subject to deformations;
- separate the soil bases under influence of overlying buildings and structures by erection of retaining walls between separate mining zones;
- reduction of differential settlements and leveling of buildings and structures by method of soil extraction (drilling) from underneath the soles of foundations;
- compensatory injection of hardeners into the soil;
- arrangement of temporary compensation trenches to reduce efforts from horizontal deformations of the bases.

Structural protection measures include:

- separation of individual elements of buildings and structures with expansion joints;
- strengthening of individual structural elements or the whole structure reinforced concrete belts;
- installation of metal ties-struts;
- leveling the verticality of buildings and structures with jacks.

Protection measures should be selected on the basis of a technical and economic comparison of available options, taking into account the level of responsibility, design features, minimal impact on the operation modes of protected structures, the results of forecasts of deformations of their foundations, as well as existing experience. The first group of protective measures is normally preferred, except of during the extraction of particularly valuable minerals.

If these measures are insufficient or they cannot be implemented, then geotechnical and structural measures that will not compromise the stability of the protected structures should be applied.

Test questions to chapter 3.11. Undermined territories

1. What territories are called undermined territories?
2. Causes of deformations during undermining works.
3. The causes of dips and troughs.
4. Protective measures for buildings and structures during underground works.

Chapter 3.12. FLOODING OF TERRITORIES BY GROUND WATERS

Groundwater flooding is an engineering-geological process that manifests itself in certain environmental conditions in urban areas and agricultural lands, in which there is a rise in groundwater (GW) table and a significant increase in soil moisture. When GW levels are excessive, construction conditions and operation of buildings and structures are disrupted and there are destruction of green spaces, salinization and waterlogging of land (Fig. 3.12.1). This process occurs due to the combined impact of a whole range of causes and factors of both natural and anthropogenic (technogenic) origin.

In cases of prolonged flooding of territories, a number of negative consequences are observed. The development of the flooding process is accompanied by a change in the physical and mechanical properties of soils and a decrease in the bearing capacity of soil bases, as a result of which the destruction of buildings and structures occurs. During a flood – building basement is flooded, water-salt regime changes in the soils of the aeration zone, corrosion of metal structures and degradation of vegetation due to the submersion of the root system occur, the living conditions of the population are sharply worsened due to increased humidity in the premises, mosquitoes, etc. In areas with difficult engineering and geological conditions, flooding activates the development of harmful and dangerous geological processes such as landslides, erosion and salinization of soils, waterlogging, karst, suffusion, and quicksand.



Fig. 3.12.1. Waterlogging during flooding

<http://www.casaycosastandil.com/image/13197/drenaje%20pobre.jpg>

Significant material loss entailing poor living conditions on flooded lands affect the population with an increasing proliferation of diseases.

The current situation with flooding in a number of countries is largely caused by the shortcomings that exist at all stages of urban planning, from geotechnical surveys for construction to improper exploitation of territories. In flooded urban areas, the existing protective measures are implemented to eliminate flooding of individual objects but are not appropriate for additional anthropogenic pressures to prevent the development of flooding in the future and emergency situations.

In urban areas where flooding is caused by anthropogenic factors (disturbance of surface runoff, leakage from water-bearing networks, inefficient operation of drainage systems), the dynamics of this process have certain specificities.

Flooding is often associated with disturbance of the groundwater regime of mining operations or during the “wet” conservation regime of mines. The subsidence of the day surface over mountain mining causes dangerous phenomena, sharply worsen environmental conditions and lead to swamping of large areas, the emergence of sources, lakes and marshes in lowlands.

Activation of flooding process may cause emergence of new, previously absent, technogenic horizons of groundwater. A feature of new man-made aquifer horizons is that it may appear 2 to 3 years after the development of new areas and after 5 to 10 years, their level often reaches a critical depth of 2 meters or less from the earth's surface.

Construction of massive irrigation systems and canals often leads to a significant change in hydrogeological conditions in these regions. Where groundwater was initially occasional or totally absent, irrigation groundwater start appearing in the form of localized groundwater, which join other localized systems to form a single hydraulic system. Not only irrigated lands, but also neighboring settlements, including cities and villages, ultimately find themselves in the flood zone.

Flooding affects the territories of settlements located near the large canals. The need to provide water to cities and villages in low-water supplied regions, but the absence of the provision of balance between water consumption and water disposal may become a significant reason for the flooding of the territories and villages.

Underestimation of the formation and development of future flooding processes leads to tremendous additional funding needed to compensate for

harmful and dangerous environmental impacts, often leading to disastrous consequences.

The main natural conditions which trigger flooding processes are the presence of poorly permeable soil formations, the location of water-resistant layers relatively close to the surface and poor natural drainage of territories.

The main technogenic causes of flooding of cities and settlements include the following:

- changing conditions of surface runoff (the absence of vertical layout and drainage networks, the intersection of surface runoff paths with roads and embankments, the creation of cascades and reservoirs on small rivers, among others);
- backfilling of natural drains – ravines, gullies, small streams, lakes;
- reduction of evaporation and condensation of moisture in the soils of the aeration zone as a result of the effect of shielding by buildings;
- shortcomings in the device of sewage or its absence;
- a developed water supply network but poor domestic sewage networks;
- barrage effect of embankments of roads, foundations of buildings, pile fields, large collectors and subways;
- large leakage of water from water-bearing networks and other water bodies;
- the influence of industrial enterprises with wet production technologies;
- closing and flooding of coal and other mines.

In accordance with standards “Engineering protection of territories and structures from flooding”, the following types of territories are distinguished:

Flooding caused by a surge of soil moisture, a rise of groundwater level or flood that has already led or could lead in the future (according to forecasts) to a significant deterioration in the living conditions of the population and economic activities. In separate areas of the flooded territories, various stages of development of the processes of flooding are observed.

Flooded territories where groundwater rises permanently or temporarily for a sufficiently long period (month or more) above the maximum depths, increase in groundwater level and flooding, which significantly affect the operation of economic facilities in regulated mode. This does not take into account accidental emergencies.

Flooded areas in need of urgent protection are areas related to flooded territories in which an emergency situation has arisen due to flooding and its consequences, often leading to unsatisfactory sanitary and ecological conditions.

Potential flood prone territories are areas where conditions for their attribution to the flooded territories have not yet developed, but this is possible by the forecast or by an analysis of existing factors and reasons related to construction or retaining structures. These are territories with high occurrence of water-resistant layers, soils with lithological structure and relief, which contribute to the accumulation of sediments, infiltration of waters, including leaks from water-bearing networks.

Protection against flooding

When designing the engineering protection of territories and structures against flooding, a set of measures have to be developed to prevent the flooding and elimination of its negative impact and related processes, depending on the requirements of regulatory use of the territories and environmental protection.

Engineering protection of territories and structures from flooding is performed with the purpose of ensuring uninterrupted and reliable activity of the economy, creation of proper environmental and social conditions of life of the population and enforcement of normative sanitary and hygienic conditions.

Limiting depths of groundwater, which should be provided in the territories of cities and towns by taking measures of engineering protection against flooding, are accepted in accordance with the figures shown in table 3.12.1, provided that the height of the capillary elevation Δh_k of the flooded soil layer does not exceed 0.5 m, and there are no karst phenomena in the territory.

In territories with industrial development, the limiting depths of groundwater are determined in accordance with the technical requirements of production and industrial standards.

Measures for engineering protection against flooding are subdivided into *preventive measures and construction of engineering protective structures*.

Preventive measures apply to potentially flooded and flood prone territories aiming to compensate for man-made changes in the water balance or related increase of surface territorial limitations.

Protective structures provide a direct reduction of groundwater levels or prevent flooding in submerged areas and areas requiring immediate protection, they also serve to protect against the flooding of individual buildings and structures.

Table 3.12.1

**Limit depths of groundwater for territories of cities and towns
(according to DBN B.1.1-25-2009)**

Purpose of the territory	Maximum depth to groundwater level, m	Notes
Multi-storey capital development:		
if the freezing depth is 0.7 m or more	Not less than 2.0	not less than 0.5 m from the soles of the foundations of structures
the same, less than 0.7 m	Not less than 1.5	Same as above
With basements	From the basement floor not less than 1.0	Same as above
With developed underground space (underground pedestrian and transport facilities, communication tunnel channels and collectors)	not less than 0.5 m from the floor of buried structures	
Low-rise manor-house	Not less than the depth of freezing	Same as above
Streets, roads, squares no less		Same as above
Intercity motorways within cities and towns	Same as above	Not less than the depth of normal tree growth *
From the bottom of drinking water pipelines	Local water supply is required for capital construction	
Parks, squares, green spaces	Not less than the depth of freezing	Same as above
Stadiums, playgrounds, other planar structures		Same as above
* Limit values of groundwater depths required for normal tree growth: poplar – 0.4 m; pine – 1.0 m; fruit trees – 1.0–1.5 m; birch – 1.5 m; for other tree species – according to special reference books		

Measures to prevent flooding of territories and structures relate to the elimination of causes and factors triggering rise in groundwater levels or to artificially raise the surface markings. These measures should be taken for all potentially flood prone areas. In flooded territories, these measures are taken if, according to a preliminary assessment, they are determined to be effective and environmentally sound.

Measures to prevent flooding are taken as part of a set of works on engineering preparation of the territory for construction. In built-up territories and in other individual cases, such activities are performed independently.

The main preventive measures are as follows:

- Artificially increasing the planning marks of the earth's surface in the protected area (Fig. 3.12.2);
- compliance with regulatory requirements for compaction of the soil when backfilling pits and trenches;
- ensuring reliable drainage of surface water by means of storm sewers, compliance with slopes of asphalt and concrete surface coatings;
- ensuring the rigorous implementation of work regulations on the construction of water-bearing networks, artificial water-containing objects;
- the device of high-quality waterproofing of foundations, buried structures and communications;
- arrangement of anti-filter screens under industrial water storage devices and curtains around them;
- construction of coastal, head, intercepting and other types of drainage to prevent flooding of the territory as a whole.

Artificial increase of planning marks of the surface of the territory is generally used in floodplain and swampy areas, which are intended for development according to their intended purpose. Artificial elevation of the marks is carried out by adding or washing up the soil, with compulsory preliminary filling of the drainage layer. The composition of the accompanying work includes clearing and straightening the channels of rivers and streams, conditioning of their banks.



Fig. 3.12.2. Backfilling to increase the level of the territory
http://megawood.pro/file/2015/11/29/vyravnivanie_1.jpg

The protection against groundwater flooding of urban territories, as well as individual structures in flooded territories, is carried out mainly as follows:

- device of drains of various types;
- external or internal waterproofing of flooded buildings and structures.

The use of anti-filtration screens (curtains) for protection against flooding is often impractical due to the creation of dangerous increase in the level of groundwater from the groundwater flow, which contributes to the development of the barrier effect.

For the lowering of the groundwater levels in cities, it is deemed necessary to provide closed type drainage. An open drainage network is used in areas with low-rise (buildings) development, parks and squares.

Engineering protection of territories and individual structures against groundwater flooding include the following types of drainage: horizontal, vertical, combined, radiation, internal or special types of drainage (vacuum, electric drainage, etc.)

Horizontal drainage is the most common type of drainage. According to the conditions for laying drains, there are two types of structures that are used in various soil conditions:

- perfect type drainage – in all aquifers without limits;
- drainages of imperfect type – in well-permeable soils (in other soils – if there is justification for the effectiveness of the application).

Structurally, the horizontal closed drainage consists of perforated pipes surrounded with a sand-gravel mixture or wrapped with geotextile or pipe filters made of large-porous filtration concrete or synthetic materials. Drainage pipes are made of synthetic materials (including PVC and fiberglass), ceramics, asbestos and concrete. The selection of the pipe material takes into account the corrosion, temperature and mechanical properties of the soil and the chemical composition of the drainage water.

In areas with sandy soils, head and coastal drains are used along a slope or channel groundwater inflow. Street drains are connected to them for the collection and interception of infiltration feeders. In areas with clay soils, additional local ring and associated drains should be provided, which reinforce protection against flooding of individual buildings, structures and utilities.

Vertical drainage is most effective in cases where poorly permeable soils are underlain by permeable soils with pressure waters which contribute to flooding.

Combined drainage is used in cases of complex structure of the soil strata, when the upper low-permeable layer of bigger thickness is underlain by

layers of water-permeable soils of lower thickness with an aquifer (pressure or non-pressure).

Radiation drainage is used to significantly and reliably lower the level of groundwater. It is effective for drainage of territories with a complex topography and variable soil layers, in areas with dense buildings and underground space with diverse communications.

Internal drainage is used to protect buildings and structures when it is impossible to install classical drainage systems in the following cases:

- repair or reconstruction of the basement, when the underpinning of the foundation is not possible under the restrictions of surrounding objects (buildings, structures, roads, communications, vegetation, etc.) or if this leads to inappropriate material costs for the restoration of such objects;
- when using top-down construction methods, which do not allow installation of another type of drainage. In these cases, the joint use of internal drainage together with a waterproofing coating is possible with the further installation of humidity control systems for the premises of the underground part of the building.

Internal drainage systems are often used in the reconstruction of buildings and structures when there are no strict requirements for humidity in the room and in the absence of concentrated ground inflow into the basement. If there is a need to ensure standard humidity within premises, then humidity control systems are installed.

Special types of drainage are used to enhance the drainage effect of poorly permeable soils (accelerate the rate of drainage, improve the performance of drainage filters). These include vacuum, electric drainage, ventilation and other drains.

Test questions to chapter 3.12. Groundwater flooding

1. What is groundwater flooding?
2. What are the negative consequences of prolonged flooding of territories?
3. What is the difference between flooded territories and potentially flooded territories?
4. Define the concepts: flooding in natural conditions, technical flooding and natural-technical flooding.
5. The main factors of flooding.
6. The main technogenic causes of flooding of cities.
7. The maximum depth of groundwater for urban territories.
8. Measures to prevent flooding of territories and structures.
9. What are the main types of drainage.

Chapter 3.13. FLOODING OF TERRITORIES BY SURFACE WATERS

Flooding by surface waters is defined as an excessive rise of free surface water in a territory, as a result of an increase in the level of watercourses, reservoirs and accumulation of surface water in the lowlands. Flooding of territories can be permanent (for example, when creating reservoirs) or temporary.

Flooding is usually marked by a temporary significant submersion of an area which is caused by natural or man-made causes and occurs mostly as a result of rising water levels in rivers, lakes and seas due to heavy rains, snow melting, seawater surge on coasts, breakthroughs of dams of natural lakes or artificial reservoirs and other reasons. Floods significantly threaten people's health which often lead to loss of lives and huge material and environmental damage.

According to the UN, the highest number of deaths among all types of natural disasters is mainly caused by hydrometeorological disasters, which include floods in the first place, geological – in second place and thirdly man-made. Floods are most common in areas with a tropical monsoon climate (Fig. 3.13.1).

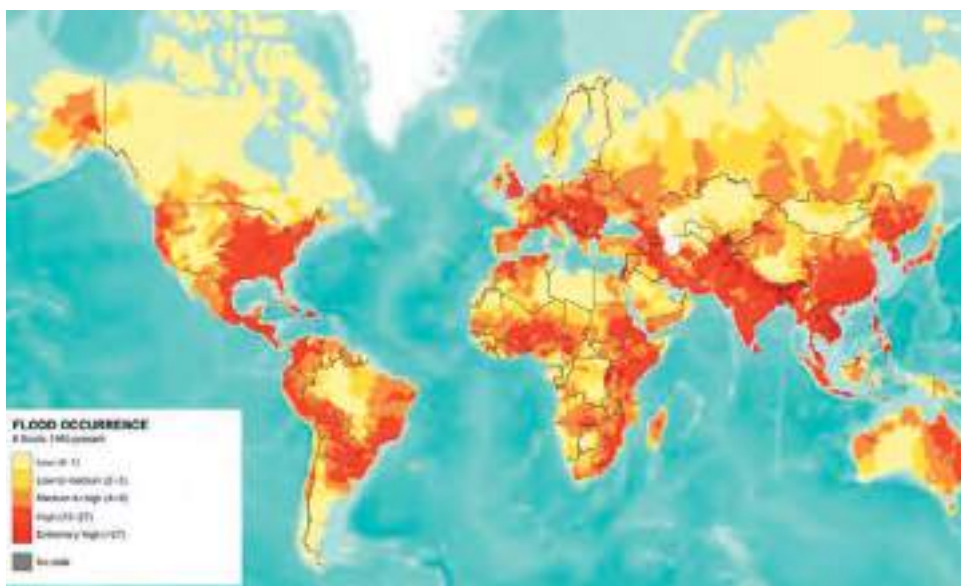


Fig. 3.13.1. Map of the likelihood of flooding (light yellow areas indicate areas with a low probability of flooding, dark red indicates a high probability)
http://www.drrplatform.org/images/0_F2F-2015-Introduction-EST-111115.pdf

Some examples of the most significant historical and recent floods are as follows:

The flood of St. Mary Magdalene (July 22, 1342) is the largest among the floods described in the chronicles in Central Europe. On this day, the large European rivers Rhine, Moselle, Main, Danube, Weser, Elba, Vltava and their tributaries overflowed the surrounding lands. Many large cities, such as Vienna, Cologne, Mainz, Frankfurt, Wurzburg, Regensburg, Passau were flooded and seriously affected. The total death toll is reliably unknown; it is estimated that around 6 thousand people drowned in the Danube only. This flood is associated with the plague epidemic that followed, due to water pollution, that claimed the lives of one third of the European population.

Flooding of St. Felix, (November 5, 1530). On St. Felix de Valois's day, most of Flanders and Zealand, the provinces of the Netherlands, were flooded. Historians believe that more than 100 thousand people died as a result of the flood. Subsequently, the day of disaster was called Evil Saturday.

The Burchardi flood occurred in the night of October 11–12, 1634 in Germany and Denmark as a result of a storm water surge caused by a hurricane. In several places along the coast of the North Sea, protective dams were destroyed, and water flooded the coastal cities of North Friesland. About 8–15 thousand people lost their lives.

The St. Petersburg flood, November 19, 1824 (poetically described in poems by A. S. Pushkin) occurred in St. Petersburg and claimed 200–600 human lives, destroying many buildings. The rise in water level in the Neva River and canals was 4.14–4.21 meters above the usual level. Material damage from the flood was estimated in the range of 15–20 million dollars at that time. This is a noticeable, but far from the only flood that occurred in St. Petersburg. Territories of the city on the Neva have been flooded more than 330 times.

The "Great Flood of 1931 in China" occurred as a result of intense rains in July, when the water level in the Yangtze River rose sharply. The river overflowed the banks and soon reached the city of Nanjing, which at that time was the capital of China. Many people drowned, and later many died from waterborne infections such as cholera and typhoid.

The Great Flood of 1993 was one of the most devastating floods in US history.

Already in the XXI century: the flood in Mumbai, India in 2005 led to the deaths of more than 1000 people; floods in Turkey and Pakistan in 2010 led

to the deaths of many people, loss of crops, the destruction of transport infrastructure.

Flash Flood in Mauritius, 30th March, 2013: At least eleven people died due to flooding in the capital of Mauritius, Port Louis. The tragedy happened on Saturday March 30th, 2013. The flooding was caused by a huge rainfall and the city of Port Louis suffered around 15 cm of torrential rain in around 2 hours. The worst tragedy so far was the eight victims who died in an underground car park during the flooding. A national day of mourning was been declared. Hundreds of people were left homeless, roads impassable, and the area left flooded with rain water, but also sewage, which is likely to cause problems with drinking water cleanliness. The rescue teams had to work hard to find missing people and those stranded or in difficulty.

Extensive floods are often caused by tropical cyclones and storms due to surge phenomena. The powerful hurricane “Katrina” hit the city of New Orleans, USA in 2005 and caused its flooding.



a



b



c



d



e



f



g

Fig. 3.13.2. Examples of floods: **a** – flood of Burchardi, 1634; **b** – St. Petersburg, 1824; **c** – Paris, 1910; **d** – Nanjing, China, 1931; **e** – Irkutsk region 2019; **f** – Passau, southern Germany, 2013; **g** – Port Louis after flood, 2013

a https://ru.wikipedia.org/wiki/%D0%9D%D0%B0%D0%B2%D0%BE%D0%B4%D0%BD%D0%B5%D0%BD%D0%B8%D0%B5_%D0%91%D1%83%D1%80%D1%85%D0%B0%D1%80%D0%B4%D0%B8#/media/%D0%A4%D0%B0%D0%B9%D0%BB:Erschrecklichewasserfluth.jpg; **b** https://ru.wikipedia.org/wiki/%D0%9D%D0%B0%D0%B2%D0%BE%D0%B4%D0%BD%D0%B5%D0%BD%D0%B8%D1%8F_%D0%B2_%D0%A1%D0%B0%D0%BD%D0%BA%D1%82-%D0%9F%D0%B5%D1%82%D0%B5%D1%80%D0%B1%D1%83%D1%80%D0%B3%D0%B5#/media/%D0%A4%D0%B0%D0%B9%D0%BB:7_%D0%BD%D0%BE%D1%8F%D0%B1%D1%80%D1%8F_1824_%D0%B3%D0%BE%D0%B4%D0%B0_%D0%BD%D0%B0_%D0%BF%D0%BB%D0%BE%D1%89%D0%B0%D0%B4%D0%B8_%D1%83_%D0%91%D0%BE%D0%BB%D1%8C%D1%88%D0%BE%D0%B3%D0%BE_%D1%82%D0%B5%D0%B0%D1%82%D1%80%D0%B0.jpg; **c** <https://my-journal-omsk.livejournal.com/35171.html>; **d** <https://www.5-tv.ru/news/256475/kak-obezopasit-seba-vovrema-navodnenia/>; **e** <https://www.5-tv.ru/news/256475/kak-obezopasit-seba-vovrema-navodnenia/>; **f** <https://nesovet.livejournal.com/133681.html>; **g** <https://www.lexpressproperty.com/en/news-advice/news/the-flash-flood-of-march-2013>

Recent global climate changes lead to an increase in the number of floods, which is clearly illustrated by the diagrams in Fig. 3.13.3.

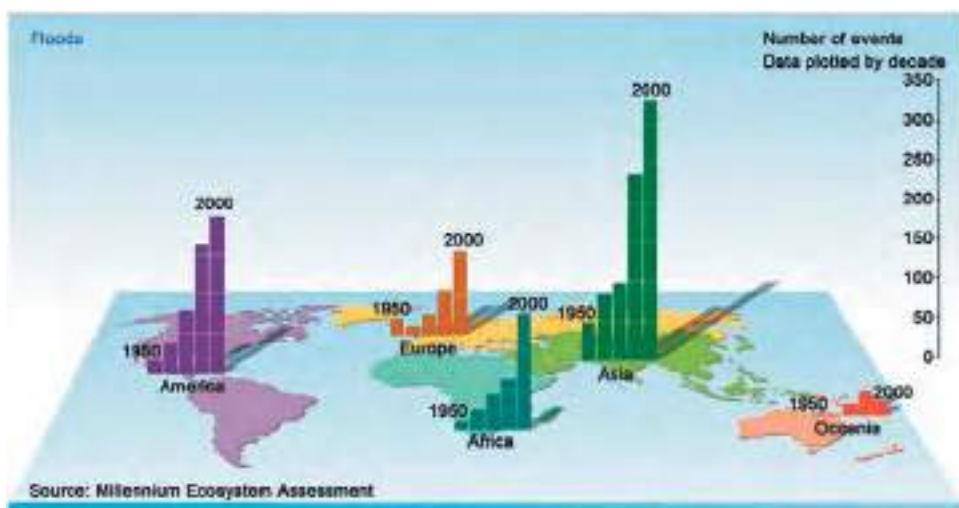


Fig. 3.13.3. Number of floods per decade from 1950 to 2000
https://www.researchgate.net/figure/Number-of-flood-events-by-continent-and-decade-since-1950_fig3_311091404

Floods, as a natural disaster in the 21st century, became almost intolerable. The scientific, engineering and economic feasibility of measures to protect against flooding of territories with surface waters is one of the most important tasks of specialists, primarily hydraulic engineers, hydrologists and ecologists.

The main types and causes of flooding

Among the many causes of floods, hydrologists distinguish five main types:

1. Floods associated with maximum surface runoff during spring rapid melting of the snow cover. They are classified as the greatest during the year with a rather significant rise in the water levels of rivers.
2. Floods caused by intense rains. They are characterized by a rapid, but relatively short-term rise in water levels.
3. Floods in cold climates caused by obstacles that the water stream encounters in the riverbed. This happens generally at the beginning or end of winter. With early freezing, ice in the form of sludge (loose pieces of intra-water ice and wet snow that formed in the upper river) often clogs the riverbed in narrow places, and the river overflows. Such phenomena, sometimes called glitches, at the end of winter or spring, may cause ice jamming leading to similar results.
4. Floods caused by winds on the coast of the seas or lakes on the shores of oceans, seas, large lakes and reservoirs, often in sea estuaries.

5. Floods associated with the breakthrough of dams and other hydraulic structures. When the hydraulic structure or part of it is destroyed, uncontrolled movement of large volumes of water occurs. Such floods are generally technogenic in nature.

Anthropogenic factors and causes of flooding

The immediate causes of anthropogenic (man-caused) floods are associated with the destruction of various dams, barrage in rivers, artificial reservoirs and various industrial reservoirs, which can occur as a result of serious emergency situations or during military operations.

For example, in 1938, a flood on the Yellow River was artificially created at the beginning of the Sino-Japanese War. In order to prevent the advance of Japanese troops, the government in Central China decided to open dams on the Yellow River near the city of Zhengzhou. Water flooded the adjacent provinces of Henan, Anhui and Jiangsu (Fig. 3.13.4). As a result of the flood, many villages were destroyed, thousands of km² of agricultural land were flooded and several million people became refugees. According to various sources, 400 to 800 thousand people drowned. Subsequently, this flood was called “the largest environmental war in history”.



Fig. 3.13.4. Scheme of the flood zone flood on the Yellow River. By area, it approximately corresponded to the territory of entire countries, for example, the Czech Republic or Georgia
<https://vikond65.livejournal.com/919849.html>

In 1941, the flood caused by the demolition of part of the Dnieper hydroelectric dam in the city of Zaporozhye during the retreat of Soviet troops led to numerous civilian casualties in villages located downstream of the Dnieper (Fig. 3.13.5).



a **b**
Fig. 3.13.5. Dam of the Dnieper hydroelectric station:
a – after the explosion in 1941; **b** – 15.10.1943 г.

a <https://www.5.ua/en/obshchestvo/vydeo-100-tisich-ukrayntsev-pohybly-yz-zapodriv-dneprohes-hodovshchyna-chudovyshchnoho-prestupleniya-nkvd-123297.html>

b <http://iz.com.ua/articles/4006-dneproges-i-nemcy>

Indirect causes of anthropogenic flooding are:

- deforestation, in which the surface runoff to rivers sharply increases and water consumption during transpiration by vegetation decreases; the maximum runoff during deforestation can increase three times;
- drying of wetlands which are natural drain accumulators and this phenomenon can increase water levels by 1.3–1.6 times;
- industrial and housing development of coastal territories, which leads to a change in the hydrogeological regime of rivers due to an increase in the proportion of the surface component of runoff. There is a decrease in evaporation due to waterproof coatings (asphalt, concrete) and other developments. The presence of such coatings in an urbanized area increases floods three times compared with natural floods;
- during land preparation for agricultural purposes, the ability of soils to infiltrate water decreases and the intensity of their erosion increases;
- reducing the cross-sectional area of the flow by supports of bridge crossings, roads, dams along channels, which reduces the river output and raises the water level;

- disruption of the natural regime of flow rates and water levels, as occurs in many large rivers with seasonal regulation of flow by reservoirs. The need for electricity in the winter period increases water consumption by 2 to 3 times, which in the presence of ice cover is accompanied by an increase in water level (winter floods), which can sometimes be higher than during normal flooding.

It should be emphasized that floods at each specific water body are often caused by several factors, and therefore, to determine the estimated characteristics of possible flooding, a comprehensive analysis should be carried out, taking into account the probability distribution laws that are characteristic to different types of floods.

Major floods in Ukraine occur on average once every 5–10 years. Their duration can reach 7–20 days or more. At the same time, flooding is possible not only on farmland, but also on many urban areas and industrial environmentally hazardous facilities.

Examples of flooding by surface waters as a result of river spills, heavy rains, etc. are shown in Fig. 3.13.6.

The need and nature of protection of territories of river floodplains and lowlands from flooding by surface waters is determined by the need and degree of exploitation of certain sections of these territories for urban or industrial development or for other purposes. Planning for new construction within the boundaries of potential flooding zones (at 1% water level in adjacent water bodies) should be carried out in compliance with the requirements of the Water Code.

The following types of flooding can be distinguished: deep-water (covering the surface of the land with water up to more than 5 m deep), medium (from 2 m to 5 m) and shallow (up to 2 m).

Floods are more characteristic to large rivers; in Ukraine it is the Dnieper and the Danube. They are accompanied by flooding of significant territories and cause the need of partial evacuation of people, causing significant material damage. Floods on mountain rivers (the Upper Dniester, Tisza, Prut, Crimea rivers) occur very quickly, which makes it necessary to devise an efficiency methodology of forecasting and warning the population.

The negative impact of land flooding by reservoirs should be evaluated depending on the modes of operation of reservoirs and the duration of the impact of flooding on the coastal territory. In this case, the following types of flooding should be distinguished: constant – below the mark of the dead volume level (ULV); periodic – between marks of the normal retaining level (LLL) and ULV; temporary.



a



b



c

Fig. 3.13.6. Examples of flooding of cities in Ukraine:

a – Galich, Ivano-Frankivsk region; **b** – the city of Lugansk; **c** – Odessa

a <http://www.volynnews.com/files/news/2008/09-02/1173-3u.jpg>

b http://www.novostimira.com.ua/images/news/1378270210_724.jpg

c http://3.bp.blogspot.com/-icYtDclp_Hw/T75eanKWMuI/AAAAAAAAAZA/y9wCl5-5OdU/s1600/bpicturepicture_5298385439827_62338.jpg

Flood protection

The main engineering structures for flood protection are flood dams, barriers for protection of populated areas, industrial and other facilities, as well as agricultural land, which should be designed and built in accordance with the requirements of existing building codes, for example DBN B.2.4-3.

The surface runoff coming from the watershed to the facilities to protect the territories from flooding should be diverted using upland ditches, and if necessary, with large volumes of incoming water, provide water amenities for accumulating part of the surface runoff.

Structures for regulating surface runoff are designed using rate of water flow depending on the class of consequences (responsibility) of the protected objects, taking into account the amount of rain and melt water entering the protective structures through temporary and permanent streams.

Structures of engineering protection against flooding may include: embankment dams, drainage and spillway networks, drains, upland spillway channels, rapid currents and drops, pipelines and pumping stations.

There are two possible approaches to protect flooded territories; common for the entire territory and for individual sites. It is advisable to apply the general delineation of the territory if there are no watercourses on the protected territory or when the flow of existing watercourses can be transferred to reservoirs or a river through a diversion channel, pipeline or using a pump station.

The following should be considered when choosing options for structures of the embankment dams:

- topographic, engineering-geological, hydrogeological, hydrological, climatic conditions in the construction area;
- cost indicators of the structures of protective structures;
- the capacity of water discharge during floods and rain floods;
- the population density of developments of territories and the size of exclusion zones, requiring removal of buildings from flood zones;
- the feasibility of using local building materials, construction machines and mechanisms;
- the timing of the construction of facilities and ease of operation;
- environmental requirements.

Dams

To protect territories from flooding, two types of dams are used – non-flooded and flooded.

Non-flooded dams are used for permanent protection against flooding of housing and industrial territories adjacent to reservoirs, rivers and other water bodies. *Flooded dams* can be used for temporary protection against flooding of agricultural lands during the cultivation of agricultural crops on them, while maintaining a normal retaining level (NPU) in the reservoir, for the formation and stabilization of riverbeds and river banks, regulation and redistribution of water flows and surface runoff.

In river sections with a meander type of channel process, the following structures for channel regulation should be included as part of engineering measures to protect territories from flooding:

- longitudinal dams, limiting the width of the river's water flow to the required design value;
- directing dams – longitudinal, rectilinear or curvilinear, providing a smooth approach of the flow to the culverts of bridges, dams, water inlets and other hydraulic structures;
- dams (dams) that block the channel from coast to coast, designed to block the flow of water in the arms and channels (Fig. 3.13.7);



Fig. 3.13.7. New Croton Dam, built between 1892 and 1906 across the Croton River on the Hudson River, 35 km north of New York, USA
<https://lifeglobe.net/places/111/blog?t=ARCHITECTURE&p=8>

half-dams – transverse structures in riverbeds and in floodplains, providing straightening of channels and protection of coasts, as well as formation of navigable depths;

- spurs (short half-dams), installed at a certain angle to the direction of flow to ensure protection of the banks from erosion;
- coastal embankment dams, which protect coasts and dams from erosion by the current and waves;
- through structures that are being built to regulate the channel and sediment runoff through the redistribution of water flow along the channel width and the creation of a slow (non-erosion) flow rate off the coast.

In the case of a significant length of dams along the watercourse or in the zone of pinching out of the reservoir, the ridge mark is reduced in the direction of flow in accordance with the longitudinal slope of the free surface of the water at the calculated level.

For soil dams, two types of structures are used: a compressed and a flattened profile. The dam profile (flattened or crimped) is selected taking into account the availability of local building materials, the technology of the work, the parameters of the wind waves on the upper slope and the output of the filtration stream on the lower slope.

The types of enclosing dams are selected taking into account natural conditions: topographic, engineering-geological, hydrological, climatic, seismic, as well as the availability and type of local building materials, operating conditions, environmental requirements.

The design of the embankment dams should be carried out in accordance with the requirements of the relevant building codes.

If the dam passes through a landslide or potentially landslide site, anti-landslide measures should be developed.

Dam paths should be selected depending on the topographic and engineering-geological conditions of construction, based on the conditions of minimum changes in the hydrological regime of the watercourse and maximum use of the area.

In the case of overflow with overflow dams, all protected structures should be designed for temporary flooding during the flood period.

During the setting out of dams within the city limits, the possibility of using protected areas for development should be provided.

Engineering protection projects should make provision for the possibility of using the ridges of the embankment dams for the construction of roads or other facilities. At the same time, the width of the dam crest and the radii of curvature must be taken according to the requirements of the relevant building codes. In all other cases, the width of the dam crest should be set to the minimum, taking into account the conditions for the implementation of construction operational work.

Structures that connect soil dams with concrete structures must provide:

- a smooth approach of water to culverts from the upstream side and a smooth spreading of the stream in the downstream – to prevent erosion of the body and base of the dams and bottom of the watercourse;
- prevention of filtration along the contact line of soil structures with concrete.

Ditches

Upland ditches are used to intercept the surface runoff that enters the protected area from the catchment located higher in elevation. The dimensions of the cross section and the slopes of the uphill ditches are determined by hydraulic calculation with the condition that the estimated water velocity should be less than the allowable erosion and greater than that which leads to siltation of the watercourse. The slope coefficient and the roughness coefficients of the bottom of the uphill ditches should be taken in accordance with construction standards for reclamation canals.

The slopes of the uphill ditches without fixing the bottom and slopes should ensure the passage of the minimum flow rates at a speed not exceeding 0.3–0.5 m/s. The largest permissible longitudinal slopes of uphill ditches without fastening are 0.005. The minimum radius of curvature of the uphill ditch should be at least twice the width of the ditch along the water edge at the estimated flow rate. The permissible non-erosive water velocity for upland ditches with flow rates of more than 50 m³/s is adopted on the basis of research and calculations.

Mountain ditches up to 5 m deep and water flow rates up to 50 m³/s, as well as aqueducts, should be designed in accordance with the requirements of building standards for drainage canals (DBN V.2.4-1).

Pumping stations and auxiliary facilities

The composition, layout and design of the construction of pumping stations are set depending on the volume of pumped water and the possibilities of creating storage tanks.

Types, classes of consequences (responsibility) and power of the equipment of pumping stations are determined in compliance with the requirements of prevailing standards, and also:

- estimated flow rate, feed height and fluctuations in water horizons;
- type of energy source;
- ensuring the optimal efficiency of pumps, the type and quantity of which are determined by calculation depending on the type of pumping station, taking into account the values of the calculated flow rate and water pressure and the amplitude of the horizon fluctuations in the lower and upper pools.

Water intake facilities and a pumping station may be of a combined type or as separate facilities.

Water intake facilities should provide:

- water withdrawal in accordance with the water supply schedule and taking into account the water levels in the water source;
- standard operating mode, as well as the ability to repair equipment (maintenance);
- protective structures acting as fish deterrent.

The water outlets of the pumping stations should ensure a smooth release of water into water bodies, with the exception of the possibility of a back flow of water.

Environmental protection

As part of engineering protection projects against flooding, the section “Organization of an observational hydraulic regime network” is required. This section is compiled in accordance with the technical conditions issued by a specialized organization in a given area in accordance with the norms on territorial activities in construction (DBN A.2.3-1). The technical conditions consider the requirements for the arrangement of observation wells and the organization that will conduct the monitoring.

The hydraulic mode network is designed to perform monitoring of groundwater in the zone of influence of engineering protection facilities and monitoring the effectiveness of the facilities.

The section “Environmental Impact Assessment” (EIA) as part of engineering protection projects for territories and structures from flooding must strictly be respected.

Test questions for Chapter 3.13:

1. Definition of the terms flooding and flood.
2. Where are floods most common?
3. The main causes and types of flooding and floods.
4. What are the causes of anthropogenic (technogenic) floods?
5. Causes and factors of flooding.
6. Protective measures against flooding.

Chapter 3.14. PROCESSES RELATED TO WATER DRAINAGE AND WATER SUPPLY

Intensive or prolonged pumping of groundwater, extraction of oil or gas from the depth of the earth can cause subsidence of the its surface due to a decrease in their pressure (levels) and diminution in the weighing effect of the liquid, causing an increase in stresses within the soil mass. The terms “subsidence of the earth’s surface” or “dehydration-hydraulic compression of soils and subsidence of the surface (according to F. V. Kotlov)” currently refer specifically to subsidence caused by this activity. The dynamics of the development of subsidence of the earth’s surface depends on a number of factors: the geological structure and geomorphological conditions of the region, the thickness and composition of the subsiding stratum of soils and their physical and mechanical properties, the intensity of withdrawal of underground fluids (oil, gas, condensate, gas-water-oil mixtures, among others) and the magnitude of the pressure head.

The negative effects of the subsidence phenomenon were observed in Japan, Mexico, the USA, Italy, the Netherlands and Thailand. The maximum subsidence, covering large areas, is associated with the extraction of water, oil and/or gas from the bowels of the Earth. Typical examples of subsidence are given in table 3.14.1.

Table 3.14.1

Examples of the scale, pace and causes of subsidence of the earth’s surface (according to G. A. Razumov)

Territory, country	Settling rate, cm/year	The maximum depth of subsidence, m	Causes
Tokyo, Japan	18	4	Pumping water
Niigata, Japan	50	Not available	Gas production
Osaka, Japan	N/A	2,8	Pumping water
Mexico City, Mexico	50	8	Pumping water
Long Beach Harbor, USA	75	9	Oil production
San Joaquin Valley, USA	N/A	8,5	Pumping water
Texas Coast, USA	N/A	3	Pumping water
Po River Delta, Italy	50	N/A	Gas production
Ravenna, Italy	11	N/A	Oil production

A lesser degree of subsidence is recorded in different countries and in many cities: Tallinn, Venice, London, cities of the Netherlands, etc.

The subsidence of the earth's surface in some cases is so intense that it causes huge ecological and material damages. This process is associated with an increase in the level of groundwater with swamping of the territory, flooding of buildings and industrial structures, flooding of coastal areas of seas and rivers; in case of uneven precipitation – deformation and destruction of buildings, bridges, roads and underground utilities, ports, embankments and other structures.

In Tokyo, as at date, almost a fifth of the city's territory has dropped below sea level and is fenced off from the water by dams, which, when destroyed (for example, after an earthquake), threatens many areas of the city with flooding. The level of rivers and canals flowing into Tokyo Bay is located above the surface of the earth.

Groundwater is pumped in large volumes in many parts of the world mainly for the purpose of domestic water supply and irrigation. The main water intakes are confined to places of intensive groundwater consumption: cities, large industrial zones and agricultural irrigation tracts. Water intake facilities include dozens and hundreds of wells located in a relatively small area.

With intensive pumping of groundwater, a decrease in the level of groundwater aquifers or a decrease in pressure in artesian horizons occurs. The emerging depression funnel covers areas of hundreds and thousands of km². Around London, the area of the depression funnel was 1800 km², in Tokyo – 300 km², in the San Joaquin Valley, USA (where very intensive water intake for groundwater irrigation is made) – 11 thousand km². Depression funnel depth (according to G. A. Razumov) reaches: in London – more than 100 m, in Kyiv – 60 m, in Moscow and St. Petersburg – 50 m, the San Joaquin district – up to 150 m.

Above the territories of development of depression funnels caused by intensive pumping of underground water, there are also troughs of subsidence of the earth's surface. Thus, American researchers in Texas found that the sedimentation volume of soils amounted to almost 22% of the volume of water extracted from sand and clay strata. Sediments of the surface of irrigated massifs in the San Joaquin Valley, USA, since the 20s of the 20th century amounted to more than 0.3 m (with a maximum of 8.5 m near water intakes). This region is the largest territory of intensive surface subsidence on Earth.

Surface subsidence can occur even during short-term pumping of groundwater during construction of buildings where lowering of the groundwater table is performed in order to protect the pits of buildings under construction, transport tunnels and other structures. A decrease in the groundwater level causes an increase in pressure and compression of the soil stratum under its own weight. The amount of subsidence of the surface in this case depends on the depth of the water decrease and the degree of compressibility of the soil. Within the radius of influence zone (depression zone), the pumping of the surface sediment is often uneven: the maximum is most often observed in the center and decreases towards the edges.

Figure 3.14.1 illustrates the scheme of deep-water reduction using two water-reducing wells.

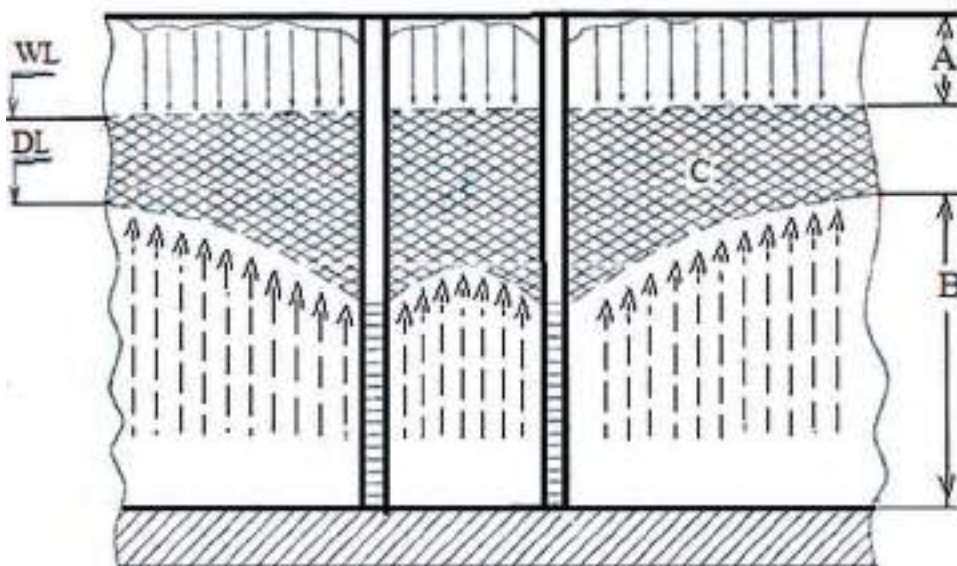


Fig. 3.14.1. Scheme of precipitation of the earth's surface during groundwater lowering:
A – zone of aeration before water reduction, **B** – zone of full water saturation,
C – zone of dried soil during water reduction (Simanovsky, Chelnokova, 2017)

In fig. 3.14.1 it is seen that in the zone of depression of the GW (zone C), the weighing effect of water is significantly reduced, which can cause subsidence of the earth's surface.

Predictive calculation of subsidence of the earth's surface with a decrease in groundwater level

If the groundwater level decreases by more than 2 m, especially in weak clay soils, peat and silt, it is necessary to calculate the expected settlement of the earth's surface in the zone of development of the depression funnel. According to the technique developed at the Department of Geotechnics of St. Petersburg State University of Architecture and Civil Engineering, calculation of settlement of the territory S_{gr} is performed by the formula:

$$S_{gr} = \Delta\gamma S^2 / 2 \cdot E$$

where $\Delta\gamma = \gamma - \gamma_{sb}$, γ is the specific gravity of the soil of the engineering-geological element (IGE), within which there was a decrease in groundwater level, kN/m^3 ;

$$\gamma = g\rho,$$

ρ – soil density in g/cm^3 , corresponding to IGE; g – gravity = 9.8 m/s^2 ;
 γ_{sb} – specific gravity of the soil below the groundwater level, kN/m^3 :

$$\gamma_{sb} = (\gamma_s - \gamma_w) (1 - n),$$

γ_s – specific weight of solid particles of soil, kN/m^3 :

$$\gamma_s = g\rho_s,$$

ρ_s – the density of solid particles of soil, g/cm^3 , is taken according to the data for the corresponding IGE; γ_w is the specific gravity of water, $\gamma_w = 9.8 \text{ kN/m}^3$;
 n – porosity, is taken according to the data for the corresponding IGE.

S – the value of water reduction in m; E – the modulus of the total soil deformation in the zone of the depression funnel, kPa (kN/m^2).

The formula for calculating S_g is valid provided that $R/H_B \geq 3$, where R is the radius of influence, and H_B is the thickness of the aquifer.

Test questions to chapter 3.14. Drainage and dewatering processes

1. What is the reason for the subsidence of the earth's surface or the dehydration-gravitational compression of soils?
2. What are the factors which determine the dynamics of the development of sediments on the earth's surface?
3. The negative effects of sediment.
4. Surface settlement during short-term lowering of groundwater during construction.
5. Methodology for calculation of surface settlement.

PART IV.

FUNDAMENTALS OF SOIL SCIENCE

Soil determination

In engineering geology, according to E. M. Sergeev, the term “soil” should be understood as any rocks, soils, topsoils which are multicomponent systems that change in time, studied in order to know them as an object of engineering activity.

In construction practice, soils are rocks, loose or coherent sedimentary deposits and man-made formations that serve as foundations for buildings and other structures, as well as material for the construction of various soil structures.

According to DSTU B.V.2.1-2-1996, soils are rocks, soils, technogenic formations, which are a multicomponent and diverse geological system of mineral-dispersed formations and are an object of human engineering and economic activity.

Our view is preferable to the following definition: *soils are any rocks, soils, topsoils and technogenic formations that are part of the geological environment, the properties of which are studied in connection with civil engineering and human activities.*

Soils are classified in accordance with state standards for construction, the effect of which applies to all soils and sets their classification indicators used in the production of engineering surveys, design and construction of buildings and structures.

Currently, Ukraine has DSTU B V.2.1-2-96, identical to GOST 25100-95 “Soils. Classification”. Many provisions of this regulatory document are outdated and require processing and additions. Therefore, this manual also provides data from more modern foreign standards:

GOST 25100-2011 “Soils. Classification”. Designed to replace GOST 25100-95. Effective from 01.01.2013 in seven CIS countries (Belarus, Kazakhstan, Russia, etc.);

ISO 14688-2: 2004. Geotechnical research and testing – Identification and classification of soils – Part 2: Principles of classification and quantification of characteristics. It is valid in all countries of the European Union;

ACTM D 2487-2000. Standard test method for soil classification for engineering purposes. It is valid in the USA and other countries of America.

Chapter 4.1. GENERAL CLASSIFICATION OF SOILS

In modern classifications, soil is considered as part of the ground mass which is homogeneous in composition, structure and properties. Soil classification includes the following taxonomic units, distinguished by groups of features:

1. Class (subclass) – by the nature of structural relationships;
2. Types – by genetic origin (subtype) and by material, petrographic or lithological composition (subspecies);
3. Varieties – by quantitative indicators of the composition, structure, properties and condition of soils.

Additional indicators can be introduced to the names of soils and their characteristics if it is necessary for a more detailed subdivision of soils, taking into account the natural conditions of the area and the specifics of certain types of construction. In addition, the soil description should contain information about their geological age in accordance with local stratigraphic schemes.

The entire variety of soils is divided into classes of rocks (Tab. 4.1.1), dispersed material commonly called soil (Tab. 4.1.2, 4.1.3) and frozen (Tab. 4.1.4) soils.

Rock class

Soils of this class have rigid structural (crystallization and cementation) bonds between the particles that make up the soil. They are represented by igneous, metamorphic, or sedimentary cemented rocks.

The types (subtypes) and subspecies of rocky soils are distinguished according to their genetic origin and material composition, as shown in table 4.1.1. Varieties of rocky soils are identified by quantitative indicators of their mineral and chemical composition, structure, condition and properties.

Class of dispersed (non-rocky) soils

All soils of this class are represented by sedimentary rocks, with mechanical and water-colloidal structural bonds between particles. Soils with mechanical structural bonds arising due to friction between particles are separated into a subclass of non-cohesive (loose in the dry state) soils, and soils with physical and physicochemical structural bonds are further classified as cohesive soils.

According to the genesis and material composition in the class of dispersed soils, the types, subtypes, types and subspecies shown in table. 4.1.2 and 4.1.3.

Varieties of dispersed soils are distinguished by quantitative indicators of their material composition, structure, condition and properties.

Class of frozen soils

Soils of this class, along with other structural bonds, have cryogenic bonds (due to ice). Soils with cryogenic and simultaneously with crystallization or cementation structural bonds are allocated to a subclass of frozen rocky soils; soils with cryogenic and simultaneously with physical and physicochemical structural bonds – into a subclass of dispersed frozen soils; soils only with cryogenic bonds are isolated into a subclass of ice soils.

According to the genesis and material composition in the class of frozen soils, respectively, the types, subtypes, species and subspecies shown in table 4.1.4. Varieties of natural frozen soils are distinguished by quantitative indicators of their material composition, structure, condition and properties.

This chapter examines the classes of rocky and dispersed soils, as the most common. Frozen soils, which have a number of specific properties, are not found in regions with a warm climate, and in temperate climates they can occur only in winter during limited and temporary periods. They are not used as the foundations of buildings and structures; therefore, this part is outside the scope of this chapter.

Table 4.1.1

Class of rocky soils

Type (subtype)	Description	Subspecies (most common soils)	Varieties
Igneous (intrusive) rocks	Ultrabasic	Peridotites, dunites, pyroxenites	Stand out by: strength, density, weathering, softness in water, solubility
	Highly basic	Gabbro, norites, anorthosites, labradorite	
	Moderately basic	Diorites, syenites	
	Basic	Granites, granodiorites, quartz porphyry	
Igneous (effusive) rocks	Ultrabasic	Picrites, komatiitis	in water, permeability, salinity structures, textures.
	Highly basic	Basalts, dolerites, porphyrites	
	Moderately basic	Andesites, trachytes	
	Basic	Riolites, dacites	
Metamorphic rocks	Silicate	Gneisses, various schists, quartzites, hornfelses, skarns, greisens, berezites, propylites, secondary quartzites, hydrothermally altered rocks	
	Carbonate	Marble and others	

Table 4.1.2
Class of dispersed soils (subclass of disconnected soils)

Subclass (Group)	Type	Subtype	Species	Subspecies (most common soils)	Varieties	
Non-cohesive	Sedimentary	Alluvial, deluvial, aeolian, marine, glacial.	Mineral	Coarse soil Various sands	They are distinguished by: granulometric and mineralogical composition; water saturation; density; organic matter content, salinity.	
			Mineral organic	Silted sands		
	Volcanogenic sedimentary (pyroclastic)		Mineral	Coarse clastic volcanogenic soils, volcanic sands and ashes		
			Mineral and Mineral Organic	Coarse soil, various sands of weathering crust and soil		
	Technogenic	Natural soils altered by natural occurrence	Soils modified by technical reclamation methods	Compacted, rammed soils		
			Soils modified by negative anthropogenic impact	Soils watered, loosened, littered with industrial and agricultural wastes		
		Natural displaced soils	Bulk soils with desired properties	Soil pillows, embankments of roads and railways.		
			Soils spontaneously sprinkled	Bulk soil		
		Anthropogenic soils	Soils created by means of hydromechanization	Washed soils		
				Naturally formed soils		Household, industrial and construction waste, slag, sludge, ash.
				Rocks extracted from the bowels of the mining industry		Overburden, dump soil.

Table 4.1.3

Class of dispersed soils (subclass of cohesive soils)

Subclass (Group)	Type	Subtype	Species	Subspecies (most common soils)	Varieties
Cohesive	Sedimentary	Alluvial, deluvial, aeolian, marine, glacial.	Mineral	Clays, loams, sandy loam, loess	Stand out by: ductility; plasticity; consistency; indicators of swelling and subsidence; particle size distribution; water saturation; density; organic matter content, salinity.
			Mineral organic	Silted and peaty clay soils	
	Lake, marine, marsh, alluvial-marsh, etc.	Organic	Silts, peat, sapropels		
		Mineral and Mineral Organic	Clay soils of dispersed zones of weathering crust and soil		
	Eluvial				
Technogenic	All subtypes, types and subspecies are the same as for disconnected soils				

Table 4.1.4

Class of frozen soils

Subclass	Type	Subtype	Type	Subspecies	Varieties
Rocky Frozen	Natural frozen	Magmatic intrusive and effusive, metamorphic, sedimentary, volcanic-sedimentary	Rocks	All types of rocks	Allocated according to application
	Man-made frozen and frozen	Natural soils, technologically altered in conditions of natural occurrence	All types of technologically altered natural rock soils.	All subspecies of technologically altered natural rock soils.	
Dispersed frozen	Natural frozen	Sedimentary, volcanic-sedimentary, eluvial	All types of dispersed soils	All subspecies of dispersed soils	Ices of different composition Ice soils of different composition All subspecies of artificial ice
	Man-made frozen and frozen	Natural soils modified under natural conditions and displaced natural frozen soils	All types of technologically modified natural dispersed soils	All subspecies of technologically modified natural dispersed soils	
Icy	Constitutional ices: intra-ground, buried, cave-vein	Anthropogenic frozen and frozen soils	Ice	Ices of different composition	
		Segregation, injection, glacial, ice, river, lake, sea, bottom, infiltration, vein, re-vein, cave	Ice soil	Ice soils of different composition	
	Man-made, artificial	Anthropogenic frozen ice	All kinds of frozen ice	All subspecies of artificial ice	

Control questions to Chapter 4.1

1. What is soil?
2. How are soils classified?
3. What are the types of rocky soils?
4. Into which groups are dispersed soils divided?
5. Subtypes of dispersed soils?
6. Subclasses and types of frozen soils?

Chapter 4.2. ROCKY SOILS AND THEIR ENGINEERING PROPERTIES*Origin and general engineering-geological characteristics*

Rocky soils are called soils having rigid structural bonds between constituent mineral grains or particles of crystallization and/or cementation type.

The rock class includes igneous, metamorphic and cemented sedimentary rocks. Very strong bonds between the grains of the minerals composing the rock are formed during its formation and are observed in the structures of igneous and metamorphic rocks – granites, basalts, quartzites and gneisses. In cemented sedimentary rocks, the bond between the grains of minerals or rock fragments is carried out by cement of various composition. The most durable are siliceous and ferruginous cements, the less strong are calcareous and gypsum cements and the weakest cement is clay. Cemented rocks include sandstones, conglomerates and breccias, various limestones, marl, chalk, limestone, volcanic and calcareous tuffs.

The most widespread rocky soils are in mountainous areas, where they are often located on the earth's surface. On the plains, these soils are usually located at various depths under the thickness of uncemented sedimentary rocks and are rarely observed on the surface of the earth, most often in the valleys of large rivers, for example, in Ukraine – the Dnieper, Southern Bug; less commonly observed in the valleys of small rivers – Ros, Teterev among others (Fig. 4.2.1, 4.2.2).

Rocky soils also occur in the form of continuous arrays of intrusive rocks, such as granite, diorite, for example – batholiths are known in Ukraine: Umansky, Zhitomirsky, Boguslavsky; Laccolite – Mount Ayu-Dag, Crimea; Olivine basalt and its derivatives on the island of Mauritius in the southern hemisphere. They have solidity and high density and have significant strength due to crystalline structural bonds. The upper part of the rock masses in contact with the atmosphere is usually destroyed due to weathering. This destroyed zone is called the weathering crust and consists of fragments of the initial rocks of various sizes – from lump-block to crushed, sandy and clay. Rocky soils encountered as sedimentary rocks, usually lie in layers among non-cemented rocks.

Many rocky soils have water-tight rigid bonds between mineral grains and are physically and mechanically close to such solid and elastic materials as concrete and reinforced concrete, and often surpass them in strength. At the same time, many rocky soils are anisotropic, as they are composed of various minerals, have stratification, a system of cracks, increased susceptibility to weathering, and sometimes (limestone, gypsum, rock salt) solubility.



Fig. 4.2.1. Rocky soils of magmatic intrusive origin – granites in the valley of the Ros River. Photo by V. Iegupov



Fig. 4.2.2. Rocky sedimentary soils – chalk and glandular sandstone in the Dniester River valley. Photo by V. Iegupov

4.2.1. Classification characteristics of rocky soils

One of the main characteristics of rocky soils is the ultimate uniaxial compressive strength R (MPa) of the soil and is the ratio of the load at which the sample is destroyed (kN) to the area of its original cross section (according to GOST 12248, British Standards BS1377). To determine the strength of the rocks under uniaxial compression, cylindrical (sometimes cubic) samples are made with a height to diameter ratio of unity (1 to 2 as per BS), with a deviation from this ratio of up to 5%. The loading on the samples is carried by loading of the latter, using a hydraulic press.

The temporary resistance of rocky soil with uniaxial compression R is calculated by the formula:

$$R = P_{\max} / F_0,$$

where $P_{\max}$ is the maximum load on the sample at the time of rupture, kN and F_0 – the initial cross-sectional area of the sample, cm^2 .

Examples of equipment for determining the strength of soil samples and test results are shown in Fig. 4.2.3.

According to the strength properties, rocky soils are subdivided by the value R_c – ultimate strength for uniaxial compression in a water-saturated state, MPa. Compression tests of samples are carried out after soaking for two days in water, as per specifications.

Varieties of soils depending on R_c are given in Table 4.2.1.

Rocky soils with $R_c \geq 5$ MPa are called semi-rocky soils.

Table 4.2.1

Varieties of soil depending on R_c

Varieties of soils	CHARACTERISTIC	R_c , MPa
Rocky	Very durable	$R_c > 120$
	Durable	$120 \geq R_c > 50$
	Medium strength	$50 \geq R_c > 15$
	Low strength	$15 \geq R_c > 5$
Semi-rocky	Reduced strength	$5 \geq R_c > 3$
	Low strength	$3 \geq R_c > 1$
	Extremely low strength	$R_c < 1$



a



b



c



d

Fig 4.2.3. Equipment for determining the strength index R and test results:
a – hydraulic press PSU-125; **b** – hydraulic press PSU-10; **c** – rock monolith
 (siltstone) before the test and **d** – monolith after testing. Photo by V. Iegupov

Indicative values of strength and porosity are given in table. 4.2.2.

Table 4.2.2

Strength characteristics of some rocky soils

Types of soil	Uniaxial compressive strength in water-saturated state R_c , MPa	Porosity, n, %
Granite	100–230	0,06–2
Dense basalt	80–350	3–6
Gneiss	80–220	1–2
Dense limestone	60–200	5–13
Porous limestone	7–50	10–22
Sandstone clay	1,5–5	16–26
Shell rock	0,4–15	7–27

As seen from the table. 4.2.2, the values of the ultimate strength of soils of the same type can vary over a very wide range, which depends on the structure, density, porosity, mineralogical composition and other features of specific samples. For example, the presence of biotite and other micas leads to a decrease in the strength of all igneous rocks. Monolithic basalts are characterized by high density (up to $3\text{--}3.3\text{ g/cm}^3$) and strength R_s up to $300\text{--}350\text{ MPa}$. However, the strength decreases sharply in basalts with a porous, slag texture, the porosity of which can be up to 50%. The latter type is often encountered as vesicular volcanic basalt, for example in Mauritius as shown in fig. 4.2.4 below.

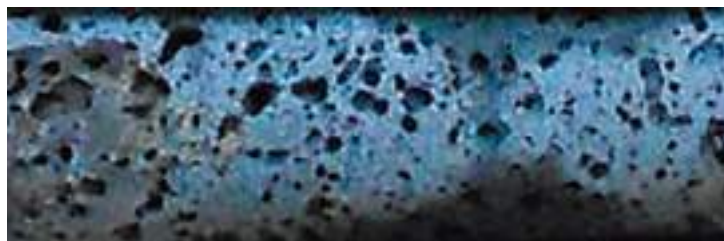


Fig 4.2.4. Vesicular volcanic basalt. Photo by R. Goodary

An indicator of the ability of rocky soils to reduce strength under the influence of water is the coefficient of softness in water k_{sof} which is determined by the ratio:

$$k_{\text{sof}} = \frac{R_c}{R_s},$$

where R_c and R_s are the uniaxial compression strength limits of soil samples, respectively, in water-saturated and air-dry states, MPa.

In terms of softness, rocky soils are divided into two varieties (Tab. 4.2.3).

Table 4.2.3

Varieties of soils in terms of softness

VARIETIES OF SOILS	Index k_{sof}
Non-softening	$k_{\text{sof}} \geq 0,75$
Soft	$k_{\text{sof}} < 0,75$

Slow cemented rocks with weak types of cement (gypsum, clay) have low softening factors. Igneous and metamorphic rocks are rarely softened.

An indicator that characterizes the degree of soil destruction under the influence of weathering factors (temperature fluctuations, exposure to oxygen, water, wind, solar radiation and living organisms.) is the coefficient of weathering k_{wr} , which is determined by the ratio:

$$k_{\text{wr}} = \frac{\rho}{\rho_m},$$

where ρ – the density of the soil/rock under investigation, g/cm^3 (t/m^3), determined as per standards; ρ_m – density of the same soil in a monolithic un-weathered state, g/cm^3 (t/m^3), i.e. lying in the parent un-weathered part of the rock mass.

In terms of weathering, rocky soils are divided in accordance with table. 4.2.4.

Table 4.2.4

Varieties of soils in terms of weathering

Varieties	Characterization of soil massifs and their degree of weathering
Un-Weathered also called “fresh” (Monolithic)	Solid array $k_{\text{wr}} = 1$
Slightly weathered (fissured)	$1 > k_{\text{wr}} \geq 0,9$
Weathered	Accumulation of fragments passing into fractured rock $0,9 > k_{\text{wr}} \geq 0,8$
Highly Weathered	The entire array as separate fragments $k_{\text{wr}} < 0,8$
Completely Weathered	Reduced to dispersed gravelly soil

The foundations of various constructions are very often the underlying parent rock, i.e. foundations, as a rule, must cut through the weathering crust.

If this is not possible, for example, with a large thickness of weathered soils, the foundations can also be seated on soils of the weathering crust, but for this they should be strengthened (conditioned), by using ground improvement techniques, to the required strength.

Some semi-rock type soils may contain various salts, the dissolution of which may adversely affect the mechanical properties of the soil. According to the degree of salinity of the soil D_{sal} , % – the ratio of the mass of water-soluble salts in the soil to the mass of absolutely dry soil – varieties are distinguished in accordance with Table. 4.2.5.

Table 4.2.5

Varieties of soil in terms of salinity *

Varieties of soils	The degree of salinity, D_{sal} %
Non saline	Less than 2
Saline	2 and more

*Note. Salinity classification is used only for dispersed soils.

Some types of rocky and semi-rocky soils that have sedimentary origin can dissolve in water. The degree of solubility in water q_{sr} , g/l, is a value reflecting the ability of the soil to dissolve in water under normal conditions due to the dissolution of inorganic and organic substances. It is determined when the ratio of soil and water is 1: 5 and is equal to the concentration of the resulting equilibrium solution. In accordance with the degree of solubility, the soils are divided according to the table. 4.2.6.

Table 4.2.6

Varieties of soils by degree of solubility in water

Varieties of soils	Solubility, q_{sr} , g/l	Characteristic soils
Insoluble	$q_{sr} \leq 0,01$	Igneous and metamorphic rocks
Sparingly soluble	$0,01 < q_{sr} \leq 1$	Limestone, dolomite
Medium Soluble	$1 < q_{sr} \leq 10$	Gypsum, chalk, anhydrite,
Readily soluble	$10 < q_{sr} \leq 100$	Rock salt, potassium salt
Highly soluble	$q_{sr} > 100$	

In addition to the above varieties, some standards also identify varieties of rocky soils according to the density of dry soil (skeleton of the soil) ρ_d , porosity n and water permeability K_f (Tab. 4.2.7, 4.2.8, 4.2.9).

Table 4.2.7

Varieties of rocky soils according to the density of dry soil

Varieties of soils	Dry soil density, ρ_d , g / cm ³
Very dense	$\rho_d \geq 2,50$
Dense	$2,50 > \rho_d \geq 2,10$
Medium density	$2,10 > \rho_d \geq 1,20$
Low density	$\rho_d < 1,20$

Table 4.2.8

Varieties of rocky soil porosity

Varieties of soils	Porosity, n , %
Non-porous (compact)	$n \leq 3$
Slightly porous	$3 < n \leq 10$
Moderately porous	$10 < n \leq 30$
Highly porous	$n > 30$

Table 4.2.9

Rock permeability varieties permeability *

Varieties of soils	Filtration coefficient, K_f , m/day
Waterproof	$K_f \leq 0,005$
Slightly permeable	$0,005 < K_f \leq 0,3$
Permeable	$0,3 < K_f \leq 3$
Highly permeable	$3 < K_f \leq 30$
Extremely permeable	$K_f > 30$

* It is also applied to the class of dispersed soils.

Arrays of rocky soils are divided according to the degree of fracture in accordance with the criteria of continuity of the massif, exogenous changes in the massif, relative velocity of elastic waves in the massif and moduli of deformation. In addition, among the recommended characteristics in current

standards there is an *indicator of rock quality* – Rock Quality Designation RQD, % – the ratio of the total length of core pieces longer than 10 cm to the length of the drilling run in the borehole.

The main modern letter designations, as well as international names of the characteristics of rocky soils are given in table. 4.2.10.

Table 4.2.10

Designations and names of the main characteristics of rocky soils

Designation, Name of characteristic	Unit of measurement	International name of the characteristic
R_c	MPa	Tensile strength in uniaxial compression
R_s	MPa	
ρ	$\text{g/cm}^3, \text{t/m}^3$	Soil density
ρ_d	$\text{g/cm}^3, \text{t/m}^3$	Dry soil density
n	Unit shares	Porosity
q_{sr}	g/l	Solubility
E	MPa	Modulus of deformation
RQD	%	Rock Quality Designation
k	m/day, cm/s	Coefficient of permeability

4.2.2. Examples of determining the classification construction characteristics of rocky soils

Example 1. Single layer incision

Initial data:

IGE1 – rocky soil – yellowish-gray oolite limestone, with ironing spots, inclusions of mollusk shells, highly fractured near the surface

The density of weathered soil – $\rho = 1.90 \text{ g/cm}^3$;

The density of un-weathered soil – $\rho_m = 2.77 \text{ g/cm}^3$;

The density of dry soil $\rho_d = 1.7 \text{ g/cm}^3$;

Temporary resistance to uniaxial compression in the air-dry state – $R_s = 14.4 \text{ MPa}$;

Temporary resistance to uniaxial compression in a water-saturated state – $R_c = 5.7 \text{ MPa}$;

The degree of solubility in water $q_{sr} = 0.05 \text{ g/l}$;

Permeability = 60 m/day;

Porosity $n = 20\%$.

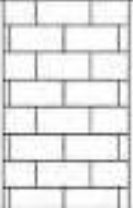
Geological index	IGE Number	Depth of bedding, m	Depth of the soil, m	Layer power, m	Lithological column	Geological and lithological description
lv	1	0	10	10		oolitic limestone, yellowish gray, with iron spots, inclusions of mollusk shells, fissured

Fig. 4.2.5. Engineering-geological logging (column) for example 1

The procedure for determining:

1. According to table 4.2.1, we determine the variety of soil in terms of $R_c = 5.7$ MPa. Therefore, the soil is of low strength.

2. We find the softness coefficient in water:

$$k_{\text{sof}} = \frac{R_c}{R_s} = \frac{5,7}{14,7} \approx 0,4 ,$$

According to table 3, the soil is soft.

3. We find the coefficient of weathering of the soil:

$$k_{\text{wr}} = \frac{\rho}{\rho_m} = \frac{1,90}{2,77} = 0,69 ,$$

In accordance with table 4.2.4, the soil is *highly weathered (crumble)*.

4. There are no data on soil salinity, therefore this indicator is not involved in the full classification name of soil.

5. According to table 4.2.6, we determine the type of soil according to the degree of solubility in water. At $0.01 < q_{\text{sr}} \leq 1$, the soil is *hardly soluble*.

6. Varieties of rocky soils by the density of dry soil are determined by the table. 4.2.7. At $2.10 > \rho_d \geq 1.20$, *medium density soil*.

7. Varieties of rocky soil porosity determined by the table. 4.2.8. At $10 < n \leq 30$, the soil is *moderately porous*.

8. The variety of rocky soils by water permeability is determined by table 4.2.9. At $K_f = 60$ m/day, the soil is *very highly permeable*.

CONCLUSION: soil – oolitic limestone of low strength, medium density, soft, highly weathered, sparingly soluble, medium-porosity, very highly permeable.

Example 2. A two-layer incision

Geological index	IGE Number	Depth of bedding, m	Depth of the sole, m	Layer power, m	Lithological column	Geological and lithological description
Vol	1	0.0	5	8		Volcanic Tuff Andesite
YPR	2	5	12	7		Granite light gray, fissured, coarse-grained, reddish

Fig 4.2.6. Engineering-geological logging (column) for example 2

Initial data:

IGE 1

Rocky soil – volcanic tuff andesitic.

The density of weathered soil – $\rho = 1.1 \text{ g / cm}^3$;

The density of un-weathering soil – $\rho_m = 1.51 \text{ g / cm}^3$;

Density of dry soil $\rho_d = 1.38 \text{ g / cm}^3$;

Temporary resistance to uniaxial compression in the air-dry state –
 $R_s = 65.4 \text{ MPa}$;

Temporary resistance to uniaxial compression in a water-saturated state –
 $R_c = 33.6 \text{ MPa}$;

The degree of solubility in water is $<0.01 \text{ g / l}$;

Permeability $K_f = 7 \text{ m/day}$;

Porosity $n = 35\%$.

IGE 2

Rocky soil – light gray granite, fissured coarse-grained.

The density of weathered rock – $\rho = 2.86 \text{ g/cm}^3$;

The density of un-weathered soil is $\rho_m = 2.97 \text{ g/cm}^3$;

Density of dry soil $\rho_d = 2.8 \text{ g/cm}^3$;

Temporary resistance to uniaxial compression in the air-dry state –
 $R_s = 360.5 \text{ MPa}$;

Temporary resistance to uniaxial compression in a water-saturated state –
 $R_c = 345.4 \text{ MPa}$;

The degree of solubility in water is insoluble;

Permeability $K_f = 0.05$ m/day;

Porosity $n = 5\%$.

The procedure for determining:

IGE 1

1. According to table 4.2.1, we determine the variety of soil in terms of $R_c = 33.6$ MPa. Consequently, the soil is of *medium strength*.

2. We find the coefficient of softness in water:

$$k_{\text{sof}} = \frac{R_c}{R_s} = \frac{345,4}{360,5} \approx 0,95,$$

According to table 4.2.3, the soil is *soft*.

3. We find the coefficient of weathering of the soil:

$$k_{\text{wr}} = \frac{\rho}{\rho_m} = \frac{2,86}{2,97} = 0,96,$$

In accordance with table 4.2.4, the soil is highly *weathered (crumble)*.

4. There are no data on soil salinity, therefore this indicator is not involved in the full classification name of soil.

5. According to table 4.2.5, we determine the type of soil by the degree of solubility in water. Soil is *insoluble*.

6. Varieties of rocky soils by the density of dry soil are determined by the table. 4.2.7. At $2.10 > \rho_d \geq 1.20$, *medium density soil*.

7. Varieties of rocky soil porosity determined by the table. 4.2.8. At $n > 30$, the soil is *highly porous*.

8. The variety of rocky soil permeability is determined by the table. 4.2.9. At $3 < K_f \leq 30$, the soil is highly permeable.

CONCLUSION: soil – volcanic tuff of medium strength, soft, highly weathered, insoluble, medium density, highly porous, highly permeable.

IGE 2

1. According to table 4.2.1, we determine the variety of soil in terms of $R_c = 345.4$ MPa. Therefore, the sample is *very strong*.

2. We find the softness coefficient in water:

According to table 4.2.3, the soil is *non-softening*.

3. We find the coefficient of weathering of the soil:

Since $1 > k_{wr} \geq 0.9$, then, in accordance with table 4.2.4, the soil is slightly weathered (*fractured*).

4. There are no data on soil salinity, therefore this indicator is not involved in the full classification name of soil.

5. According to table 4.2.6, we determine the type of soil according to the degree of solubility in water. *Soil is insoluble*.

6. Varieties of rocky soils according to the density of dry soil are determined according to table 4.2.7. At $\rho_d \geq 2.50$, the *soil is very dense*.

7. Varieties of rocky soils by porosity are determined according to Table 4.2.8. At $3 < n \leq 10$, the soil is *slightly porous*.

8. The variety of rocky soil permeability is determined by the table. 4.2.9. At $K_f = 0.05$ m/day, the soil is *poorly permeable*.

CONCLUSION: soil – very strong granite, non-softening, slightly weathered, insoluble, very dense, weakly porous, poorly permeable.

Control questions to chapter 4.2. Rocky soils and their building properties

1. What is rocky soil?
2. What is the ultimate tensile strength of soil in uniaxial compression?
3. What soils are called semi-rocky soils?
4. Name the types of soil according to the ultimate strength of the soil for uniaxial compression.
5. Describe the method used to determine the softness coefficient in water?
6. What types of soil are softened in water?
7. How do we determine the coefficient of weathering?
8. What are the varieties of rocky soils in terms of weathering?
9. How is rocky soil divided by salinity?
10. What types of soils are soluble in water?
11. How is rocky soil classified by the density of dry soil, by porosity and by permeability?

Chapter 4.3. DISPERSED SOILS AND THEIR ENGINEERING PROPERTIES

Dispersed soil – is a heterogeneous natural material consisting of individual solid particles: grains of minerals, rock fragments and other elements between which there are physical, physico-chemical or mechanical structural bonds. Dispersed soils, as a rule, are normally sedimentary and less often of pyroclastic origin.

Sedimentary rocks differ sharply from igneous and metamorphic rocks (rocky soils). The composition of the components that make up dispersed soils of sedimentary genesis is often very heterogeneous, because they are most often formed from a variety of matter – rock fragments, organic residues, chemogenic formations, and more recently, technogenic ones have been added to natural components. The characteristic features of sedimentary rocks associated with the conditions of their formation are stratification – occurrence in the form of more or less regular horizontal or slightly inclined formations, the composition and properties depending on the climate of the area, the presence of inclusions of organic matter and various salts. More than half (up to 60 %) of the composition of the sedimentary rocks of the earth's crust and, accordingly, of dispersed soils, are represented by relatively young terrigenous sediments – thick strata of fine clastic complexes of clay and loam; in second place (15–17 %) – loose and cemented clastic rocks with fragments ranging from huge blocks to sand and silt (Fig. 4.3.1, 4.3.2).



Fig. 4.3.1. Block soil with sand and clay aggregate, Thailand. Photo by V. Benko

Rocks of sedimentary origin occupy $\frac{3}{4}$ of the earth's surface and, therefore, dispersed soils in the form of terrigenous (clastic) sedimentary rocks are the most common bases for various buildings and structures. In addition, dispersed

soils are widely used as building materials: rubble, crushed stone, sand or as raw materials for the production of building materials, for example, sand – in concrete, clay and loam – for brick production.



Fig. 4.3.2. Sandy grounds, Novoselivsky mining and processing plant, Kharkiv region, Ukraine. Photo by V. Iegupov

4.3.1. Classification characteristics of dispersed soils

According to the size of the particles, the mineral components that make up the soil are subdivided as shown in tab. 4.3.1.

Table 4.3.1

Composition and names of fragments in the composition of dispersed soils

Fragments and particles composing soil	International names	Fractions	Size, mm
Boulders (rounded), blocks (angular)	Boulders	Large	> 800
		Medium	400–800
		Small	200–400
Pebbles (rounded), crushed stone (angular)	Cobbles	Large	100–200
		Medium	60–100
		Small	10–60

Table continuation 4.3.1

Fragments and particles composing soil	International names	Fractions	Size, mm
Gravel (rounded), grit (angular)	Gravel	Large	4–10
		Small (fine)	2–4
Sand particles	Sand	Large	1–2
		Coarse	0,5–1
		Medium	0,25–0,5
		Small	0,1–0,25
		Fine	0,05–0,1
Dusty particles	Silt	Large	0,01–0,05
		Fine	0,002–0,01
Clay particles	Clay		< 0,002

In the class of dispersed soils, two subclasses (groups) are distinguished:

- *cohesionless or granular soils* – dispersed soils having only mechanical structural bonds between particles and flowability in a dry state;
- *cohesive soils* – dispersed soils with physical and physico-chemical structural bonds in the form of mineral (silty-clay), mineral-organic (silt, sapropel) and organic formations (peat).

4.3.1.1. Subclass (group) of cohesionless or granular soils

4.3.1.1.1. Coarse soil. Origin and general engineering-geological characteristics

Coarse soil consists of separate rock fragments, between which there are only mechanical interactions due to friction. They are usually relatively weakly compressible, have a fairly high shear resistance and a very significant permeability. Under natural conditions, these soils are most often represented by pebble and gravel with sand or clay aggregate.

The largest components that form the soil framework, mainly determine the deformation characteristics of the soils under consideration at the foot of various structures. The petrographic composition, the different shape and degree of angularity or roundedness of the fragments depend on the composition of the destroyed rocks and the genesis of large-fragment clasts, which have different engineering and geological features.

For example, *alluvial coarse clastic* soils are widespread in the valleys of mountain rivers, which usually have a fast, rapid current capable of transporting large material (gravel, pebbles, and sometimes boulders). Due to the coarse-grained composition of these deposits, they have low compressibility under load and high shear resistance, as well as very high permeability (coefficient of permeability up to 100 m/day or more).

Extensive cones of the removal of poorly sorted clastic material, which are one of the types of proluvial deposits, are deposited when temporary waters flow out of the mountains onto the plains. A special variety of the latter is mudflow deposits – the result of mudstone flows, in a state of semi-fluid viscous masses overloaded with solid material. *The proluvial coarse clastic soils* (deposits of drift cones and especially mudflow formations) are characterized by weak sorting and angularity of the debris. The total porosity of the considered coarse soil can be very low (15–20%). Unlike washed and well-sorted alluvial deposits, proluvial and especially mudflow deposits may contain soluble salts, which is especially typical for areas with arid and hot climates.

Coarse clastic soils are formed during the destruction of rocks on the shores of the seas due to the activity of sea waves (abrasion). As a rule, they have high water permeability, the content of small-fragment aggregate in their composition, as a rule, is very small. These deposits are characterized by a very dense arrangement of pebbles and gravels. Almost incompressible vertically, at the same time, they may have a reduced resistance to lateral shear due to the fact that the rounded fragments have a smooth polished surface.

Eluvial coarse clastic soils are formed on the site of igneous or metamorphic rocks under the influence of factors of predominant physical weathering and form clusters of large rock fragments at the place of their destruction. The eluvial formations differ little in petrographic composition from the parent rock, which lies deeper. However, in its properties, it can qualitatively differ from the bedrock. In the event that rocks are deposited on steep slopes, under the influence of gravity, rock fragments fall, slide down and from the impacts received by them, break up into smaller parts. The accumulations of such masses are the particular strata of coarse clastic soils – *gravitational deposits*.

A special group consists of *technogenic coarse soil*: dumps of mining enterprises, artificial structures – dams, (Fig. 4.3.3), embankments of railways and roads; accumulations of industrial and construction waste. The properties of such soils vary over a very wide range.



Fig. 4.3.3. Coarse clumpy soil on the lower slope of the dam of the cooling pond of the South Ukrainian NPP. Photo by V. Iegupov

4.3.1.1.2. Classification characteristics of coarse soil

Mandatory regulatory requirements for the characteristics of coarse soil are the allocation of their varieties relative to the following five indicators:

- particle size distribution, determining the name of the soil;
- the degree of heterogeneity of the particle size distribution of Cu;
- coefficient of water saturation (degree of saturation) Sr;
- coefficient of weathering of large fragments Kwr;
- coefficient of abrasion of large fragments Kfr.

Non-cohesive soils are classified by their particle size distribution (percentage by weight of fragments of various sizes) with the appropriate name. The particle size distribution curve is generally established by the sieve method (according to standards). Evaluation of the angularity or roundedness of soil particles is carried out by visual inspection.

The name of coarse soil, depending on the particle size distribution – the percentage of fractions (debris) of various sizes, is selected in accordance with table. 4.3.2.

Table 4.3.2

Classification of coarse soil by particle size distribution

Varieties of soils		Size of fractions, mm	Content of fractions, %
From rounded debris	From the angular debris		
Boulder soil	Block soil	>200	>50
Pebble soil	Gravelly soil	>10	>50
Gravel	Grit	>2	>50

Note: to establish the name of the soil by tab. 4.3.2 the percentages of the fractions of the test soil are summed up successively: first, larger than 200 mm, then larger than 10 mm, then larger than 2 mm. The name of the soil is taken according to the first satisfactory indicator in the order of the names in the tab. 4.3.2.

If there is more than 40% of sand aggregate in coarse soil or clay aggregate more than 30% of the total mass of air-dry soil, the name of the aggregate type is added to the name of coarse soil and the characteristics of its state are indicated. The type of aggregate is established after removing particles larger than 2 mm from coarse soil. If clastic material is represented by a shell in an amount of $\geq 50\%$, the soil is called shell, if 30 to 50% is added to the name of the soil with a shell.

According to the degree of heterogeneity of the granulometric composition of Cu, coarse soils and sands are classified according to tab. 4.3.3

Table 4.3.3

**Classification of coarse and sandy soils
according to the heterogeneity of particle size distribution**

Varieties of soils	The degree of heterogeneity of the particle size distribution of, C_u
Homogeneous soil	$C_u \leq 3$
Heterogeneous soil	$C_u > 3$

The degree of heterogeneity of the particle size distribution of Cu, is determined by the formula

$$C_u = d_{60}/d_{10},$$

where d_{60} is the diameter of the particles, less than which 60% of the particles are contained (by weight) in this soil;

d_{10} – particle diameter, less than which in this soil contains (by weight) 10% of the particles.

To determine d_{60} and d_{10} , an integral curve of the particle size distribution of the soil is used, which is a graph that reflects the total percentage by weight of all fractions (debris) to a certain diameter.

According to the coefficient of water saturation (degree of saturation) S_r – large-fragmented soils and sands are classified according to the table. 4.3.4

Table 4.3.4

Classification of coarse and sandy soils by water saturation coefficient

Varieties of soils	Degree of saturation, S_r %
Slightly saturated (low moisture)	$0 < S_r \leq 0,5$
Moderately saturated (wet)	$0,5 < S_r \leq 0,8$
Saturated	$0,8 < S_r \leq 1,0$

The degree of saturation S_r – is an indicator that represents the fraction of the filling of soil pores with water, determined by the formula:

$$S_r = \frac{V_w}{V_n} = \frac{W\rho_s}{e\rho_w},$$

where V_w is the volume of water in the soil sample, cm^3 ; V_n – pore volume in the soil sample, cm^3 ; e – soil voids ratio equal to

$$e = \frac{V_n}{V_s} = \frac{\rho_s}{\rho} - (1 + W) - 1,$$

where V_s is the volume of solid particles in the soil sample, cm^3 ; W – natural soil moisture; ρ – soil bulk density (natural moisture), g/cm^3 ; ρ_s – soil particle density, g/cm^3 ; ρ_w is the density of water, taken equal to $1\text{ g}/\text{cm}^3$.

According to the coefficient of weathering of large fragments K_{wrt} , large-fragmented soils are classified according to tab. 4.3.5.

Table 4.3.5

**Classification of coarse soil
by the coefficient of weathering of large fragments**

Varieties of soils	The weathering coefficient of large fragments, K_{wrt}
Slightly weathered	$0 < K_{\text{wrt}} \leq 0,5$
Moderately weathered	$0,5 < K_{\text{wrt}} \leq 0,75$
Highly weathered	$0,75 < K_{\text{wrt}} \leq 1,0$

The weathering coefficient of coarse soil K_{wrt} , is determined by the formula:

$$K_{wrt} = \frac{K_1 - K_0}{K_1},$$

where K_1 is the ratio of the mass of particles less than 2 mm in size to the mass of particles larger than 2 mm after the abrasion test in a shelf drum; K_0 – the same K_1 but in a natural state.

According to the coefficient of abrasion of large fragments K_{fr} , large-fragmented soils are divided according to table. 4.3.6.

Table 4.3.6

Classification of coarse soil by the coefficient of abrasion of large fragments

Varieties of soils	Abrasion coefficient of large fragments K_{fr}
Very durable	$K_{fr} \leq 0,05$
Durable	$0,05 < K_{fr} \leq 0,20$
Medium strength	$0,20 < K_{fr} \leq 0,30$
Low strength	$0,30 < K_{fr} \leq 0,40$
Reduced strength	$K_{fr} > 0,40$

The coefficient of abrasion of coarse-grained soils K_{fr} , is determined by the formula:

$$K_{fr} = \frac{q_1}{q_0},$$

where q_1 is the mass of particles smaller than 2 mm after testing coarse fractions of the soil (particles larger than 2 mm) for abrasion in a shelf drum; q_0 is the initial sample weight of coarse fractions (before the abrasion test).

Generally, coarse-grained soils serve as good foundation for buildings and structures, when densely packed, they are only slightly compacted under load, and have high permeability. However, the experience of building road embankments and hydraulic structures from coarse soil indicates that insufficient knowledge or underestimation of their features in some cases can lead to significant deformations causing destruction of objects. In addition, significant difficulties arise in the construction of structures due to the lack of rational technology for compaction of coarse soil in the body of embankments.

Fragments of rocky soil can be water resistant (softening coefficient above 0.75), for example, fragments of igneous and metamorphic rocks that do not

change their strength properties when wetted, for example granite, basalt and diorite are waterproof (softening coefficient below 0.75). Non-water-resistant, softened varieties include such easily weathering rocks as marl, flask, mudstone, siltstone and shale.

Many varieties of coarse soil, containing a large amount of clay material or a non-water-resistant skeleton, are characterized by a significant deterioration in engineering properties during wetting. The increased content of clay aggregate in the composition of coarse soil leads to a decrease in its strength (angle of internal friction ϕ and cohesion c) and deformation (deformation modulus E) characteristics; permeability sharply decreases with possible manifestation of heaving.

These features should be taken into account when using coarse soil as the basis of construction objects or material in the construction of artificial structures.

4.3.1.1.3. Sandy soil (sand). Origin and general engineering and geological characteristics

Sandy soil or sand is a soil, consisting mainly of individual mineral particles with a size of 0.05–2 mm. Sands are extremely widespread on Earth. They are the products of the destruction of rocky and coarse hard rocks mainly under the influence of factors of physical weathering: climate, water and wind. Usually, sand contains mostly quartz, as the most stable mineral in the composition of the initial rocks subjected to weathering. Due to the predominance of quartz in its composition, sand is the main raw material in glass production. Millions of tons of sand are used in the melting of metals; they serve as raw materials for the manufacture of many building products and materials (brick, concrete). Sandy soils often serve as the basis for buildings and engineering structures.

The characteristic features of sand, their physical and mechanical properties are largely determined by their genesis. Sands, of origin, can be sea sand, river sand, lake sand, aeolian sand, among others. For practical purposes, the conditions of occurrence and the properties of the sand are important, since these conditions determine the possibility of their use as bases or environments for construction projects.

Genetic classification of sand according to P. I. Fadeev, containing their main types and processes of formation is given in tab. 4.3.7.

Alluvial sands are most common among sandy soils, among which there are a number of varieties that differ in particle size distribution, the presence of clay

and organic impurities due to their genesis (channel, old, floodplain, sediments of river terraces, etc.). The most characteristic feature of sand in riverbed sediments is a regular change in their composition from the source to the mouth of the river: the size of sand grains decreases downstream and its uniformity increases. Sufficiently good sorting and rounding of particles in channel sands, medium-density and loose addition contribute to their relatively high permeability. Sands that were deposited in the floodplains and rivers are mainly represented by small and dusty fractions having horizontal, oblique or lenticular stratification; they often contain clay and organic material impurities. These sands are much less permeable compared to channel sands and have much higher compressibility under load.

Table 4.3.7

Genetic classification of sand (according to P. I. Fadeev)

Exogenous processes	Types of processes			Genetic types of sand	Varieties of sand
	Weathering			Eluvial	-
	Denudation	Water activity	Rain and melt	Deluvial Proluvial	Eluvial
			River	Alluvial	River delta floodplain
			Glacial	Glacial	Fluvio-glacial
			Lake Marine	Lake Marine	Coastal and deep
		Ice activity		Glacial (moraine)	-
		Wind activity		Aeolian	Dune
Endogenous processes	Volcanic			Volcanic	-

The thicknesses of sea sands occupy large areas, have thickness up to several meters; they are most often well sorted by particle size, often monomineralic, for example, exclusively quartz (Fig. 4.3.4). Sea sands, with rare exceptions, have a high uniformity and good roundness of sand grains and also, their water permeability is usually very high. Sands formed under shallow water conditions are usually dense, especially those deposited in the surf zone. At the same time, deep sea sands often have loose structure and, consequently, the ability to give greater sediment under external loads.



Fig. 4.3.4. Sands of marine origin, consisting of 99.97% of quartz, Novoselovsky GOK, Kharkiv region. Photo by V. Iegupov

Aeolian sands are formed as a result of the corrosion-deflationary activity of the wind, especially manifested in deserts (Fig. 4.3.5). However, sands of mixed aeolian-alluvial origin are most widespread in the deserts of the world. This is due to the fact that most of the sand deserts of the world, paradoxically, have an alluvial origin. Aeolian processes, widely developed at present, intensified after the disappearance of rivers and desertification of territories. Under conditions of natural occurrence, aeolian sands are loose in composition and, in accordance with this, are significantly compacted under the action of loads. Sand grains in aeolian sands are ellipsoidal, sometimes almost spherical in shape. Good grading, uniform granulometric composition of these sands determines their high mobility and water permeability.



Fig. 4.3.5. Aeolian sands. "Oleshkivsky Sands" (Kherson region, Ukraine) – the largest sand desert in Europe
http://www.avestravel.com.ua/tour_image/tour_13_10_38_2.jpg

Fluvioglacial sands formed as a result of the activity of water flows from melting glaciers are represented by heterogeneous varieties: sands can be large, medium-sized and small. They contain a significant amount of coarse and angular material (gravel, blocks of moraine origin). Water-glacial sands are also widely developed, represented by fine sands and sands of medium size, formed during the retreat of the glaciers of global continental glaciation. These sands on Earth cover an area of hundreds of thousands of square kilometers.

Sands can differ significantly in the composition of the constituent particles and in their shape (Fig. 4.3.6).



Fig. 4.3.6. Different types of sand under a microscope: **a** – alluvial sand; **b** – coral sand dunes; **c** – aeolian gypsum sand; **d** – sea sand of shallow lagoons
a <https://www.q-files.com/earth/rocks>; **b** <https://upload.wikimedia.org/wikipedia/commons/thumb/c/c2/CoralPinkSandDunesSand.JPG/1280px-CoralPinkSandDunesSand.JPG>; **c** <https://upload.wikimedia.org/wikipedia/commons/thumb/8/8f/WhiteSandsGypsum.jpg/1280px-WhiteSandsGypsum.jpg>; **d** <https://www.spagece.ru/pesok-uvelichennyi-krupinki-peska-pod-mikroskopom.html>

4.3.1.1.4. Classification characteristics of sandy soils

Modern mandatory regulatory requirements for the characteristics of sandy soils are the allocation of their varieties according to the following indicators:

- particle size distribution, determining the name of the soil;
- the degree of heterogeneity of the particle size distribution of C_u ;
- coefficient of water saturation (degree of saturation) S_r ;
- density, depending on the porosity coefficient e .

In addition, for bulk sands, the following should be determined:

- density index I_D .

In the case of the presence of organic impurities in sandy soil, peat, soluble salts, it is necessary to determine:

- relative content of organic matter or peat I_r ;
- the degree of salinity of soils with easily and moderately soluble salts of D_{sal} .

The name of the sandy soil, depending on the particle size distribution, is determined in accordance with table. 4.3.8.

Table 4.3.8

Name of sandy soil by percentage of fractions

Varieties of soils	Sizes of fractions, mm	Content of fractions, %
Gravely sand	> 2	> 25
Coarse sand	> 0,5	> 50
Medium sand	> 0,25	> 50
Fine sand	> 0,1	³ 75
Dusty sand	> 0,1	< 75

By the degree of heterogeneity of the granulometric composition S_u and the coefficient of water saturation (degree of moisture) S_r , sandy soils are also classified as coarse soils (see tab. 4.3.3, 4.3.4).

The density of sand of natural origin is determined by tab. 4.3.9 in accordance with the name of the sandy soil and the value of the coefficient of porosity (voids ratio) e .

Table 4.3.9

Varieties of sandy soils by density

Kind of sand	The porosity coefficient e , unit fraction		
	Sands are gravely, large and medium-sized	Fine sands	Dusty sands
Dense	$e \leq 0,55$	$e \leq 0,60$	$e \leq 0,60$
Medium density	$0,55 < e \leq 0,70$	$0,60 < e \leq 0,75$	$0,60 < e \leq 0,80$
Loose	$e > 0,70$	$e > 0,75$	$e > 0,80$

According to the density index I_D , artificial sands are divided according to tab. 4.3.10.

Table 4.3.10

Varieties of artificial sands by density index I_D

Varieties of sand	The density index I_D
Loosely packed	$0 < I_D \leq 0,33$
Moderately packed	$0,33 < I_D \leq 0,66$
Densely packed	$0,66 < I_D \leq 1,00$

The density index of the sand I_D , is determined by the formula:

$$I_D = \frac{e_{\max} - e}{e_{\max} - e_{\min}},$$

where e is the coefficient of porosity, $e_{\min}$ is the porosity coefficient in the extremely dense condition, $e_{\max}$ is porosity coefficient in extremely loose condition.

According to the relative content of organic matter I_r , sandy and clay soils are classified according to table. 4.3.11.

Table 4.3.11

Relative organic matter I_r in sandy and clay soils

Varieties of soils	The relative content of organic matter, I_r
Mineral	$I_r \leq 0,03$
Organic and mineral:	
- mixed with organic matter	$0,03 < I_r \leq 0,10$
- low in organic matter	$0,10 < I_r \leq 0,30$
- high in organic matter	$0,30 < I_r \leq 0,50$
Organic	$I_r \geq 0,50$

Peat sandy soils are subdivided according to the relative content of organic matter I_r , according to the table. 4.3.12.

Table 4.3.12

Relative organic matter I_r in peaty sandy soils

Varieties of soils	The relative content of organic matter, I_r
Traces of peat	$0,03 \leq I_r \leq 0,10$
Slight peat content	$0,10 < I_r \leq 0,25$
Medium peat content	$0,25 < I_r \leq 0,40$
High peat content	$0,40 < I_r \leq 0,50$
Peat	$I_r \geq 0,50$

According to the degree of salinity of soils with readily and moderately soluble salts, D_{sal} %, soils are classified in accordance with the tab. 4.3.13 and 4.3.14.

Table 4.3.13

Soil salinity degree with readily soluble salts

Varieties of soils	Soil salinity degree with highly soluble salts D_{sal} %	
	chloride, sulfate-chloride salinity	sulfate, chloride-sulfate salinity
Non saline	$< 0,5$	$< 0,5$
Slightly saline	$0,5 \leq D_{\text{sal}} < 2,0$	$0,5 \leq D_{\text{sal}} < 1,0$
Saline	$2,0 \leq D_{\text{sal}} < 5,0$	$1,0 \leq D_{\text{sal}} < 3,0$
Highly saline	$5,0 \leq D_{\text{sal}} \leq 10,0$	$3,0 \leq D_{\text{sal}} \leq 8,0$
Excessively saline	$D_{\text{sal}} > 10,0$	$D_{\text{sal}} > 8,0$

Table 4.3.14

The degree of salinity of soils with medium soluble salts

Varieties of sandy soils	The degree of salinity of soils by medium-soluble salts (gypsum, anhydrite) D_{sal} %
Non saline	$D_{\text{sal}} \leq 3$
Slightly saline	$3 < D_{\text{sal}} \leq 7$
Saline	$7 < D_{\text{sal}} \leq 10$
Highly saline	$10 < D_{\text{sal}} \leq 15$
Excessively saline	$D_{\text{sal}} > 15$

According to the degree of frost heaving, dispersed soils are classified according to table. 4.3.15 *.

Table 4.3.15 *

Degree of frost heaving

Varieties of soils	Degree of heaving ϵ_{fn} %
Non-heaving	$\epsilon_{\text{fn}} < 1,0$
Weakly heaving	$1,0 \leq \epsilon_{\text{fn}} \leq 3,5$
Moderately heaving	$3,5 < \epsilon_{\text{fn}} \leq 7,0$
Strongly heaving	$7,0 < \epsilon_{\text{fn}} \leq 10,0$
Excessively heaving	$\epsilon_{\text{fn}} > 10,0$

* It is also used for the class of frozen soils.

The main modern letter designations, as well as international names for the characteristics of dispersed coarse and sandy soils, are given in the tab. 4.3.16.

Table 4.3.16

**Designations and international names of the
main characteristics of dispersed coarse and sandy soils**

Designation	Units	Characteristic name	Term used
ρ	$\text{g/cm}^3, \text{t/m}^3$	Soil density	Soil density
ρ_s	$\text{g/cm}^3, \text{t/m}^3$	Density of soil particles	Solid particles density
ρ_d	$\text{g/cm}^3, \text{t/m}^3$	Dry soil density	Dry soil density
n	fraction units	Porosity	Porosity
e	fraction units	Porosity coefficient	Void ratio
$e_{\max}$	fraction units	Sand porosity coefficient in extremely loose state	Maximum index void ratio
$e_{\min}$	fraction units	Sand density porosity	Minimum index void ratio
I_D	fraction units	Degree of density	Density index
w	fraction units	Moisture	Water content
S_r	fraction units	Water saturation coefficient	Degree of saturation
d	mm	Particle diameter	Particle diameter
C_u		The degree of heterogeneity of particle size distribution	Uniformity coefficient
D_{sal}	%	Soil salinity	Soil salinity degree
I_r	fraction of units	Relative organic content	Relative organic content
$\epsilon_{\text{fn}'}$	%	Degree of frostiness	The extent of frost heaving
E	MPa	Deformation modulus	Modulus of deformation
φ	degree	Friction	Angle of internal friction
c	kPa	Cohesion	Specific cohesion
K_f	m/day, cm/s	Permeability	Coefficient of permeability

When predicting the engineering properties of sand, i.e. the possibility of their use as the foundations of various buildings and structures, first of all, their density is estimated (Tab. 4.3.9). It depends on the granulometric composition of the sands and the porosity coefficient e . In general, dense sands are a good foundation for construction objects: when densely packed, the sands resist loads well and dissipate stress in the bases under the foundations. Sands of medium

density serve as a satisfactory base, and loose – regarded as poor base. It is possible to use loose sands as bases only after carrying out measures for the technical reclamation of soils (compaction, vibration compaction, silicification, etc.). In addition, the loose composition of the sand often goes into dense composition during water saturation and vibration-dynamic effects. The deformation modulus of the sand varies from 10 to 50 MPa and naturally decreases from coarse and dense to dusty and loose types of sand.

The presence of organic impurities and peat significantly worsens the bearing capacity of soils, since over time the organic matter decomposes, and structures built on organ-mineral and peat soils can suffer due to uneven settlement of the bases. Similar settlement can occur in saline base soils.

The permeability of sand naturally increases with increasing size of mineral grains. If the sands do not contain clay and organic material, then due to open porosity they are always permeable. In dusty sands, the Kf filtration coefficient is 0.1-1 m/day, in coarse sands – 40–50 m/day, and in gravelly sands – up to 80–100 m/day.

4.3.1.2. Subclass (group) of cohesive soils

4.3.1.2.1. Origin and general engineering-geological characteristics

A *cohesive soil* is a dispersed soil with physical and physico-chemical structural bonds (ion-electrostatic, capillary and molecular) between the particles composing the soil.

The most common types of cohesive soils are:

- *Mineral clay soils* – these are cohesive soils, consisting mainly of dusty and clay (at least 3%) particles, which have the property of plasticity when moistened (Fig. 4.3.7). These soils are represented by clay, loam, sandy loam and loess.



Fig 4.3.7. Cohesive clay soil plasticity
<http://semidelov.ru/media/uploads/glinyanyj-zamok-vokrug-fundamenta-kak-sdelat-oblast-primeneniya-o/Lv2NQbEnbs.jpg>

Organic and mineral soils are those containing from 3 to 50% by weight of organic matter. These include peat (or silty) soil – sand or clay soil, containing in its composition from 3 to 50% by weight of peat (or silt), including the following:

- *sludge* – a recent marine or freshwater sediment consisting of mineral and organic substances containing more than 3% by weight of organics, having a flowing consistency $I_L > 1$, porosity coefficient, as a rule, $e \geq 0.9$ and containing particles smaller than 0.01 mm, usually 30% or more by weight;

- *sapropel* – a recent (or buried) organo-genic-mineral or organic sediment of freshwater stagnant water bodies containing more than 10% by weight of organic matter, usually having a porosity coefficient $e > 3$ and a fluid-plastic or fluid consistency;

Organic soils are soils containing 50% by mass or more of organic matter, these include:

- *peat soil* (peat) – organic soil containing in its composition 50% by weight or more of organic matter, represented by plant residues and humus.

Eluvial soils are clay soils of dispersed zones of the weathering crust and soil (the surface layer of dispersed soil, consisting of inorganic and organic matter and having good fertility).

Mineral clay soils (clays, loams, sandy loams) are the soils most commonly found on Earth, and therefore they serve as the most common base for construction sites. The properties of these soils vary, depending on their genesis and composition.

The main source material for the formation of clay minerals in the composition of these soils is feldspars, which are contained in a large number of igneous and metamorphic rocks, during the decay of which they form under the influence of weathering processes.

Clay consists of one or several minerals of the group of layered aluminosilicates: kaolinite (by the name of the area of Khao Ling in China), montmorillonite (from the area of Montmorillon, France) or other clay minerals, but may also contain sand and carbonate particles. Generally, kaolinite is the rock-forming mineral in most clays. The diameter of the particles in the clay is less than 0.005 mm; rocks, consisting mainly of larger particles, are usually classified as loam and loess. Most clays are gray in color, but clays of white, red, yellow, brown, blue, green, purple and even black are also found (Fig. 4.3.8 a, b). Coloring is due to the presence of ion impurities – chromophores, mainly ferric iron, giving red, yellow color or ferrous iron – green, bluish.

In the mineral composition of loams (Fig. 4.3.8 c), in addition to clay minerals, there are (up to 30–50%) quartz, feldspars and other mineral grains having a particle size of 0.005–0.05 mm, called dusty.

In the *sandy loam* composition (Fig. 4.3.8 d), the main minerals are those remaining from the original weathered rocks (quartz, feldspars, etc.) in the form of sand particles (0.05–2.0 mm) and clay minerals are in a smaller amount – up to 10–20%.



a



b



c



d

Fig. 4.3.8. Mineral cohesive soils: **a, b** – clays; **c** – loam; **d** – sandy loam

a <https://ru.wikipedia.org/wiki/Clay#/media/File:Clay-ss-2005.jpg>;

b http://medicenterprises.com/wp-content/uploads/2014/08/2014-8-30_image9.jpg;

c Photo by V. Iegupov; **d** <http://6400999.ru/nerudnye-materialy/supes.jpg>

The subclass of cohesive soils includes rocks of sedimentary origin, but of various genetic types – alluvial, diluvial, marine, eluvial, glacial, among others.

Alluvial silty-clay deposits are very widely developed in the valleys of lowland rivers formed in the channels and rivers with a relatively slow flow. These deposits are distinguished by a diverse composition, properties, as well as numerous inclusions of organic material. This is due to the formation of clay alluvial strata in various conditions (channels and estuaries).

Diluvial clay soils, represented by thick strata on the slopes of mountains and other elevations, are deposits of various composition and properties. Quite

often, these deposits contain debris, gravels and other fragments of rocks, as well as plants. Artificial trimming of the diluvial stratum in the lower part of the slope, when digging a foundation pit for a building or road excavation can cause landslide movements of soils on the slope.

Marine clays are very common among deep-sea deposits in almost all seas and oceans, due to favorable hydro-chemical and hydrodynamic conditions during their formation. According to their mineralogical composition, marine clay soils are most often homogeneous, with typical soluble salts. When the clay dries up, salts can crystallize and create rigid bonds between rock particles. The presence of free silica (SiO_2) and iron oxides in marine clays increases their connectivity (cohesion), strength and water resistance. At the same time, iron sulfides and organic substances also found in their composition, when decomposed over time, cause a change in state and a deterioration in the strength properties of these soils.

Dusty clay eluvial soils are formed as a result of deep and long-term weathering of rocky soils and are mainly represented by loams and clays. Plant residues and organic matter are found in the upper soil layer formed on eluvial soils. Clays of this genetic type are often mono-mineral. These soils are characterized by a variety of geotechnical properties. The physic-mechanical characteristics of such varieties of eluvial deposits as loams and sandy loams vary widely depending on the amount and types of clay minerals in their composition. Their most plastic varieties are formed during prolonged weathering of intrusive and effusive rocks of the main composition. Weathering of rocks of an acidic composition, such as granite, yields almost non-elastic clays, having mainly kaolinite composition.

Glacial, fluvio-glacial, as well as proluvial clay deposits are most often represented by clays and loams with a characteristic poor sorting of the material and the presence of inclusions of rock fragments of various sizes. These soils are very heterogeneous in strength and water-filtration characteristics throughout their entire thickness.

4.3.1.2.2. Classification characteristics of cohesive soils

Mandatory regulatory requirements for the characteristics of cohesive soils are the allocation of their varieties according to the following indicators:

- I_p – plasticity index, which determines the name of the soil;

- percentage of sand particles;
- the presence of inclusions larger than 2 mm;
- consistency value, I_L ;
- relative swelling strain without load, ε_{sw} ;
- relative deformation of subsidence, ε_{sl} ;

If there are organic impurities, peat and soluble salts in the clay soil, it is necessary to determine:

- relative content of organic matter or peat, I_r ;
- degree of decomposition of peat, D_{dp} ;
- degree of salinity of easily and moderately soluble salts, D_{sal} .

For heaving soils, if necessary, the degree of frosty heaving, ε_{fn} , is determined.

The name of the cohesive clay soil, depending on the degree of ductility, is determined in accordance with tab. 4.3.17.

Table 4.3.17

The name of the dusty clay soil by plasticity index

Name of soil	Plasticity index I_p , %
Sandy loam	$1 \leq I_p \leq 7$
Loam	$7 < I_p \leq 17$
Clay	$I_p > 17$

The plasticity index I_p %, is a quantitative characteristic of the plastic properties of the soil and is determined by the formula:

$$I_p = w_L - w_p,$$

where w_L is the upper liquid limit or moisture at the yield point and is the maximum moisture above which the soil passes from a plastic state to a fluid one;

w_p – the lower liquid limit or moisture at the rolling border, %, this is the minimum moisture, upon reduction of which the soil passes from a plastic state to semi-solid.

According to the plasticity index and the content of sand particles, clay soils are subdivided according to tab. 4.3.18.

According to the presence of inclusions larger than 2 mm, clay soils are subdivided according to tab. 4.3.19.

Table 4.3.18

The plasticity index and the content of sand particles in clay soils

Varieties of soils		Plasticity index I_p , %	Content of sand particles (2–0.05 mm), % by weight
Sandy loam	Sandy	1–7	≥ 50
	Dusty	1–7	< 50
Loam	Slightly sandy	7–12	≥ 40
	Slightly dusty	7–12	< 40
	Highly sandy	12–17	≥ 40
	Highly dusty	12–17	< 40
Clay	Slightly sandy	17–27	≥ 40
	Slightly dusty	17–27	< 40
	Greasy clay	> 27	Not regulated

Table 4.3.19

The presence of inclusions larger than 2 mm in clay soils

Varieties of soils	The content of particles larger than 2 mm, % by weight
Sandy loam, loam, clay with pebbles and gravels or shells	From 15 to 25
Sandy loam, loam, pebble clay (gravel), gravel or shells	More than 25 to 50

The presence of sandy, and even more coarse clastic inclusions improves the strength properties of clay soils by increasing the forces of internal friction and reducing soil deformations under load.

According to the consistency value IL , clay soils are divided according to the table. 4.3.20.

I_L is an indicator of the state (consistency) of clay soils and is determined by the formula:

$$I_L = \frac{W - W_p}{I_p},$$

where w is the natural moisture content of the soil, %; w_p – soil moisture at the rolling border, %; I_p is the plasticity index, %.

hrinkage is the reverse process of swelling, which causes a decrease in the volume of a soil sample when it dries.

Table 4.3.20

Flow rate (consistency)

Varieties of soils	Consistency, I_L , fraction units
Sandy loam: - solid - plastic - liquid	$I_L < 0$ $0 \leq I_L \leq 1,00$ $I_L > 1,00$
Loams and clays: - solid - semi-solid - tough plastic - soft plastic - fluid plastic - liquid	$I_L < 0$ $0 \leq I_L \leq 0,25$ $0,25 < I_L \leq 0,50$ $0,50 < I_L \leq 0,75$ $0,75 < I_L \leq 1,00$ $I_L > 1,00$

In most cases, solid and semi-solid soils serve as good foundation for buildings and structures; plastic (sandy loam), slightly plastic to plastic (loam and clay) – satisfactory; and fluid plastic and fluid – bad. It is possible to use soils with a fluid-plastic or fluid consistency as bases, only after reconditioning measures for the technical reclamation of soils (drainage, silicification, etc).

Swelling and shrinkage of dusty clay soils

Swelling refers to the property of some fine-grained soils when moistened to increase in volume (swell), due to the thickening of the water shells around colloidal particles and secondly, due to chemical processes that entail a change in the composition and volume of the particles themselves. Almost all clay soils,



Fig. 4.3.9. Swelling clays

http://3.bp.blogspot.com/-xu5KEMJRSbM/TmWlZNwLiKI/AAAAAAAAABSE/ATbaP9KfD5w/s400/DSC_7067.JPG

including loams of deluvial and eluvial origin, can swell to a greater or lesser extent. Clay deposits of glacial lakes, consisting of alternating thin layers of fine-grained sand and clay (Fig. 4.3.9) containing the mineral montmorillonite, which, when soaked, are able to increase their volume by almost 4 times, have pronounced swelling properties.

Swelling soils are characterized by the relative swelling strain ε_{sw} , which is determined by the formula:

$$\varepsilon_{sw} = \frac{\Delta h}{h_k},$$

where Δh is the increase in sample height during swelling (swelling strain), mm; h_k is the initial height of the soil sample, mm.

Varieties of dusty clay soils by the relative deformation of swelling without load ε_{sw} are given in table. 4.3.21.

Table 4.3.21

Varieties of dusty clay soils on the relative deformation of swelling

Varieties of soils	Relative deformation of swelling without load, ε_{sw}
Non swelling	$\varepsilon_{sw} < 0,04$
Slightly swelling	$0,04 \leq \varepsilon_{sw} < 0,08$
Moderately swelling	$0,08 \leq \varepsilon_{sw} \leq 0,12$
Highly swelling	$\varepsilon_{sw} > 0,12$

Construction on swelling soils is subject to the compliance of requirements of the relevant standards.

The subsidence (collapse) of loess soils

The subsidence of loess soils is a phenomenon associated with the effect of water on the soil structure with its subsequent destruction or collapse. At the same time, additional deformation (subsidence) of loess soil vertically can occur both under the influence of its own weight, and with the total pressure of the own weight of the soil and the weight of the building (structure).

These soils include loess, loess-like loams, less often clay and sandy loam, with a high porosity coefficient $e \geq 0,7$ and low natural moisture content w from 0 to 17% ($S_r \leq 0,7$; $w < w_p$), as well as low density in dry state $\rho_d = 1.6 \text{ g/cm}^3$.

They are characterized by the relative deformation of subsidence:

$$\varepsilon_{sl} = \frac{h_p - h_{p, \text{sat}}}{h_p},$$

where h_p is the initial height of the soil sample, mm; $h_{p, \text{sat}}$ – the height of the same sample in a water-saturated state, mm.

Varieties of soils for the relative deformation of subsidence ϵ_{sl} are given in the tab. 4.3.22.

Table 4.3.22

Varieties of soils as per the relative deformation of subsidence

Varieties of soils	Relative deformation of subsidence, ϵ_{sl}
Non deformable	$\epsilon_{sl} < 0,01$
Slightly deformable	$0,01 \leq \epsilon_{sl} \leq 0,03$
Moderately deformable	$0,03 < \epsilon_{sl} \leq 0,07$
Highly deformable	$0,07 < \epsilon_{sl} \leq 0,12$
Extremely deformable	$\epsilon_{sl} > 0,12$

Construction on collapsible soils should be carried out in accordance with the requirements of standards.

According to the relative content of organic matter I_r clay soils are divided according to the table. 4.3.11, as well as sand.

Peat clay soils are divided according to the relative content of organic matter I_r according to tab. 4.3.23.

Table 4.3.23

Relative content of organic matter in peat clay soils

Varieties of soils	The relative content of organic matter, I_r
With peat	$0,05 \leq I_r \leq 0,10$
Slight peat content	$0,10 < I_r \leq 0,25$
Moderate peat content	$0,25 < I_r \leq 0,40$
High peat content	$0,40 < I_r \leq 0,50$
	$I_r \geq 0,50$

According to the degree of decomposition D_{dp} , peat is divided according to Table 4.3.24.

Table 4.3.24

Degree of decomposition D_{dp} of peat

Variety of peat	Degree of decomposition D_{dp} , %
Poorly decomposed	$D_{dp} \leq 20$
Decomposed	$20 < D_{dp} \leq 45$
Highly decomposed	$D_{dp} > 45$

According to the degree of salinity with readily soluble salts of D_{sa} , clay and sandy soils are subdivided according to tab. 4.3.13, and medium soluble according to tab. 4.3.25.

Table 4.3.25

The degree of salinity of soils with medium soluble salts

Varieties of soils	The degree of salinity of soils by medium-soluble salts (gypsum, anhydrite) D_{sal} , %	
	Loam	Sandy loam
Non saline	$D_{sal} \leq 5$	$D_{sal} \leq 5$
Slightly saline	$5 < D_{sal} \leq 10$	$5 < D_{sal} \leq 10$
Saline	$10 < D_{sal} \leq 20$	$10 < D_{sal} \leq 20$
Highly saline	$20 < D_{sal} \leq 35$	$20 < D_{sal} \leq 30$
Excessively saline	$D_{sal} > 35$	$D_{sal} > 30$

According to the degree of frost heaving ϵ_{fm} , clay soils, as well as sandy soils, are divided according to table. 4.3.15.

The main designations, as well as international names for the characteristics of dispersed cohesive soils are given in the tab. 4.3.26.

Table 4.3.26

**Designations and international names
of the main characteristics of dispersed cohesive soils**

Letter designation	Units	Name of characteristic	International name of the characteristic
ρ	g/cm^3 , t/m^3	Soil density	Soil bulk density
ρ_s	g/cm^3 , t/m^3	Density of soil particles	Solid particles density
ρ_d	g/cm^3 , t/m^3	Dry soil density	Dry soil density
n	fraction units	Porosity	Porosity
e	fraction units	Porosity coefficient	Voids ratio
w	%, fraction units	Moisture	Water content
S_r	fraction units	Water saturation coefficient	Degree of saturation
w_L	%, fraction units	Yield point	Liquid limit
w_p	%, fraction units	Rolling border	Plastic limit
I_p	%, fraction units	Plasticity number	Plasticity index
I_L	fraction units	Flow rate, consistency	Liquidity index

Table continuation 4.3.26

Letter designation	Units	Name of characteristic	International name of the characteristic
d	mm	Particle diameter	Particle diameter
D _{sal}	%	Soil salinity	Soil salinity degree
I _r	fraction units	Relative organic content	Relative organic content
ε_{fnt}	fraction units	Degree of frostiness	The extent of frost heaving
E	MPa	Deformation module	Modulus of deformation
φ	degree	Angle of internal friction	Angle of internal friction
c	KPa	Specific grip	Specific cohesion
k	m/day, cm/s	Filtration coefficient	Coefficient of permeability

4.3.2. Examples of determining the classification construction characteristics of dispersed soils

Example 3. Single layer logging

Geological index	IGE Number	The depth of the roof, m	Depth of the sole, m	Layer thickness, m	Lithological column	Geological and lithological description
gQ+	1	0.0	5.0	5.0		Coarse clastic soil from not rounded fragments of gneiss, m

Fig. 4.3.10. Engineering-geological column (logging) for example 3

Initial data: Coarse-grained soil, consisting of not rounded fragments of gneiss.

Granular composition of soil:

> 200 mm – 35%

200–100 mm – 25%;

100–60 mm – 10%;

60–40 mm – 9%;

40–20mm – 7%;

20–10 mm – 6%;

10–5 mm – 8%.

The degree of saturation $S_r = 0.3$.

The coefficient of weathering of large fragments $K_{wrt} = 0.8$.

The coefficient of abrasion of large fragments $K_{fr} = 0.3$.

The procedure for determining:

1. We determine the name of coarse soil by the percentage of fractions according to tab. 4.3.8:

For this purpose, we perform a summation over fractions starting with large sizes:

the content of particles larger than 200 mm is 35%, which is less than 50%, therefore the soil is not block soil;

the content of particles larger than 10 mm is $35 + 25 + 10 + 9 + 7 + 6 = 92\% > 50\%$, therefore, the classification name of this soil is *crushed stone*.

2. We build the total curve of the grain composition of crushed stone soil.

Table 4.3.27

Initial data for constructing the total curve of the particle size distribution of the soil

Particle diameter d, mm	<10	<100	<200
The content of particles by weight, %	8	65	100

The total curve of the grain composition of the soil is shown in fig. 4.3.8.

$d_{10} \approx 12$ mm, $d_{60} \approx 120$ mm

$$C_u = \frac{d_{60}}{d_{10}} = \frac{120}{12} \approx 10 > 3 ,$$

According to the degree of heterogeneity of the particle size distribution, $C_u = 10$ according to tab. 4.3.3 the soil is *heterogeneous*.

3. According to the degree of humidity S_r (Tab. 4.3.4), we note that the soil is *low moisture content*.

4. According to the coefficient of weathering of large fragments, K_{wrt} is *highly weathered* (Tab. 4.3.5)

5. According to the coefficient of abrasion of large fragments K_{fr} (Tab. 4.3.6) – *medium strength soil*.

Conclusion: The name of the variety of soil: crushed stone soil, heterogeneous, low moisture, highly weathered, moderately strong.

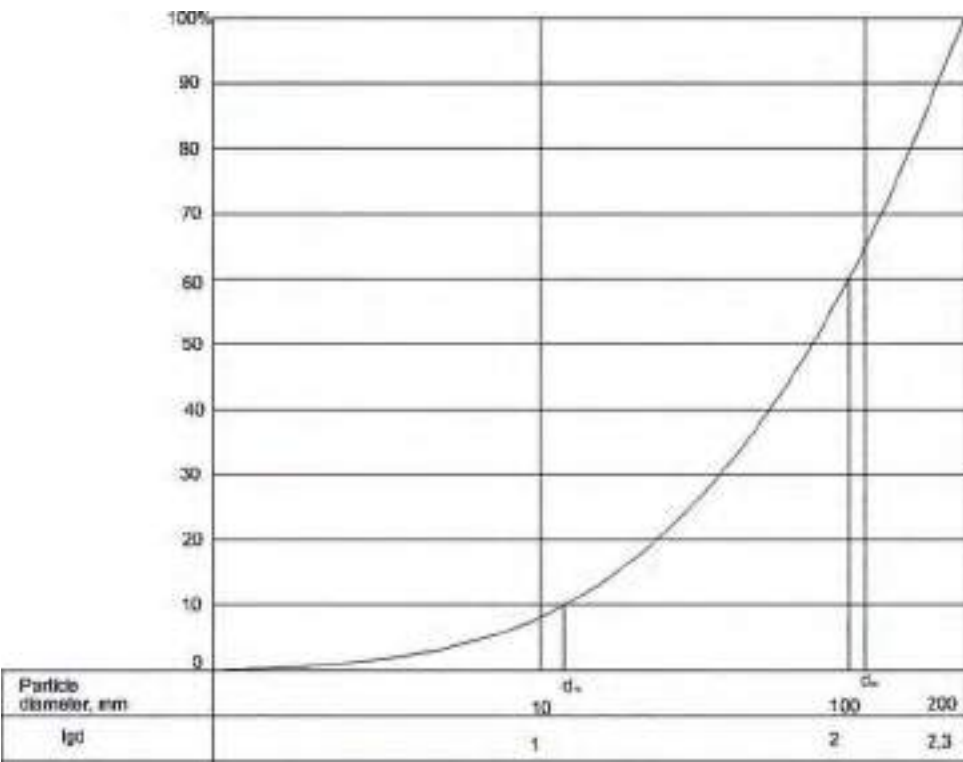


Fig. 4.3.11. The integral curve of the grain composition of coarse soil in a semi-logarithmic scale, for example 3

Example 4. Single layer logging

Geological index	IGE Number	Depth of bedding, m	Depth of the sole, m	Layer power, m	Lithological column	Geological and lithological description
dQs	1	0.0	6.5	6.5		Sand quartz fine-grained, dark gray, water-saturated, silted

Fig. 4.3.12. Engineering-geological column for example 4

Initial data: Sand quartz fine-grained dark gray water-saturated, silted.
Granular composition of soil:

10–2 mm – 1.5%;
 2–0.5 mm – 22%;
 0.5–0.25 mm – 24%;
 0.25–0.1 mm – 20%;
 0.1–0.05 mm – 22%;
 0.05–0.01 mm – 9%;
 0.01–0.005 mm – 0.8%;
 < 0.005 mm – 0.7%.

Voids ratio, $e = 0.65$.

Degree of saturation $S_r = 0.85$.

The relative content of organic matter $I_r = 0.05$.

The degree of frost heaving $\epsilon_{fn} = 0.8$.

The procedure for determining:

1. Determine the name of the sandy soil by the percentage of fractions according to tab. 4.3.8.

To do this, we perform a summation over fractions starting with large sizes:

- the content of particles larger than 2 mm is 1.5 %, which is less than 25 %, therefore, the sand is not gravel;
- the content of particles larger than 0.5 mm is $1.5 + 22 = 23.5\% < 50\%$ – the sand is not coarse;
- the content of particles larger than 0.25 mm is $23.5 + 24 = 47.5\% < 50\%$ – sand is not medium in size;
- the content of particles larger than 0.1 mm is $47.5 + 20 = 67.5\% < 75\%$ – the sand is not fine;
- since the sum of fractions larger than 0.1 mm is less than 75 %, *sand is dusty*.

Therefore, the classification name of the soil is *dusty sand*.

2. We build the total curve of the grain composition of sandy soil.

Table 4.3.28

Initial data for constructing the total curve of the granular composition of sandy soil

Particle Diameter d, mm	<0,005	<0,01	<0,05	<0,1	<0,25	<0,5	<2	<10
The content of particles by weight, %	0,7	1,5	10,5	32,5	52,5	76,5	98,5	100

The total curve of the grain composition of sandy soil is shown in Fig. 4.3.10.

$d_{10} \approx 0,04$ mm, $d_{60} \approx 0,31$ mm

$$C_u = \frac{d_{60}}{d_{10}} = \frac{0,31}{0,04} \approx 7,75 > 3 ,$$

According to the degree of heterogeneity of the particle size distribution, $C_u = 7.75$ according to the tab. 4.3.3 *sand is not uniform*.

3. According to the degree of saturation S_r (Tab. 4.3.4), we determine that the sand *is saturated with water*.

4. Varieties of sandy soil is determined by the tab. 4.3.9: *medium density sand*.

5. Variation in the relative content of organic matter I_r is determined by tab. 4.3.11: *organic-mineral soil mixed with organic matter*.

6. By the degree of frost heaving ϵ_{fn} , the *sand is not porous* (Tab. 4.3.15).

Conclusion: the name of the variety of soil: *dusty, non-uniform dusty sand, medium density, saturated with water, mixed with organic matter, non-porous*.

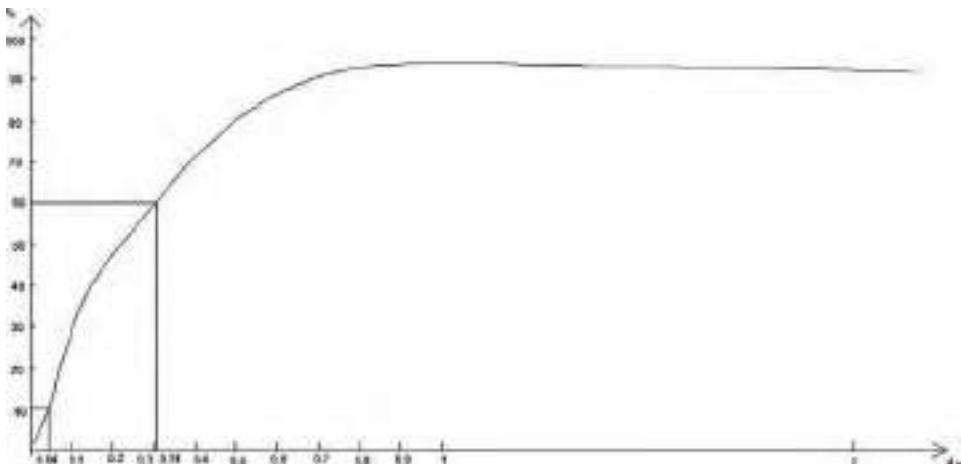


Fig. 4.3.13. The total curve of the grain composition of sandy soil for example 4

Initial data:

IGE 1

Loam is brownish-gray, massive, with inclusions of crushed stone and hard rocks up to 50%, with an inclusion depth increase.

The density of the soil is $\rho = 2.07 \text{ g / cm}^3$.

The plasticity index $I_p = 14.1\%$.

The consistency index $I_L = 0.35$.

The presence of inclusions larger than 2 mm – up to 50%.

$I_r = 0.01$.

Thickness – 4.6 m.

Example 5. Multilayer logging

Geological index	IGE Number	Depth of bedding, m	Depth of the sole, m	Layer power, m	Lithological column	Geological and lithological description
sdQsr	1	0	4.8	4.8		Loam is a stiff plastic brownish-gray, massive, with inclusions of crushed stone and debris of hard rocks up to 50%, with an inclusion depth increase.
sdQKr	2	4.8	5.1	0.5		Semi-solid loam, with cluses up to 20% gravel of limestone, brownish gray
Kr	3	5.1	10.3	5.2		The clay is hard, argillite-like, greenish-gray, layered, slightly ferruginous, slightly fissured, without inclusion, highly swelling

Fig. 4.3.14. Engineering-geological column for example 5

IGE 2

Loam is brownish gray with the inclusion of up to 20% of gravel and limestone.

The density of the soil is $\rho = 2.08 \text{ g / cm}^3$.

The plasticity number $I_p = 0.156$.

$I_L = 0.02$.

The presence of inclusions larger than 2 mm – up to 20%.

Thickness – 0.5 m.

IGE 3

Argillite clay is greenish-gray, dense, slightly ferruginous, slightly cracked, without inclusions, swelling.

The density of the soil is $\rho = 2.09 \text{ g / cm}^3$.

The plasticity index $I_p = 0.199$.

$I_L = -0.33$.

The presence of inclusions larger than 2 mm – nil.

Relative swelling $\epsilon_{sw} = 0.2$

Thickness – 5.2 m

Procedure:

IGE 1

1. Determine the name of the cohesive clay soil, depending on the plasticity index (Tab. 4.3.17). At $7 < I_p \leq 17$, the soil is *loam*.
 2. By the presence of inclusions larger than 2 mm in tab. 4.3.19 determine that the *loam is crushed*.
 3. According to the consistency I_L (Tab. 4.3.20) we find that the *loam is semi-solid*.
 4. In the absence of ϵ_{sw} and ϵ_{sl} , we conclude that the soil is *neither swelling nor subsiding*.
 5. Peat clay soils are subdivided according to the relative organic matter I_r (Tab. 4.3.23): *loam without admixture of peat*.
 6. Determine the degree of salinity D_{sal} easily soluble salts as per the tab. 4.3.13, and moderately soluble – according to the table. 4.3.25 – *non-saline soil*.
- Conclusion: Loam is semi-solid, crushed, not swelling, not subsiding, without peat admixture, non-saline.

IGE 2

1. Determine the name of the cohesive clay soil, depending on the plasticity index (Tab. 4.3.17). At $7 < I_p \leq 17$, the soil is *loam*.
 2. By the presence of inclusions larger than 2 mm in tab. 4.3.19 determine that the *loam is chipped*.
 3. According to consistency, I_L (Tab. 4.3.20) we find that the *loam is semi-solid*.
 4. In the absence of ϵ_{sw} and ϵ_{sl} , we conclude that the soil is *neither swelling nor subsiding*.
 5. Peat clay soils are subdivided according to the relative organic matter I_r according to tab. 4.3.23. *Loam without admixture of peat*.
 6. Determine the degree of salinity D_{sal} easily soluble salts on the tab. 4.3.13, and moderately soluble – according to the table. 4.3.25 – *non-saline soil*.
- Conclusion: Loam is stiff, crushed, non-swelling, non-subsiding, without peat admixture, non-saline.

IGE 3

1. Determine the name of the cohesive clay soil, depending on the plasticity index (Tab. 4.3.17). At $I_p > 17$, the soil is *clay*.

2. By the presence of inclusions larger than 2 mm in tab. 4.3.19, we determine that the *clay without inclusions*.

3. According to the indicator of consistency I_L (Tab. 4.3.20) we find that the *clay is solid*.

4. At $\varepsilon_{sw} = 0.2$, the clay is *highly swelling*.

5. Peat clay soils are subdivided according to the relative organic matter I_r (Tab. 4.3.23): *clay without admixture of peat*.

6. Determine the degree of salinity D_{sal} easily soluble salts on the tab. 4.3.13, and moderately soluble – according to the table. 4.3.25 – *non-saline soil*.

Conclusion: The clay is solid, without inclusions, highly swelling, not subsiding, without peat admixture, non-saline.

General conclusion: The first layer (clay loam) and the second (semi-solid loam) may serve as a good base. For the third layer (hard clay, highly swelling), it is necessary to take into account the requirements of prevailing standards.

Example 6. Multilayer base

Initial data:

IGE 1

Organic soils are represented by clay humus with the roots of plants, from a depth of 0.5 m – salt marsh.

Thickness – 0.8m.

IGE 2

Clay, subsiding gray-yellow with the inclusion of amorphous gypsum and spots Mn and Fe lumpy hard.

The bulk density of the soil is $\rho = 1.75 \text{ g / cm}^3$.

The plasticity index $I_p = 24.4\%$.

Index $I_L = -0.09$.

The presence of inclusions larger than 2 mm – up to 10%.

Relative settlement $\varepsilon_{sl} = 0.02$

$I_r = 0.01$

Thickness – 6.7m.

IGE 3

The clay is brownish-yellow, ironized with a columnar structure, swelling.

The density of the soil is $\rho = 1.88 \text{ g / cm}^3$.

The plasticity index $I_p = 24.8\%$.

The value $I_L = -0.1$.

IGE 2

1. Determine the name of the cohesive clay soil, depending on the plasticity index (Tab. 4.3.17). At $I_p > 17$, the soil is *clay*.

2. By the presence of inclusions larger than 2 mm in tab. 4.3.19, we determine that the *clay without inclusions*.

3. According to the indicator of consistency I_L (Tab. 4.3.20) we find that the *clay is solid*.

4. At $0.01 \leq \varepsilon_{sl} \leq 0.03$ – the soil is *slightly subsiding*

5. Peat clay soils are subdivided according to the relative organic matter I_r (Tab. 4.3.2). *Clay without admixture of peat*.

6. Determine the degree of salinity D_{sal} easily soluble salts from tab. 4.3.13, and moderately soluble – according to the table. 4.3.25 – *non-saline soil*.

Conclusion: Solid clay without inclusions, non-swelling, slightly subsiding, without peat admixture, non-saline.

IGE 3

7. Determine the name of the cohesive clay soil, depending on the plasticity index (Tab. 4.3.17). $I_p > 17$, the soil is *clay*.

8. By the presence of inclusions larger than 2 mm in tab. 4.3.19, we determine that the *clay without inclusions*.

9. According to the consistency I_L (Tab. 4.3.20) we find that the *clay is solid*.

10. At $\varepsilon_{sw} = 0.11$, the clay is *moderately swelling*.

11. Peat clay soils are subdivided according to the relative organic matter content I_r (Tab. 4.3.23). *Clay without admixture of peat*.

12. Determine the degree of salinity D_{sal} easily soluble salts from tab. 4.3.13, and moderately soluble – according to the table. 4.3.25 – *non-saline soil*.

Conclusion: The clay is solid, without inclusions, moderately swelling, non-subsiding, without peat admixture, non-saline.

IGE 4

13. Determine the name of the cohesive clay soil, depending on the plasticity index (Tab. 4.3.17). At $I_p > 17$, the soil is *clay*.

14. By the presence of inclusions larger than 2 mm in tab. 4.3.19 determine that the *clay without inclusions*.

15. In terms of consistency I_L (Tab. 4.3.20) we find that the clay is *semi-solid*.

16. At $\varepsilon_{sw} = 0.13$, the clay is *highly swelling*.

17. Peat clay soils are subdivided according to the relative organic matter I_r (Tab. 4.3.23). *Clay without admixture of peat.*

18. Determine the degree of salinity D_{sal} soluble salts from tab. 4.3.13, and medium-soluble – according to Table 4.3.25 – *non-saline soil.*

Conclusion: Clay is semi-solid, without inclusions, highly swelling, non-subsiding, without peat admixture, non-saline.

General conclusion: The first layer cannot be used as a base. For the second layer (subsiding clay), it is necessary to take into account the requirements of prevailing standards. For the third layer (medium hard swelling clay) and the fourth layer (semi-solid strong swelling clay) it is again necessary to take into account the requirements of standards.

Test questions to chapter 4.3.

Dispersed (non-rocky) soils and their engineering properties

1. What is dispersed soil?
2. What subclasses are dispersed soils divided into?
3. What is non cohesive granular soil?
4. What are cohesive soils?
5. What are alluvial soils?
6. What are proluvial soils?
7. What is marine coarse soil?
8. What are eluvial soils?
9. What is technogenic coarse soil?
10. How are coarse-grained soils classified by particle size distribution?
11. How are coarse clastic soils classified by degree of heterogeneity?
12. How are coarse clastic soils classified by moisture?
13. What is the coefficient of weathering of coarse soil?
14. What is the coefficient of abrasion of large fragments?
15. What is sandy ground?
16. What are the varieties of sandy soils by the percentage of fractions?
17. What are the varieties of sandy soils by density?
18. What are the varieties of sandy soils by the relative content of organic substances?
19. How are dispersed soils classified by frost heaving?

20. What are the mineral-clay soils?
21. What are organo-mineral clay soils?
22. What are organic clay soils?
23. What are eluvial soils?
24. How is clay soil divided by the liquidity index (consistency)?
25. How is clay soil divided by consistency?
26. What is swelling?
27. How is clay soil divided by relative swelling?
28. What is shrinkage in soils?
29. What is the subsidence of loess soils?
30. What types of dusty clay soil are distinguished by relative subsidence?

Chapter 4.4. ARTIFICIAL SOILS AND TOPSOILS

Artificial soils are called rocks and soils that have undergone displacement as a result of the production and economic activities of people, or purposely changed by man in solving various engineering and construction problems. The engineering and geological properties of artificial soils depend on the composition, structure, bedding conditions of the original natural rocks, as well as the nature and intensity of human exposure to them. Their petrographic and lithological compositions, as well as the inclusion of various organic and inorganic substances can be very diverse. Depending on the main processes of their formation, they are divided into two subgroups.

The first subgroup combines artificial soils, which were formed in cases where special conditions for their creation were not required. This group includes *cultural layer* – that spontaneously arises on territories of populated areas, *bulk and artificial washed soils* – which are created by man during production activities, but without an aim of improving their engineering and geological properties. This subgroup of artificial soils also includes *degraded soils* – those natural soils in which the engineering and geological properties have changed in an unfavorable direction as a result of human exposure. According to standards, all of the above soils are called *man-made*, i.e. soils formed in a natural-historical way (cultural layers) or created by man in various ways. Their composition is represented by waste or products of industrial and/or economic activity that have become components of the geological environment. *Technogenic* soil is also encountered – altered, displaced or formed as a result of human engineering and economic activity.

Thus, the first subgroup of artificial soils combines rocks and soils that have arisen or noticeably changed their properties (most often in the direction of deterioration) under the influence of industrial, economic, domestic, military and other types of human activities.

The second subgroup of artificial soils combines rocks and soils that are purposely modified by human being in order to improve their engineering and geological properties. These are *improved soils*. According to standards, such soils are called *technologically altered* – that is, natural soils that have been deliberately subjected to technogenic effects of different nature (chemical, physical, physico-chemical, biological) at their place of occurrence. Issues of improving the engineering and geological characteristics of soils are handled by a special branch of soil science – *technical soil reclamation*.

4.4.1. Cultural layers, bulk and degraded soils

Cultural strata are a complex multicomponent engineering and geological formation. This stratum includes the upper soil layers of human settlements containing evidence and remnants of human activity. In places of human settlements, for decades and even centuries, layers have been formed starting from the surface of the earth, which in their material composition and properties differ significantly from the underlying natural soils. In the cultural layers, a wide variety of materials are found as residues: construction and household waste, broken brick, stone and wood debris, industrial waste, fragments of household items, clay shards, animal bones and coins, among others.

Cultural layers are located between the “mainland” (in archeology the so-called lower natural soil layer without any signs of human activity) and the upper soil and plant layer. The cultural layer is a specific formation, the study of which should be carried out with a combination of geological, historical and archaeological research methods. The cultural layer grows over time under the influence of many factors: how intensively life activity of people proceeds, building buildings being used, how much the surrounding soil is subject to erosion (desert or woodland), the location of the territory relative to the sea or rivers. Its thickness can be very different – from a few centimeters to several meters, and in ancient cities even tens of meters (Fig. 4.4.1).

The formation of the cultural layer is inextricably linked with the geological and geomorphological conditions of the area, with the history of the city or villages, with the nature of the economic, commercial and military activities of people. Cultural layers, depending on the time of their formation, are divided into ancient and modern. The ancient accumulations of the cultural layer have already managed to condense and acquire coherence and relative strength, respectively, if necessary, they can serve as foundations in the construction of roads and for the construction of foundations of small light buildings.

Under the modern bulk soil, sometimes called the *modern cultural layer* (F. P. Savarensky (1938), F. V. Kotlov (1947)), we mean loose, non-packed material often containing a lot of household garbage and undecomposed organic residues which may more correctly be called the “uncultured layer.”

The accumulation of *bulk soil* occurs during the construction of dumps during construction and excavation works, during the improvement of settlements and due to landfills of various debris. The modern layer of bulk soil is almost always unsuitable for laying building foundations.

The formation of *deteriorated soils* occurs as a result of various construction and mining operations. Deteriorated soils also include: artificially loosened (for example, during mass explosions), artificially moistened (for example, during intensive leaks from water lines), as well as thawed soils in permafrost zones. The resulting degraded soils retain their acquired properties for a long time, but often many types of degraded soils are again subjected to technical impact in order to give them the required physical and mechanical properties.

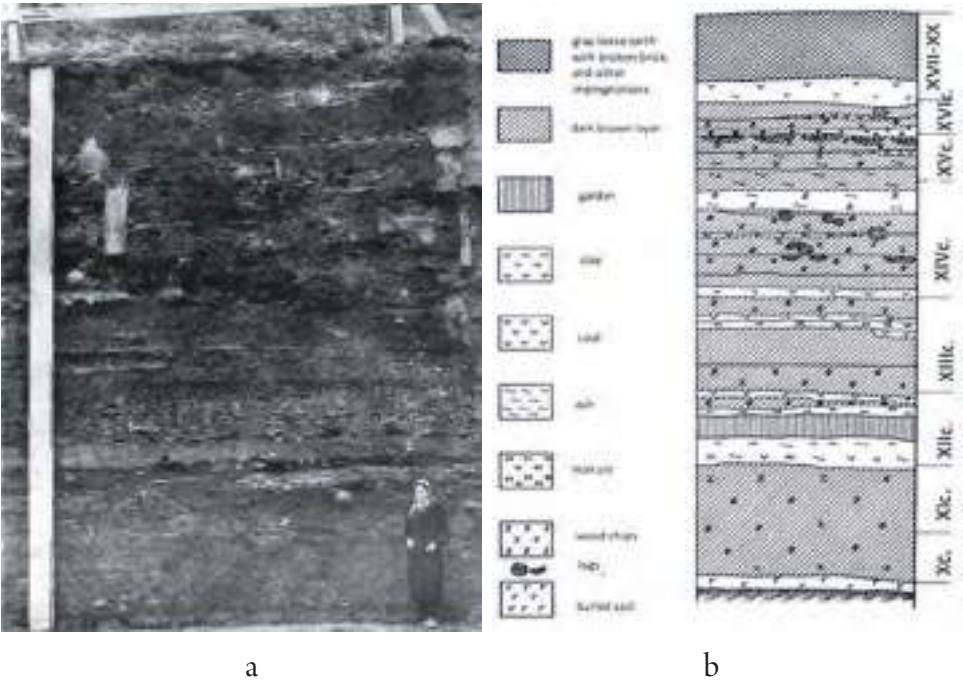


Fig. 4.4.1. The cultural layer in Great Novgorod, Russia:

a – section thickness; **b** – composition and age of deposits

<http://www.archeologia.ru/Library/Image/8dee3b31923d/show/pic87>

Over time, bulk soils are subject to self-compaction, the organic matter decomposes and soils gradually restore their natural engineering-geological properties. The standard time necessary for self-compaction of soils is given in tab. 4.4.1.

After a period of time, specified in the table. 4.4.1, bulk soils and industrial wastes are classified as compacted soils and they can be used for construction purposes.

Table 4.4.1

Duration of soil compaction

Types of bulk soil and industrial waste	Duration of self-sealing, years		
	Duration of self-sealing, years	Dump (heap)	Landfill
Coarse	0.2–1	1–3	2–5
Sand	0.5–1	2–5	5–10
Clay	2–5	10–15	20–30

Notes

1. Systematically constructed embankments are made of homogeneous soils and industrial wastes by dumping or alluvium with compaction to a given density of borrowed material.

2. Dumps are formed by dumping without compaction of various types of soils obtained during excavation of pits, overburden operations, excavation of underground workings, etc., as well as tailings of processing plants and industrial wastes.

3. Landfills, industrial waste and household waste are dumps formed as a result of unorganized accumulation of various materials.

Engineering and geological properties of bulk soils, consisting of waste from various industries are very diverse. Mining: coal, iron and other ores is associated with the extraction of a large number of rocks, storing them on the surface of the earth with possible subsequent processing. As a result, special varieties of bulk soils are created – waste rock. The same group of soils includes some solid mineral wastes of industrial production and transport, in particular slags, which, falling to the surface of the earth, become an integral part of the engineering-geological environment. Slag, which during cooling develops rigid internal bonds, can be used as reliable bases for engineering structures.

The following is recommended for natural foundations of buildings and structures:

- systematically built embankments from natural soils and environmental friendly production wastes;
- industrial dumps of soils and industrial waste (waste rock), consisting of crushed and gravel soils, coarse sands and slags.

Natural landfills and industrial waste dumps may only be used for the construction of facilities of the 3rd level of responsibility. **The use of**

landfills for the construction of natural foundations of buildings and structures is not allowed.

4.4.2. Washed soils

Washed soils are dispersed material, loose, finely fragmented waste from industrial and economic activities, as well as low-value minerals laid by hydro-mechanical methods – using various dredging mechanisms.

By reclamation, territories for residential and industrial buildings, dams, protective beaches on the shores of the seas and reservoirs, artificial islands on the shelf of the seas are created (Fig. 4.4.2).

The difference between washed soils from the original soils of natural occurrence and from bulk soils lies in the changed granulometric composition due to the removal (washing out with the hydraulic process) of some of the smallest fractions. The physic-mechanical properties of such soils can vary significantly over time: under the influence of natural compaction processes, the density of dry soil, the general strain modulus, specific adhesion, the angle of internal friction and so on.

Strength and deformation characteristics of washed soils are determined by the results of field and laboratory studies of undisturbed soils taking into account the time elapsed after the end of the deposit. The following varieties of soils are distinguished: freshly washed (1–3 months – 1 year after the end of the creation), compacted (several months to 1–3 years) and hardened (3–5 years and more).



Fig. 4.4.2. Artificially washed islands in the Persian Gulf, UAE

http://cache.emirates247.com/polopoly_fs/1.248079.1452319550!/image/image.jpg

The design of foundations on washed soils should be carried out according to the specifications of engineering and geological surveys carried out not earlier than three months after the end of the deposit process. The bases, composed of such soils, are designed taking into account their layering, variability of properties and composition in plan and section, ability to change physical and mechanical properties over time (including groundwater level fluctuations) and sensitivity to vibrational influences.

4.4.3. Topsoil

Soil is a special biogenic variation of the upper part of eluvial rocks. According to standards, topsoil is a surface layer of dispersed soil, consisting of inorganic and organic matter and having fertility. Topsoil formation is associated with the simultaneous impact on rocks/soils of two processes: weathering and topsoil formation. As a result of physical, chemical and biological weathering, clay soil is formed at its final stages and a long process of soil formation, primarily due to the activity of microorganisms and plants which introduce decomposition products of organic substances (humus) into this soil. Humus is an organic amorphous substance of black or brown color, giving the soil a corresponding color, consisting of specific organic compounds, the products of their interaction, as well as organo-mineral formations. As a result of complex soil formation processes, a surface soil-plant layer is created that lies on the original parent rocks (Fig. 4.4.3).



*Fig. 4.4.3. Topsoil-plant layer – chernozem, lying on loam, forest park in Kharkiv.
Photo by V. Iegupov*

The thickness of the soil cover is usually several tens of centimeters (for example, in the context of volcanic origin – Island of Mauritius) and for the regions of chernozems it is about 1 m, and in places even up to 2 m. These are often clay soils and more often silty loams, less often sandy loam, clay or clay sands. The soil-forming process is closely related to climatic conditions – in different natural zones, soils with different thickness and content of humus are formed: chernozem, chestnut, forest-steppe, etc. (Fig. 4.4.4).

The fertile soils of any country are the most important resource potential. The most fertile soils with a humus content of 3–7% and a thickness of a humus layer of 1 meter, which in Ukraine occupy about 10% of the territory.

Particularly valuable lands for agriculture include: chernozems on loess soils; meadow-chernozemic non-alkaline loamy soils; peat bogs with peat depths of more than one meter, as well as drained peat bogs; brown soils of the southern coast of Crimea; deep soddy soils of Transcarpathia.

Soils, due to their low density and friability, ability to easily soften when interacting with water and the presence of organic matter are unreliable bases for buildings and structures. The upper fertile layer must be removed from the construction site before construction works. In future, this soil is used for landscaping (for flower beds, greenhouses and green spaces).

Test questions for chapter 4.4.

1. What are artificial soils?
2. What subgroups are artificial soils divided into?
3. What is technogenic soil?
4. What is a cultural layer?
5. What are washed soils?

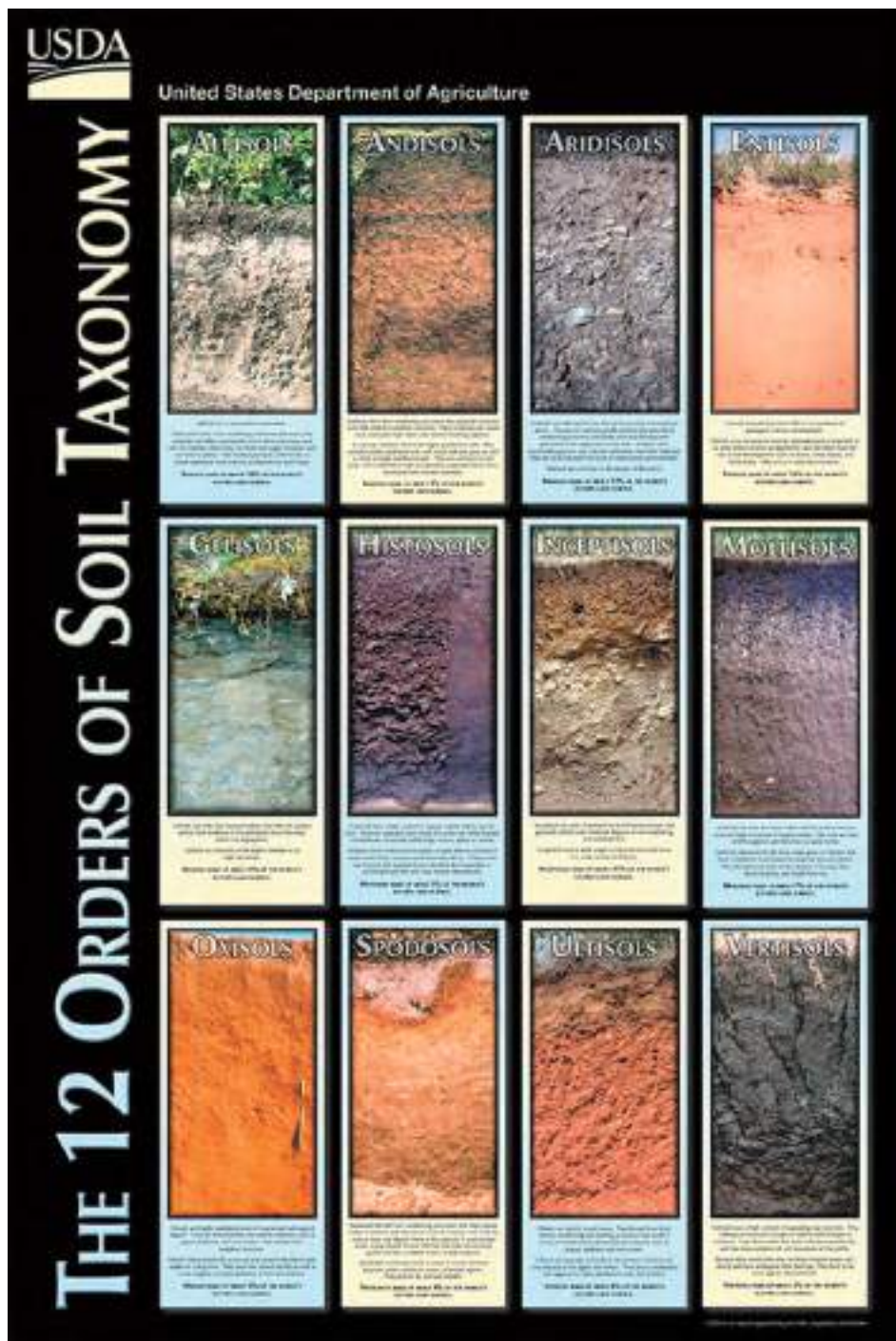


Fig. 4.4.4. Types of U. S. topsoil

https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/edu/?cid=nrcs142p2_053588

Chapter 4.5. SUBSIDING LOESS SOILS

Subsiding loess and loess-like soils are found on all continents and are covered by continuous cover under the soil layer in large areas in Ukraine (up to 80% of the territory), in the south and southeast of Russia (up to 17%), in Kazakhstan, Asia, Siberia, North and South America, Europe. The total area occupied by loess and loess-like soils on the globe is ~ 19 million km² (Fig. 4.5.1, 4.5.2).



Fig. 4.5.1. Map of the distribution of loess soils in Eurasia (according to K. I. Lukashev, 1971)
http://www.bygeo.ru/uploads/posts/2012-07/thumbs/1342708267_urok2.jpg

According to rough estimates, up to 40–50% of the cost of the construction of civil and industrial facilities on loessal soils is spent on a set of measures to prevent deformation of structures due to possible subsidence of the foundations.

Loess (from German Löss or Löss from lose, non-solid) is a loose soil of grayish-yellow, brown or pale-yellow color, having a sedimentary, most likely, aeolian or aeolian-diluvial origin. Loess in the form of continuous strata with a thickness of several meters to 50–100 m or more lies on the watersheds, slopes and high terraces of river valleys.



a



b



c



d

*Fig. 4.5.2. Loess deposits: **a** – with interbeds of Pleistocene fossil soil, Poltava region, Ukraine; **b** – Germany; **c** – Missouri, USA; **d** – Patagonia, Argentina*

a http://img0.liveinternet.ru/images/attach/c/0//43/773/43773673_011.jpg;

b http://geologie.vsb.cz/geomorfologie/Prednasky/11_obrazky/Obr_11_7_sprasovy_profil.jpg; **c** <https://upload.wikimedia.org/wikipedia/commons/thumb/8/87/LoessVicksburg.jpg/1280px-LoessVicksburg.jpg>;

d <https://ru.wikipedia.org/wiki/%D0%A4%D0%B0%D0%B9%D0%BB:ArgentinaLoess.JPG>

The largest area of loess distribution is in northeast China (Fig. 4.5.3).



Fig 4.5.3. Loess deposits in northeastern China

<https://phys.org/news/2013-10-evidence-sand-deposits-china-rivers.html>

Loess consists predominantly (up to 50 % and more) dusty particles with size in the range of 0.01–0.05 mm; finer dusty and clay fractions less than 0.01 mm in size are contained in an amount of 5–30%; sand particles larger than 0.05 mm are practically absent with less than 5%.

An important distinguishing feature of the mineralogical composition of loess is its constancy – it is almost the same in different regions of the Earth, and almost everywhere it is characterized by a high content of carbonates. The minerals that make up the loess particles are mainly quartz – up to 80% and feldspars, mainly orthoclase (15–30%); calcite (10–20%), in the form of small grains is uniformly dispersed in the rock or often forms dense contraction of various shapes, ranging in size from a few millimeters to more than 20 cm.

Loess is characterized by the absence of layering, the presence of a system of vertical macropores, and vertical columnar separateness. The natural moisture content of loess soils is very low: in the areas of arid climate – 6–12%, in more humid areas – 12–14 %, sometimes up to 17 %.

The porosity of dry and low-moisture loessal soils is very high and usually amounts to 40–47%, but often it can reach 55–60%. Large pores, up to 1 cm in size, are clearly visible to the naked eye. The presence of macropores is one of the most important diagnostic signs of the structure of *subsiding loesses*. This structural feature causes the loess to collapse into large blocks on slopes and sag (shrink vertically) when moistened or under load, for example, under weight of buildings.

Due to its porosity, the rock easily collapses during deflation or under the influence of water flows. Rivers that cut through the loess formations in China form canyons with almost vertical slopes, and the famous “yellow” river – Yellow River has a specific yellow color of water due to the transfer of a large volume of blurred loess material (Fig. 4.5.4).



Fig. 4.5.4. Yellow River – Huáng hé (China).

Water is colored yellow due to the constant erosion of loess deposits

<https://chrontime.com/publication-top-10-samyx-bolshix-rek-v-mire>

The origin of loess. Loesses are young sediments that formed recently in the Quaternary, no more than 1.5 million years ago. In some modern climatic conditions, they can form right in front of the eyes, for example, in the intermontane depressions of Central Asia. Covering loess in large areas occurs due to the rapid accumulation in the arid regions of thick layers of silty sedimentary material after passing dust storms.

The current hypothesis of the origin of loess allows us to conclude that the process of formation of loess rocks consists of two stages:

1. the accumulation of mineral dust particles, which can occur in various ways, with various exogenous, but mainly with aeolian processes;
2. the transformation of the accumulated sediment into a typical loess, that is, into subsidence, as a result of frost weathering, in which the formation of the rock occurs as a result of cyclic seasonal freezing and thawing of the initial dusty strata and removal of ice from their structure by evaporation, bypassing the liquid state.

In the thickness of loess there may be remains of plants and animals (especially rodents and mammoths), as well as layers of buried soils (Fig. 4.5.2 a).

A study of the characteristics of plant pollen and the remains of fossil animals (in particular, mammoths, woolly rhinos, etc.) buried in loess strata indicates the existence of living organisms in a cold glacial climate. And the soil horizons comprising loesses were formed under warmer conditions due to the active growth of plants and the accumulation of humus in the soil after their death. This feature made it possible to determine that a significant part of the loess deposits occurred during the glacial epoch in zones adjacent to mainland ice, and the soils buried in them during interglacial periods. On Earth, during the Quaternary period, there was a frequent alteration of extreme cold and warm periods. In cold periods, lasting about 40 thousand years, the continents were covered with continental ice, as in the Antarctica and Greenland nowadays. During intervals of warmer climate (called interglacial), the ice gradually melted and receded to the north. The most intense accumulation of loess strata occurred in the harsh climate of the Middle and Late Pleistocene centuries (from about 800 thousand to 12 thousand years ago).

Loess-like soils are similar to loesses, but have only a part of their properties: they are less uniform, diverse in composition – from loess-like sandy loams and loams to loess-like clays and have less porosity, occur mainly on slopes (Fig. 4.5.5), are formed during secondary deposition loess and weathering products of other breeds. They are more widespread and often occur with loesses in the same formation, forming gradual transitions.

Loess-like rocks were formed mainly in the Quaternary, mainly on the margins of flat deserts, in the foothills and at the foot of mountains in semi-desert regions, as well as in the marginal regions of continental glaciations. Overlying loesses and loess-like rocks, modern fertile soils, in particular chernozems, have formed.



Fig. 4.5.5. Loesslike loam often lies on slopes

<http://www.photoukraine.com/i/articles/Ukrainskoe%20Polesie%20Photos/012.jpg>

The thickness of loesses and loess-like strata is different and varies in different areas from a few centimeters to tens of meters, sometimes reaching 100 m or more. For example, in China it reaches more than 200 m. In Ukraine, the maximum thickness of loess deposits is noted in the Odessa region – up to 40 m (Fig. 4.5.6).

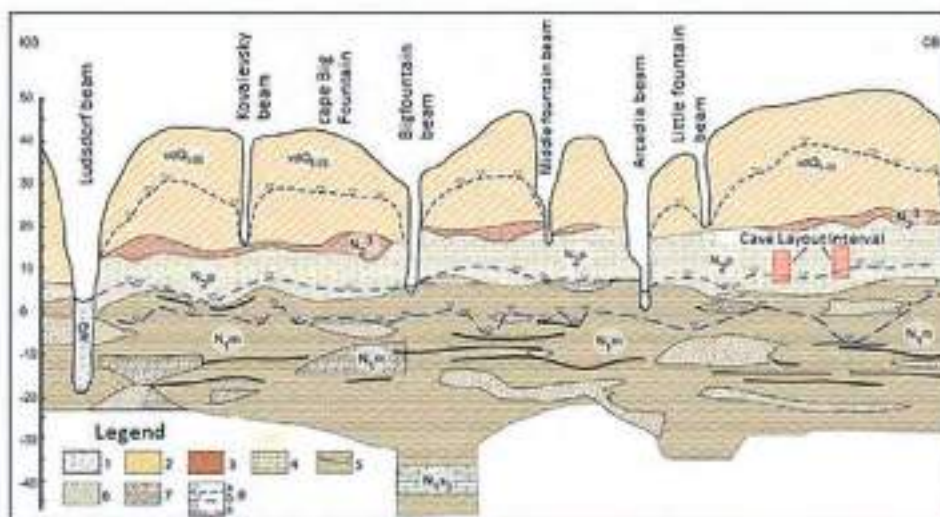


Fig. 4.5.6. Geological and hydrogeological section along the coast of Odessa

Legend: **1** – coarse and medium size sands and gravels; **2** – loam; **3** – reddish brown clay, marl in places; **4** – limestones; **5** – meotic clays; **6** – dusty sands; **7** – sandy loam with interbeds of clay and sand; **8** – aquifer levels (a – quaternary groundwater), b – pontic, c – meotic)

http://be.convdocs.org/pars_docs/refs/87/86349/86349_html_62176854.png

Subsiding loess. In natural conditions, loess at low moisture have significant mechanical strength and stability in slopes, which can maintain an almost vertical position at a slope height of sometimes more than 10 m. When moistened, their strength decreases significantly and they shrink vertically, accompanied by irreversible changes – destruction of the original soil structure. This property is called subsidence and is the most important characteristic that determines the construction properties of loess soils.

Samples of loess soils with a natural structure and laterally confined, when soaked under load in a laboratory compression device, yield several times more settlement than that of an identical soil sample at the same load at natural moisture content (without soaking).

With intensive moistening of the loess layer, sharp local failures occur with the destruction of the soil structure – subsidence or collapse. The consequence of the loess subsidence gives rise to uneven deformation of the earth's surface and excessive settlement underneath buildings and structures, often leading to destruction (Fig. 4.5.8, 4.5.9, 4.5.10).

With local soaking, saucer-shaped depressions of several meters in diameter are formed. With linear sources of soaking (in the case of water entering through a trench or channel), longitudinal subsidence of the earth's surface occurs, with the possible development of parallel cracks along the source of soaking.



Fig. 4.5.8. Destruction of the foundation during the subsidence of the underlying loess strata
http://www.ua.all.biz/img/ua/service_catalog/567991.jpg



Fig 4.5.9.
Destruction of
the school building as
a result of subsidence
of the loess layer
in the middle of
the building
[https://engiserg.files.wordpress.com/2015/10/92-2.jpg? W = 648](https://engiserg.files.wordpress.com/2015/10/92-2.jpg?W=648)

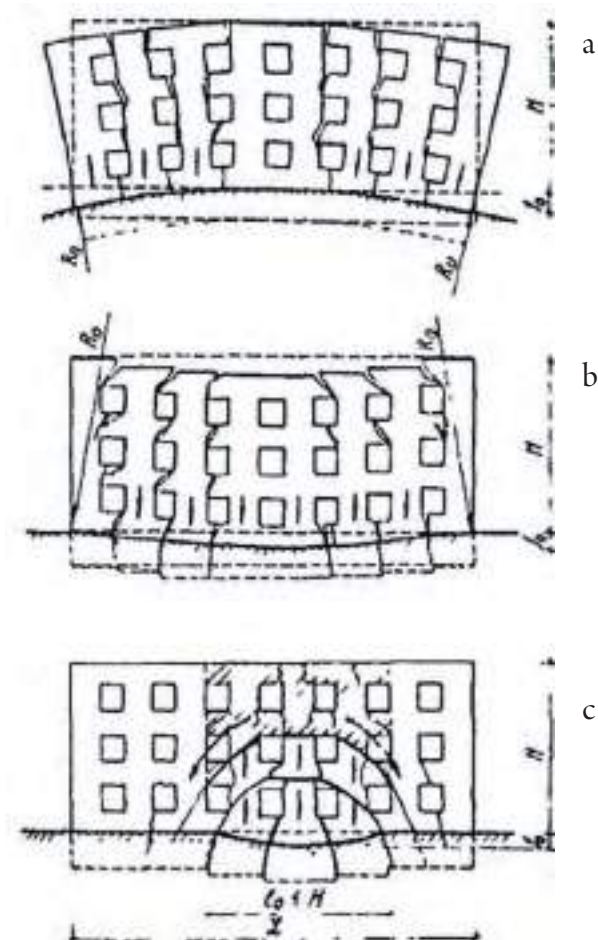


Fig 4.5.10. Deformation
and development of cracks
in the walls of buildings with
various forms of subsidence:
a – along the edges of
the building; **b** – along the entire
length of the building with
a maximum in the middle;
c – partial subsidence of soil at
a length shorter than the length
and height of the building
<http://prerek.ru/safia/rekomendacii-po-obsledovaniyu-i-ocenke-tehnicheskogo-sostoyani/19.png>

An important feature of loess strata, along with subsidence, is *the anisotropy of their filtration properties*: vertical permeability is 5–10 times higher than horizontal permeability. As a result, in places of intensive water supply (for example, during accidental or systematic leaks from water-carrying networks), “dome-shaped” rise in the level of groundwater occur. This leads to the soaking of the loess strata not only from above but also from below, causing even greater subsidence. Similar phenomena occurred in the 80s of the twentieth century at KAMAZ industrial sites in the Volgodonsk. Ground subsidence in the bases led to the deformation of a number of production workshops, which required significant resources for their restoration. In addition to strengthening of the soil base, there was a need for drainage to protect against groundwater.

Characteristics of subsidence. The criteria (nomenclature indicators) that serve to preliminary assess the possibility of manifestation of subsidence properties of soils are the degree of saturation S_r and the subsidence indicator P , determined by the formula:

$$P = (e_L - e) / (1 + e),$$

where e – the voids ratio; e_L is the voids ration corresponding to moisture at liquid limit ω_L ;

$$e_L = \omega_L \gamma_s / \gamma_w,$$

where γ_s and γ_w are the specific gravity of soil and water particles, kgf/m^3 .

In the preliminary assessment, subsidence of soils with degree of saturation $S_r \leq 0.8$ and depending on I_L , are as follows:

$$P \leq 0.10, \text{ if } 0.01 \leq I_L < 0.10;$$

$$P \leq 0.17 \text{ if } 0.10 \leq I_L < 0.14;$$

$$P \leq 0.24 \text{ if } 0.14 \leq I_L < 0.22.$$

In the event that subsidence properties have been identified in the soils, it is necessary to carry out a set of geotechnical studies to identify the subsidence characteristics.

The main quantitative characteristics of subsiding soils that determine their specific properties are: *relative subsidence* ε_{sp} , *initial subsidence* p_{sl} and *initial subsidence humidity* ω_{sl} .

Relative subsidence (or relative deformation of subsidence) is the relative compression of the soil at defined pressures and moisture contents. It is determined by the formula:

$$\varepsilon_{sl} = (h_p - h_{sl})/h_g,$$

where h_p is the height of the soil sample of natural moisture content, under pressure p (without the possibility of lateral expansion) equal to the pressure from the self-weight of the overlying soil and the calculated load from the foundation; h_{sl} is the height of the same sample after soaking (i.e. at saturation) while maintaining pressure p ; h_g is the height of the same soil sample of natural moisture content, under pressure from the weight of the overlying soil at the considered depth. The classification of soils by the relative deformation of subsidence according to standards is given in table. 4.5.1.

Table 4.5.1

Classification of soils by the relative deformation of subsidence

Varieties of soils	Relative deformation of subsidence ε_{sl}
Non-subsiding	$\varepsilon_{sl} < 0,01$
Weakly-subsiding	$0,01 \leq \varepsilon_{sl} \leq 0,03$
Moderately-subsiding	$0,03 < \varepsilon_{sl} \leq 0,07$
Highly subsiding	$0,07 < \varepsilon_{sl} \leq 0,12$
Extremely subsiding	$\varepsilon_{sl} > 0,12$

The initial subsidence pressure p_{sl} is the minimum pressure from the construction site or from the weight of the overlying soil stratum, at which subsidence properties of the soil are manifested under conditions of its complete water saturation. In laboratory tests of soils, the initial subsidence pressure p_{sl} is the pressure value at which the relative subsidence $\varepsilon_{sl} = 0.01$; during field tests (plate load test), the pressure at which the phase of normal compaction of the soil passes into the subsidence phase (with the destruction of the soil structure) and the settlement of the plate increases by at least 1.5 times. The values of subsidence pressure fluctuate, depending on the moisture and porosity of loess soils. For example, for years now, in the city of Zaporizhya, Ukraine – they are in the range of 0.07–0.09 MPa; Nikopol, Ukraine – 0.10–0.12 MPa; Dushanbe, Tajikistan – 0.01–0.03 MPa; Grozny, Chechnya – 0.04–0.07 MPa and in the Rostov region, Russia – 0.04–0.15 MPa.

The initial subsidence moisture content ω_{sl} is the minimum moisture at which soils under external load from a construction site or weight of overlying soil begins to exhibit subsidence properties. As a criterion of initial moisture during laboratory compression tests, the relative subsidence $\varepsilon_{sl} = 0.01$ is taken; in field tests (plate load testing), the pressure at which the normal compaction phase passes into the subsidence phase.

Construction on subsiding soils.

Construction on subsiding soils are carried out in accordance with the requirements of prevailing standards “Buildings and Structures in Artificial Territories and Subsiding Soils”. Decisions on the implementation of types and technologies of measures to reduce or eliminate the subsidence of loess soils are generally made at the design stage. Elimination of subsidence of soil is one of the radical measures implemented at various stages of new construction, as well as for the possibility of further safe operation of already deformed buildings and structures.

The main anti-subsidence measures are to protect the grounds from the deformation of the natural surface by prevention of contamination due to groundwater and water arriving from various water-bearing communications, as well as various design solutions to improve the soil at foundation level.

Water protection measures include: drainage around buildings and structures; laying engineering communications according to the “pipe in pipe” method to reduce

the risk of soaking of the loess soil in the event of a possible rupture of pipes. Various measures are being taken to reduce the possibility of soaking the soil under foundations, for example, arrangement of a wider blind area around buildings, an increased slope of gravity for pipelines, among others.

Often, at the stage of construction of structures, *preliminary soaking of the loess base* is performed to eliminate subsidence properties.

It should be noted that the settlement of structures during the construction period is less dangerous than during the operational period, since with ongoing work, their consequences can be quite easily eliminated.



Fig 4.5.11. *Compaction of subsidence soil with a hand vibrating compactor*
<http://profmashine.ru/wp-content/uploads/2014/03/716550514.jpg>

Surface compaction with tampers during excavation is also quite effective, since loess, having large pores, can be quite easily compacted (Fig. 4.5.11, 4.5.12). Such compaction creates a non-subsiding soil layer in the upper part of the stratum, which delays the water filtration down to the subsiding layer. The disadvantages of this method are that subsidence is only partially eliminated; the method is not used in winter conditions.

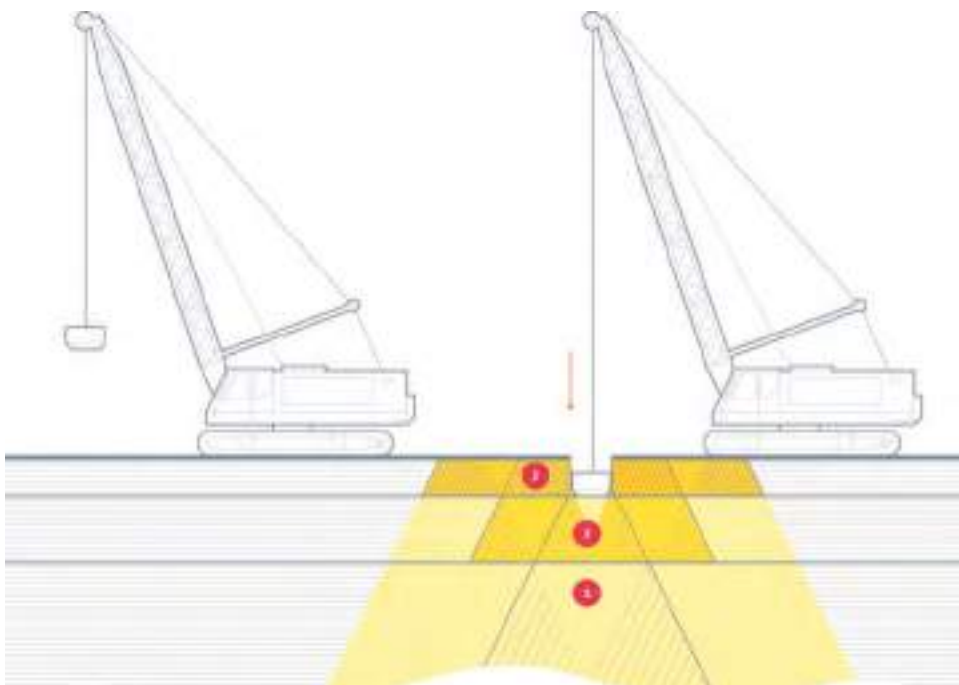


Fig. 4.5.12. Surface compaction of subsiding soils with heavy tampers. Legend: **1** – tamping with maximum impact energy on a given grid; **2** – tamping with lower impact energy on the grid between the primary grid; **3** – levelling, performed after the ramming of the site
<https://www.trevispa.com/en/Technologies/dynamic-compaction-heavy-tamping>

If it is necessary to eliminate the subsidence of loess soil down to a greater depth, the method of compaction of the base by means of soil piles is also used. The technology of manufacturing soil piles is as follows: at the beginning, metal pipes are driven from the surface of the soil – a partial compaction of the soil occurs and the subsidence of loess located along the pipe is eliminated; then the pipes are removed; the loess soil is returned to the well by tamping with the addition of small amount of water. The length of the pipes is selected from the condition of penetration of the loess stratum to its entire thickness – as a result, a soil pile is obtained, resting on non-subsiding soil (Fig. 4.5.13).

In some cases, the creation of soil piles is carried out by the «explosion method» – using explosives (Fig. 4.5.14). This option is much cheaper than the previous one, but here it is necessary to use explosives and, accordingly, involve specialized organizations. The use of this method of piling is possible only at sites located at a certain distance from existing buildings.

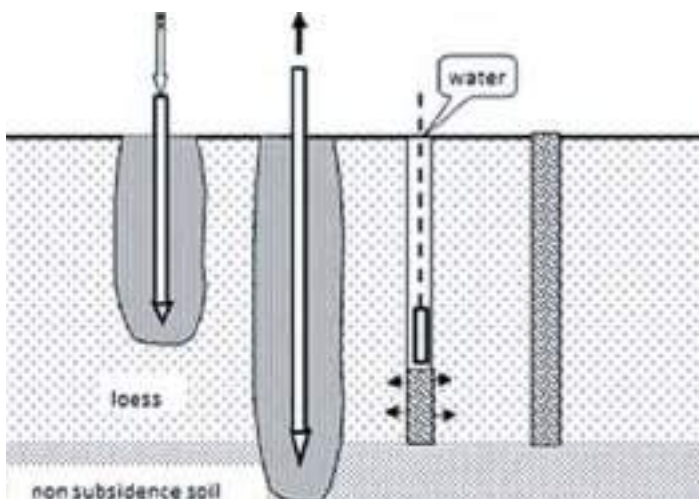


Fig 4.5.13. Technological sequence of creating soil piles in the loess base
[http://www.buildcalc.ru/\(S\(k4gtvqav1cptur55vcw1ei55\)\)/Learning/BasesAndFoundations/Chapter10/Images/ris.17.gif](http://www.buildcalc.ru/(S(k4gtvqav1cptur55vcw1ei55))/Learning/BasesAndFoundations/Chapter10/Images/ris.17.gif)

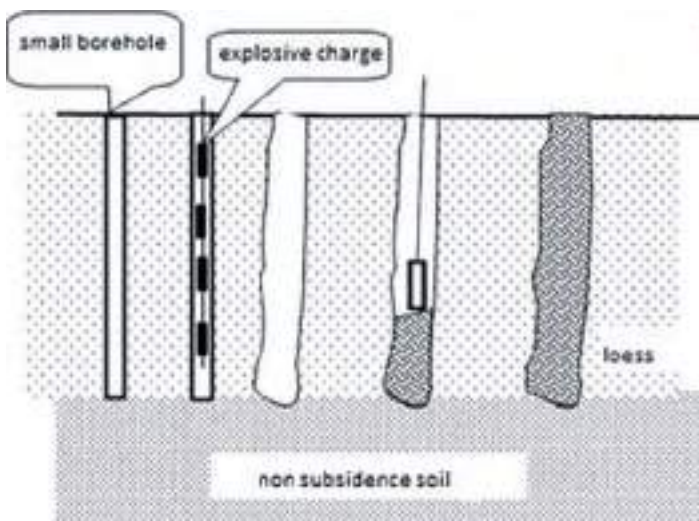


Fig 4.5.14. Implementation of soil piles for compaction of the loess base using explosives
[http://www.buildcalc.ru/\(k4gtvqav1cptur55vcw1ei55\)\)/Learning/BasesAndFoundations/Chapter10/Images/ris.18.gif](http://www.buildcalc.ru/(k4gtvqav1cptur55vcw1ei55))/Learning/BasesAndFoundations/Chapter10/Images/ris.18.gif)

It is also possible to eliminate the subsidence of loess soil by creating soil cushions from non-subsiding soil. In this case, the excavation pit for the designed structure is excavated in the loess base two meters below the level of the foundation foot. The excavated soil is laid in layers half a meter thick in the pit, with each layer being compacted by a roller, to a density of dry soil (γ_d) of at least 16.5 kN/m^3 . As a result, under the sole of the foundation, a soil cushion is created from compacted non-sagging soil, on which the foundation is laid. This method is relatively simple and economical and may be sometimes combined with other methods

Silicatization, to eliminate the subsidence of loess soil, is mainly used in emergency situations. The method is very expensive: the cost of fixing 1 m^3 of soil is almost the same as the cost of 1 m^3 of concrete; therefore, it is used mainly in emergency cases. A well-known example of soil silicification is its use in Odessa in the middle of the last century. In the building of the famous opera house in Odessa (Fig. 4.5.15), built on a loess base, deformations and cracks appeared as a result of periodic subsidence of the base due to soil moisture. Silicatization was carried out for two years and strengthened the soil foundation, ensuring the stability of the theatre.



Fig. 4.5.15. Odessa Opera House, built on loess soils, fortified with silicatization
<http://www.tic.in.ua/wp-content/uploads/2015/09/1001.jpg>

During high-temperature treatment – loesses sinter and acquire the useful property of being resistant to soaking and, in addition, the mechanical strength of the resulting rock material increases significantly, and can withstand a pressure of 100–1000 t/m². However, this method does not change the high porosity and water permeability of the loess material.

Control questions to chapter 4.5. Subsiding loess soils

1. What is loess soil?
2. The spread of loess on Earth.
3. Characteristic properties of subsiding soils.
4. The origin of loess.
5. The subsidence of loess and loess-like materials.
6. Anisotropy of the filtration properties of loesses and its significance.
7. The main characteristics of subsidence.
8. Types of soils by relative subsidence.
9. Construction on subsiding soils.

Chapter 4.6. SWELLING AND SHRINKAGE PROPERTIES OF CLAY SOILS*Main reasons for soil swelling*

Swelling is the property of some soils, when moistened, to increase in volume (swell) both due to the thickening of the water shells around colloidal particles, and also due to chemical processes that entail a change in the composition and volume of the particles themselves.

A characteristic feature of *swelling soils* (Fig. 4.6.1) is the increased density and high content (65–85%) of clay particles less than 0.005 mm in size. Clayey sands and sandy loams either do not show swelling at all, or swell insignificantly. The swelling of loams and clays increases with an increase in the content of clay and especially colloidal particles.



Fig 4.6.1. Swelling soils

<https://yandex.ua/images/search?text=%D0%BD%D0%B0%D0%B1%D1%83%D1%85%D0%B0%D1%8E%D1%89%D0%B8%D0%B5%20%D0%B3%D1%80%D1%83%D0%BD%D1%82%D1%8B%20%D1%84%D0%BE%D1%82%D0%BE&rpt=imageview&url=http%3A%2F%2Fniidg.ru%2Fwp-content%2Fuploads%2F2015%2F03%2F219874641.jpg>

Swelling soils are widespread across the globe, and are confined to zones of dry steppes and semi-deserts. The areas of development of swelling soils are

characterised by a slight amount of precipitation, a general deficit of air humidity, and prolonged dry periods in the summer.

Such soils are widespread in Egypt, Ethiopia, Sudan, South Africa, the USA, Canada, Iraq, Syria, Mauritius (Dark Magnesium Clay), and in India more than 30% of the territory is occupied by so-called cotton soils. In the CIS (Commonwealth of Independent States) countries, such soils are found in Kazakhstan, Georgia, Azerbaijan, Moldova, Russia (Volga region, North Caucasus and other areas). In Ukraine, they are found in the areas of Kupyansk, Kharkiv, Poltava and Crimea.

In the natural occurrence, these soils (mainly clay) are characterized by a solid and refractory texture with a specific gravity of 19.5 to 20.5 kN/m³. The porosity of the soil ranges from 41 to 48% with a moisture content of 15–18% at the surface layer and 25–30% in the middle layers and the sole of the stratum.

As a result of hydration of these clays, their volume increases by 12–25%, and in some cases by 30–36%. Due to swelling, the specific gravity of clays decreases to 17.7–18.7 kN/m³, and the porosity increases to 50–58%. The moisture content of the soil increases to 36–48%, which indicates the transition of clays to a plastic state, in which state, their bearing capacity is sharply reduced. The value of normal clay swelling forces in a natural occurrence reaches 350–400 kPa under the end of a pile foundation, and 30–37 kPa tangential, along the side surface of pile. When softened during swelling, clays raise the thickness of overlying cover soils, which, in turn, tend to raise the foundation footing or the upper face of the formation.

According to the bedding conditions, swelling soils, unlike loess rocks, can occupy not only a cover position, but also can be located at a considerable depth from the earth's surface.

The thickness of swelling soil strata ranges from several meters to several tens of meters.

The highest swelling (and, consequently, the most dangerous for construction) is possessed by compacted weakly cemented clays, which form in an arid climate and contain montmorillonite – a clay mineral with a moving crystalline lattice.

All clay soils, to some extent, possess the ability to swell and shrink with change in moisture. Experience shows that underestimation of the deformation of swelling and shrinkage of clay soils at the base leads to premature damage to

buildings and structures due to uneven and prolonged deformations of the soils at the base.

Swelling and shrinkage are the result of complex processes occurring in clay soils when they interact with water.

There are several *hypotheses* that explain the phenomenon of swelling of clay soils, from which two main ones can be distinguished: *physic-mechanical* and *physic-chemical*.

The *physic-mechanical* hypothesis is the Terzaghi – Gersevanov capillary theory, according to which water penetration between soil particles becomes possible after concave menisci disappear at the water-air interface in the capillaries, i.e. after capillary pressure removal. The surface tension forces acting between the capillary walls and the water form concave menisci of water, which press the soil particles against each other and bend them with concavity towards the capillaries, and negative capillary pressure develops in the liquid itself. The movement of water inside the capillaries occurs under this pressure until the hydrostatic pressure of the liquid column balances that of capillary pressure.

The second hypothesis derives from the *physic-chemical* nature of the interaction of clay particles with water. According to this hypothesis, the swelling of the soil during wetting is considered as the ability of the surface of clay particles to adsorb water due to osmotic pressures caused by the influence of aging of the crystal lattices, the exchange complex in pore and soaking solutions.

To explain the phenomena of swelling-shrinkage, A. M. Vasiliev proposed the hypothesis of hydrated or solvate shells, which later became known as the physic-chemical theory of soil swelling.

The basis of this hypothesis is the idea of a double electric layer in a colloidal particle of the soil, called a micelle. One electric layer belongs to the solid phase, i.e. particle core; the other is a liquid medium. The double electric layer forms a diffuse shell or diffuse micelle layer.

A parallel-parallel capacitor can serve as a model for a double electric layer, and a spherical capacitor as applied to a ground colloidal particle. The schematic structure of the colloidal particle is shown in fig. 4.6.2.

The first electric (ionic) layer immediately adjacent to the solid particle is called the adsorption layer, and the second – diffuse layer. Water molecules, getting into the electric field of the diffuse layer, take an oriented position, forming the hydration or solvate shell.

The sizes of diffuse micelle shells depend on the mineral composition, moisture, and particle size of the soil. The charge density and ion concentration gradually decrease with distance from the surface of the particle to the periphery of the micelle. The thickness of the diffuse shell increases with decreasing valency of the exchange cations. Montmorillonite clays are characterized by the greatest swelling.

Upon reaching maximum molecular moisture (approximately the lower limit of plasticity), the swelling strain reaches its maximum. If the saturation of the soil with water is continued, then the excess of free water no longer affects the ability to swell. A layer of loosely bound water appears around clay particles and the soil gradually turns into a fluid state.

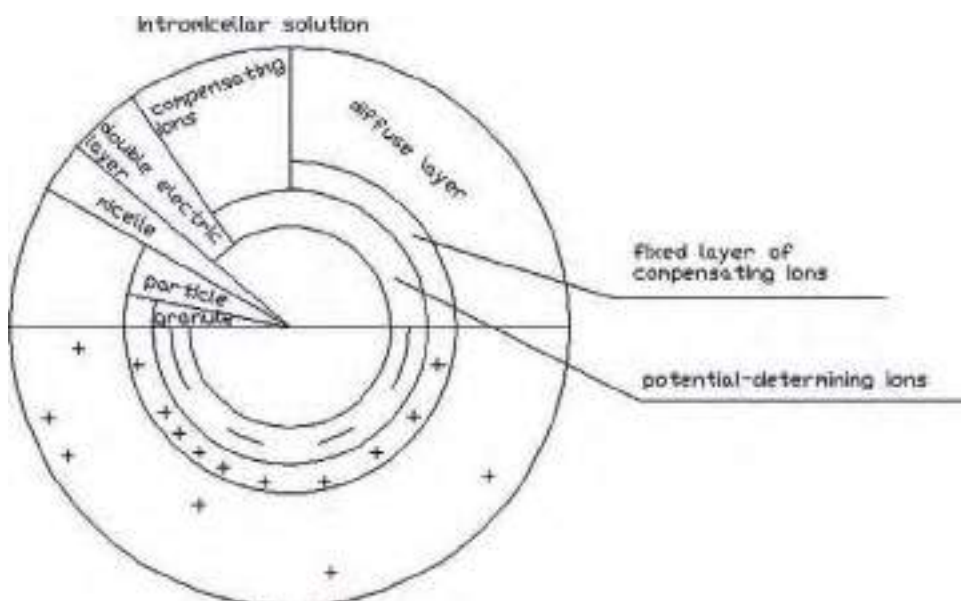


Fig. 4.6.2. Micelle structure diagramme (Khrapatova, 2006)

A graphic diagram explaining the state of the colloidal shell of a micelle, depending on moisture content, is shown in fig. 4.6.3 (according to A. M. Vasiliev).

Following this scheme, it is possible to imagine the processes occurring in clay soil during wetting from the point of view of the hypothesis of solvate (hydrate) shells. With a very small moisture content, water is not deposited on the surface of the colloidal shell, but rather gets absorbed. Physically bound water is formed – hygroscopic humidity, but there is no water as such on the surface of the colloidal shell. Soil particles are dry. The aggregates of these particles have

significant strength. With increasing soil moisture, the colloidal shell gradually acquires the properties of a lubricant and adhesive ability; plastic properties of the soil appear, the soil swells.

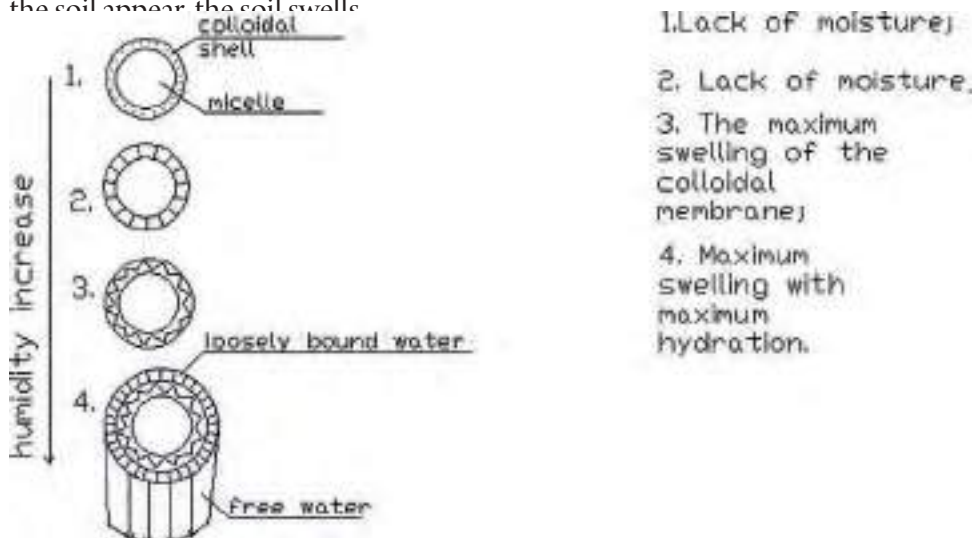


Fig. 4.6.3. Transformation of the micelle shell as moisture content in the clay soil increases (according to A. M. Vasiliev)

Research made by E. A. Sorochan, in the process of swelling and shrinkage of clay soil, shows that water molecules are attracted by the external and internal surfaces of the particles, as well as the displacement of adsorbed gas molecules, and wedging and capillary pressures arise when a monolayer is formed. As the particles moisturise and hydrate, the capillary pressure decreases, and the hydration of the exchange cations develops an osmotic pressure that exerts the same effect as the wedging pressure of water shells.

Adsorption, occurring under the action of *intermolecular forces* of the interaction of the solid part of the soil and the liquid leads to a decrease in the free energy of the surface. Intermolecular forces of interaction are divided into electrostatic, dispersion and induction.

Electrostatic interaction forces increase upon adsorption of polar molecules on a surface having ions of the same sign, for example, hydrogen or hydroxyl ions, as is the case in montmorillonite and kaolinite. In this case, the polar water molecules will combine with the hydroxyl or oxygen molecule via a hydrogen bond. *Dispersion forces* of interaction arise between any molecules or atoms and are caused by the formation of instantaneous dipoles in the molecules. *Induction forces* arise when a dipole molecule polarises another molecule in which they induce a constant dipole moment.

During the process of multilayer adsorption, hydrate shells are formed around the solid phase of the soil, which tend to push apart the soil particles. Particles move apart at the contact points of the soil particles and are caused by the appearance of a “wedging effect” of thin films of water.

Swelling caused by the formation of layers of water around particles or aggregates is called “*inter-particle swelling*”.

Another phenomenon that causes swelling of the soil is an increase in the distance between the packages of the mineral. It occurs due to the binding of water molecules in the inter-package space of minerals and is called “*intracrystalline swelling*”.

According to many researchers, the swelling properties of clay soils to a large extent depend on their *mineralogical composition and dispersion*. Minerals of the montmorillonite group possess a high swelling ability, and minerals of the kaolinite group to a much lesser extent. These minerals (kaolinite, halloysite) have a strong fixed lattice in which the distance between the packets does not change when moistened. The much lower swelling ability of kaolinite is explained by the structural features of its crystal lattice. In kaolinite, the adjoining layers of two adjacent packets are different. The crystal lattice of the kaolinite mineral is formed by layers consisting of one tetrahedral and one octahedral network, folded on one side of the surface to oxygen atoms, and on the other, to hydroxyls. With this superposition of layers, hydrogen bonds arise between them, causing the formation of rigid structures with an unchanged inter-packet distance. In addition, isomorphic substitutions inside layers (packets) are very poorly developed in the structure of kaolinite, therefore, the main active surface for this, is the process of bond breaking $\text{Si} - \text{O} - \text{Si}$, $\text{OH} - \text{Al} - \text{OH}$ (edge sections of crystals, as well as external basal planes. Of these features, kaolinite is less hydrophilic, i.e., has a significantly lower ability to bind water.

In contrast to the kaolinite group, in the minerals of the montmorillonite group (montmorillonite, illite, beidelite), the lattice becomes mobile, when moistened, it is able to move apart until the mineral breaks up into elementary crystal cells with a corresponding increase in specific surface area.

The crystalline structures of the minerals of the montmorillonite group are also composed of layers consisting of two tetrahedral networks, between which an octahedral network is located. A distinctive feature of the structure of montmorillonite is that adjacent layers face each other with a similar oxygen surface, as a result of which the bond between them is weak. Molecules of water and other polar liquids freely enter between the layers and push them

in the direction perpendicular to the layered structure, thereby reducing the molecular interaction between adjacent layers.

The montmorillonite lattice is characterised by a high ability of internal replacement of some elements by others of lower valency, as a result of which uncompensated valences remain in the lattice, which increase the adsorption capacity of such minerals. The adsorption capacity determines the extreme variability of the properties of the montmorillonite group minerals, depending on the composition of the aqueous solution, which determines the composition of external ions. Water molecules penetrate very easily into the crystal lattice and also easily remove them, changing the volume of the mineral. Moreover, the distance between the elementary packets of montmorillonite can increase by tens of times, which causes a strong swelling of montmorillonite clays.

During the interaction of montmorillonite with water, its molecules cannot penetrate into the packets, the individual parts of which, like kaolinite, are firmly connected to each other, but can penetrate between adjacent packets, the bond of which in montmorillonite is weakened. In this case, the packages are moved apart to a greater or lesser distance, depending on the amount of water absorbed. The expansion of the lattice is facilitated by the fact that there are repulsive forces between the adjacent layers of adjacent packets formed by the same charged oxygen atoms.

Many researchers in the study of the swelling process revealed the dependence of the latter on a number of *physical properties of soils*. The dependence of swelling on the particle size distribution of the soil, and more precisely on the content of clay fractions in it, is noted. This relationship is linear. But this pattern takes place within the specific regional *genetic origin of rocks*.

Inverse proportional relationship between relative swelling and pressure on the one hand and moisture capacity on the other.

E. A. Sorochan introduced the concept of “*initial swelling density*”, at which swelling does not develop.

The dependence of swelling on density is determined by porosity (Fig. 4.6.4). It is clear that this dependence is inversely proportional. Other things being equal in the soil mass, a soil with low porosity value is most susceptible to swelling. As the density of clay samples increases, the degree of their swelling and the pressure of swelling usually increase. However, artificial compaction of soils can reduce swelling due to a sharp decrease in their water permeability, as a result of which some part of the soil becomes inaccessible to water. With a mechanical disturbance of the integrity of such a sample and the appearance of cracks in it,

the swelling will be greater in denser soils. Disruption of the natural structure of the soil increases swelling.



Fig 4.6.4. Swelling soil intact structure

<http://niidg.ru/wp-content/uploads/2015/03/18662.jpg>

Layered clay soils are characterised by a pronounced *anisotropy in the manifestation of swelling*. It develops more intensively in the direction perpendicular to the bedding of the rocks than in the direction parallel to it.

Soil swelling, especially when studying them in an array, is affected by their *fracture*. Cracks are the paths of water penetration into the soil, they increase the contact surface of the soil with water and thereby intensify the swelling process. On the other hand, cracks compensate for the movement of swelling soil. For example, if there are horizontal cracks in the soil, the vertical displacements of the base will be less than in soils without cracks or with cracks of vertical orientation. To assess the effect of soil fracturing, the nature of the filling of the cracks (whether they are gaping or filled with filter rock) is important.

Clay soil swelling also depends on the *presence of salts in the solutions* circulating in the soil, their concentration and the pH of the solutions. The chemical composition of water largely determines the composition of exchange cations, and, consequently, the magnitude of the swelling of soils. In addition, in the presence of the same salts in natural water, the amount of soil swelling will vary depending on

their concentration. The higher the electrolyte content in water, the less hydrated the ions of the diffuse layer of soil micelles, the less bound water is formed in the soil and, therefore, the less its swelling will be.

Swelling also depends on the *structural connectivity of soils*. All other things being equal, soils of an undisturbed structure usually swell less than soils of a disturbed structure.

Most swelling soils have a micro-layered texture, which causes, in addition to structural features, the anisotropy of soil properties. This leads to unequal swelling vertically and horizontally. As such, in Saratian clays, the deformation and swelling pressure of the samples in the layering direction are 20% higher than in the perpendicular direction. Therefore, horizontal movements during swelling can be even greater than vertical movements.

Pressure dependence of swelling

E. A. Sorochan notes that the dependence of the swelling on pressure has a curvilinear character (Fig. 4.6.5). The most dramatic swelling decreases with increasing pressure from 0 to 0.05 MPa. The bulk part of the swelling arises as a result of the formation of peripheral layers of a hydrated shell enveloping soil particles by weakly bound water. A slight external pressure within 0.1 MPa exceeds the prop-pant pressure of hydration shells of this thickness. As the external pressure increases, the swelling decreases to a much lesser extent and at pressures exceeding 0.1–0.15 MPa, the indicated dependence is practically linear.

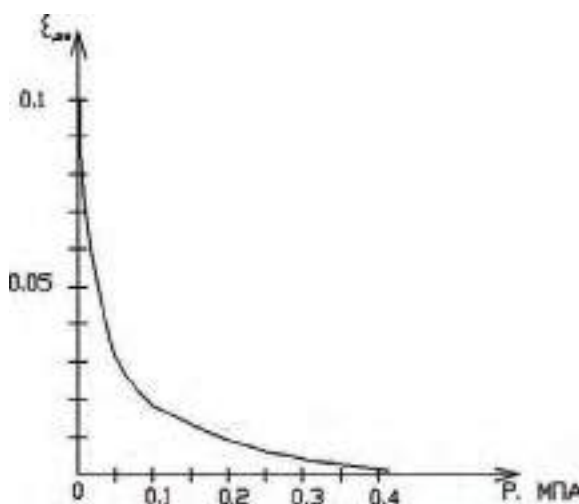


Fig. 4.6.5. Relative clay swelling from pressure

Sorochan E. A. Construction of facilities on swelling soils. Moskov: Stroyizdat. 1989. – 311 p.

The total deformation of a certain elementary volume of the soil medium is defined as the sum of the deformations from the action of the force factor and external influences (for $i, j = 1, 2, 3$):

$$e_{ij} = e_{ij}' + e_{ij}''$$

e_{ij} – the tensor of total (general) strains;

e_{ij}' – the strain tensor from the action of the force factor;

e_{ij}'' – the strain tensor from the action of external impact.

The behavior of a real soil under load is generally described by the equation of an elastic-viscoplastic body. The patterns of deformation from external influences for each type of soil are established experimentally, while the influence of external factors on the numerical values of the parameters of soil behavior under load is considered in parallel.

Relative swelling is determined by the formula:

$$\varepsilon_{sw} = m \left(1 - \frac{P_i}{P_{sw}} \right) \Delta w,$$

where m is a coefficient depending on the physical characteristics of the soil and determined by the formulas or experimentally; P_i is the pressure in the direction of swelling; P_{sw} is the swelling pressure; Δw is the change in humidity.

Swelling soils are characterized by *swelling pressure* p_{sw} , *swelling moisture* w_{sw} , *relative swelling at a given pressure* ε_{sw} and *relative shrinkage upon drying* ε_{sh} .

Varieties of dusty clay soils by the relative swelling ε_{sw} are given in tab. 4.6.1.

Tab. 4.6.1

Varieties of dusty clay soils by relative swelling

Non-swelling	$\varepsilon_{sw} < 0,04$
Slightly swelling	$0,04 \leq \varepsilon_{sw} \leq 0,08$
Moderately swelling	$0,08 \leq \varepsilon_{sw} \leq 0,12$
Highly swelling	$\varepsilon_{sw} > 0,12$

Clay shrinkage

Shrinkage of the soil is called a decrease in its volume as a result of water removal during drying or during the manifestation of physicochemical processes (syneresis, osmosis). Shrinkage of a soil can occur both in subaerial conditions during the evaporation of moisture under the influence of a temperature difference (difference in relative humidity), and in subaqueous conditions under the action of syneresis and osmosis. Only wet soil has the ability to shrink.

As a result of shrinkage, the soil becomes denser and, after drying, even hard. Compaction of clay soil during shrinkage increases its resistance to deformation, but the presence of cracks, usually accompanying shrinkage (Fig. 4.6.6), increases water permeability and reduces the stability of the surface soil layer in slopes. In dry and hot climates, shrink wedge-shaped cracks break the clay soil mass to a depth of several meters.

Shrinkage is maximally manifested in clays, while it is less characteristic of other cohesive rocks. However, the significance of shrinkage processes even in rocks such as marl and clay limestone are complex, since cracking of the rock during drying promotes the formation of loose mobile talus on the slopes that feed mud-stone flows (mudflows).

During shrinkage, not only mechanical compaction and cracking of the rock occurs, but also the redistribution of soluble chemical components of the soil. The portions of the rock through which water evaporates during shrinkage are often enriched with salts and can in some cases acquire increased strength and water resistance, but upon crystallisation of minerals such as gypsum, on the contrary, they can additionally disintegrate. Therefore, shrinkage is a complex physicochemical process, leading to a change in the nature of the structural bonds between particles.



Fig. 4.6.6. Shrinkage of swelling soils during drying

<http://niidg.ru/wp-content/uploads/2015/03/106461.jpg>

The amount of soil shrinkage is usually characterised by a decrease in the linear dimensions or volume of the sample. In accordance with this, we distinguish between relative linear (Δh) and volumetric (Δr) shrinkage.

In nature, soils that are at the limit of shrinkage are found only in arid areas (for example, in clay deserts of Kazakhstan and Central Asia) in the dry,

hot summer season. Clay soils, fully swollen, are found in the warm season, mainly in areas of excessive moisture in the forest and tundra zones. Thus, soils of natural composition, density and humidity rarely swell in the full range. However, swelling soils are undesirable founding formations for buildings and structures and materials for embankments and dams. In cases of significant changes in volume due to swelling caused by moisture or shrinkage when the soil dries, the buildings and structures undergo deformations. To prevent swelling and shrinkage, it is necessary to make provision for certain measures in building projects.

During weathering, the strong structural bonds of mudstones, siltstones and shales are destroyed. The weathering crust of these rocks in the fine crushing zone is loam or clay with soft gravel and wood and is capable of shrinkage and swelling. Thus, these half-breed rocks, if they are supposed to be used for earthworks, should be tested for swelling – shrinkage.

Determination of swelling and shrinkage of soils

Saturation of soil with water leads to a disruption of the structural bonds between the particles and the sample becomes soft and loses its strength. During swelling, in the absence of the possibility of free expansion of the soil, gives rise to a swelling pressure, reaching 5–10 kg/cm². This phenomenon must be taken into account when building engineering structures on such soils (Fig. 4.6.7). The characteristics of swelling and shrinkage of the soil should be determined by the relative deformation:

- *swelling* – in conditions that exclude the possibility of lateral expansion when the soil is saturated with water or a chemical solution;
- *shrinkage* – under conditions of free triaxial deformation during drying of the soil.

Determination of swelling is carried out until complete water saturation, and shrinkage – until complete loss of moisture.

Swelling of the soil – defined indicators:

- free swelling,
- swelling under load,
- swelling pressure,
- soil moisture after swelling;

Soil shrinkage – defined indicators:

- shrinkage of the soil in height ϵ_h , diameter ϵ_d and volume ϵ_v ,
- soil moisture at the shrinkage limit W_y ,
- linear shrinkage limit.



Fig. 4.6.7. Swelling soils

<http://niidg.ru/wp-content/uploads/2015/03/18662.jpg>

Soil swelling testing is carried out both with free swelling and in compression devices (Fig. 4.6.8). After soaking the samples, strain should be recorded after 5; 10; 30; 60 minutes, then after 2 hours during the working day, and then at the beginning and end of the working day until conditional stabilization of deformations is achieved.

When determining the swelling of the soil under load and the swelling pressure, the pressure steps on various devices should be: 0.0025 MPa / 0.025 MPa / 0.05 MPa / 0.1 MPa / further with an interval of 0.1–0.2 MPa.

The soil shrinkage test is carried out in three stages: At the 2nd stage, the soil sample is dried in air; on the 3rd – in an oven at a temperature of 105 ° C conditional completion of the test at the first stage is the absence of changes in the linear dimensions of the samples.

Field studies have shown that when soaking an array that is in a stressed state from an external load or due to its own weight, horizontal movements of soil in the wetted zone do not occur. At the same time, the soaking of the soil located on

one side of a strip footing with a length of 4 m led to a rise of the foundation by 95 mm and to an average shift of 3 mm to the side opposite from soaking.



Fig. 4.6.8. Testing swellable soils

<https://yandex.ua/images/search?text=%D0%BD%D0%B0%D0%B1%D1%83%D1%85%D0%B0%D1%8E%D1%89%D0%B8%D0%B5%20%D0%B3%D1%80%D1%83%D0%BD%D1%82%D1%8B%20%D1%84%D0%BE%D1%82%D0%BE&rpt=imageview&url=http%3A%2F%2Fwww.geops.ru%2Fupload%2Fmedialibrary%2F076%2Fnbuhanie.jpg>

Deformation zones in the massif during swelling of the soil

With increasing pressure along the sole, the foundation lift decreases, but is not completely excluded, although at certain pressures in certain layers compression is observed, i.e. the nature of soil deformations in depth is different. The part of the massif where layer-by-layer movements occur – layer rises caused by soil swelling during soaking are called “swelling zones” (Fig. 4.6.9). The height of the deformation zones depends not only on external pressure, but also on the size and shape of the foundation. With increasing pressure and the area of the foundation, the sizes of zones I and II will increase. In the case of the action of its own weight, only the swelling zone can be observed.

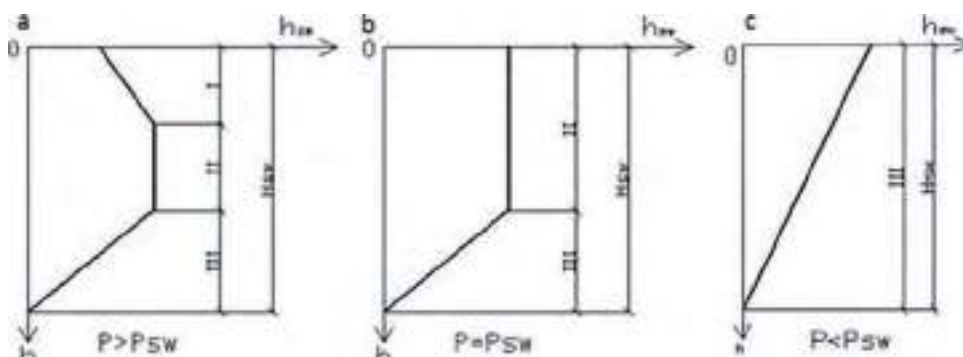


Fig. 4.6.9. Deformation zones in the massif during soil swelling

Sorochan E. A. Construction of facilities on swelling soils. Moscow: Stroyizdat. 1989. – 311 p.

Construction on swelling soils

Construction on swelling soils should be carried out in accordance with the requirements of prevailing standards.

In buildings and structures, based on swelling soils, cracks often arise in various elements and parts of these structures. Therefore, when designing, the effect of swelling on the entire system “base – foundation – structure” should be taken into account for more reliable operation of the structure. Design errors often lead to serious consequences.

So, in 2012 in Karaganda, in a five-story building of the Besoba residential complex (Fig. 4.6.10), erected on swelling soils, a crack from 10 to 15 cm wide went from the foundation to the roof, the building first tilted, and then collapsed. On the eve of the emergency, 138 people were evacuated.



Fig. 4.6.10. The collapse of a house in the residential complex “Besoba” in Karaganda, Kazakhstan
<http://s019.radikal.ru/i613/1205/a4/b3929a7421cb.jpg>
<http://s53.radikal.ru/i142/1205/8a/c26eefc4118d.jpg>

In some cases, it seems that soil swelling can be avoided by taking the pressure at the base of the foundation equal to or greater than the swelling pressure. At the same time, in the stress zone adjacent to the foundation, deconsolidation deformations may indeed be absent or soil compaction may even be observed. Therefore, when the soil is soaked, a compaction zone or neutral zone is formed at the base of the foundations. However, with a large thickness of swelling soils, there is also a swelling zone, as a result of which a foundation can be raised. This means that increasing the pressure transmitted to the ground will not eliminate the possible rise in the foundation when soaking. Rather, this measure can be effective only in the absence of a swelling zone, i.e. at a certain thickness of the layer of swelling soils.

When designing structures on swelling soils, it is necessary to proceed from the possible soaking of the soil within the entire swelling zone, and the calculation of the amount of rise should be based on this position. This is true when soaking the soil due to rising groundwater levels and leakage of water (or other liquid) from pipelines. In this case, the following options for the construction of base and foundations are possible, based on the fulfilment of conditions under which the rising of structures will be less than the maximum permissible rise.

Water protection measures:

- provide dry area around buildings with a width of 2–3 m;
- apply waterproof screens under the entire structure of polymer materials, or of asphalt;
- enclose water and sewer pipes in reinforced concrete trays, etc.

Improving the properties of the bases.

For small thicknesses of swelling soils, preliminary soaking is used and then construction is carried out as on water-saturated non-swelling soils. However, the implementation of this measure is complicated by the slow progress of this process. To accelerate it, vertical drains are sometimes used.

Compensating sand pads are sometimes used to partially smooth out uneven swelling of the soil due to a more uniform distribution of pressure over a large area. At the same time, sand cushions contribute to a relatively uniform development of the swelling, providing an outflow of moisture from the places where the swollen soil rises to a lower zone, where the swelling has slowed, thereby automatically regulating the development of the swelling process.

It is possible to eliminate the influence of adverse effects from swelling or shrinkage by completely or partially replacing the layer of swelling soil with a non-swelling soil.

Cutting swelling soils.

Cutting the foundations of swelling soils to a depth at which the remaining soil layer when soaked causes the structure to rise to an acceptable value is also a possible preventive measure. This option is based on the ability to change the depth of the foundation and the pressure on its sole in order to select such values of these quantities at which the occurrence of unacceptable deformations in structures is excluded.

Implementation of pile foundations and sheet piling wall is effective if the thickness of swelling soils does not exceed 12 m.

The use of pile foundations with full penetration of layers of swelling soils prevents the harmful effects of swelling, but does not exclude its effect on floors and structures arranged directly on the soil surface. Swelling quite often leads to a rise in the flooring at ground floor level, therefore, to eliminate this phenomenon, floors are recommended to be arranged properly. The use of pile foundations with partial penetration into the thickness of swelling soils leads to a significant decrease in the rise of the foundations, if the underlying layer of swelling soil has a small

thickness and is loaded with a significant load from the cut through the thickness.

When designing piles in swelling soil, the development of friction forces along their lateral surfaces should be taken into account. If these forces turn out to be more than the load per pile, then the foundation can rise, causing deformation of the structure.

To completely eliminate the influence of possible seasonal vertical fluctuations in the soil surface, foundations are often made of bored piles with a broadened heel (Fig. 4.6.11). Sealing the lower broadened end of piles into a non-swelling soil reduces the harmful effects of friction along the lateral surface. The horizontal effect of shrinkage and swelling is eliminated by backfilling with sand and laying

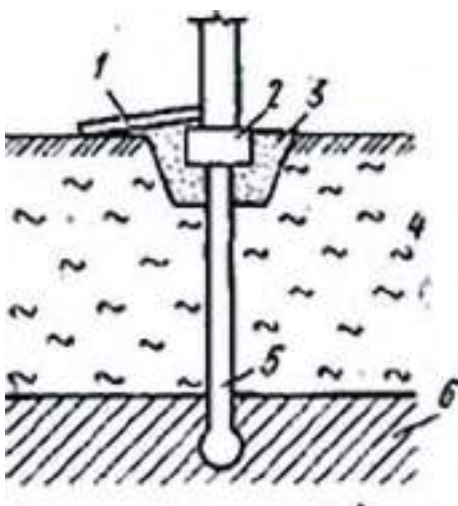


Fig 4.6.11. Foundation of bored piles with a widened heel in the conditions of swelling and shrinking soils: **1** – waterproof blind area; **2** – grillage; **3** – sand; **4** – swelling or shrinking soil; **5** – pile with broadening; **6** – non swelling soil

http://stroy-spravka.ru/gallery/osnovanie_fundamenti/image13_6.gif

of longitudinal reinforcement in the area of the sole, perceiving horizontal transverse tensile forces.

To increase the resistance forces in the embedded part of the piles, screw piles can also be used.

Compensating cushions are used to reduce the unevenness of the lifting of foundations.

The principle of operation of the compensating pillow is as follows: since the width of the sand cushion exceeds the width of the foundation, when the soil swells, sand bulges out between the foundation and the wall of the trench. Therefore, when raising the bottom of such a trench, the sand rises around the foundation, and the foundation itself remains almost motionless.

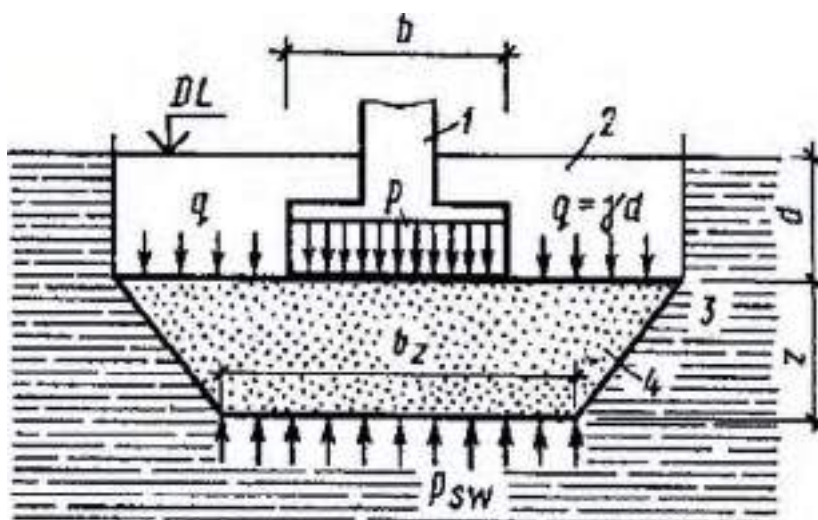


Fig. 4.6.12. Scheme of forces acting on a compensating pillow:

1 – foundation; 2 – backfill; 3 – swelling soil; 4 – sand compensating cushion

http://www.studfiles.ru/html/6911/8/html_13KeWnSgBz.ba0U/htmlconvd-73siob_html_m2d337d1f.png

Constructive measures include increasing the rigidity of the building by breaking them into separate compartments, cutting large-panel buildings with sedimentary seams into compartments less than 30 m long, reinforcing belts arranged at several levels in height.

Questions to chapter 4.6. Swelling and shrinkage of clay soils

1. What are the soils related to swelling?
2. What are the hypotheses that explain the process of soil swelling?
3. What is a “wedging effect”?
4. What is “inter-particle swelling”?
5. What is “intracrystalline swelling”?
6. What are the factors affecting swelling?
7. What is the dependence of swelling on pressure?
8. What types of dusty-clay soils are distinguished by relative swelling ε_{sw} ?
9. What is soil shrinkage?
10. How are the swelling and shrinkage of clay soils determined?
11. What zones of deformation are formed in the massif upon swelling of the soil?
12. What are the features of construction on swelling soils?

Chapter 4.7. GROUND IMPROVEMENT TECHNIQUES

Technical reclamation of soils or melioration (from Lat. Melioratio – improvement) is one of the sections of soil science aimed at developing the theory and practical methods of purposefully improving the composition, physical condition and mechanical characteristics of soils in accordance with the requirements and specificities of various types of construction.

Many soils in a natural state, as well as artificial and man-modified soils, by their properties do not meet the requirements for the construction of specific objects. Rocky or semi-rocky soils may not be strong enough, fractured, non-water resistant; dispersed soils – excessively moist, loose, subsiding or swelling, contain a large amount of organic material, among others. In this connection, in some cases there is a need to transform the soils and give them the required physic-mechanical properties necessary for construction.

The most common event in technical reclamation is a partial replacement of the foundation soil under the foundation. There can be two reasons for such a replacement: unsatisfactory indicators of the physic-mechanical properties of the soil base or the danger of developing negative geological processes and phenomena. Usually, by default, peat, sludge and the top vegetable soil layer are subject to replacement. In the case of a forecast of the development of frost heaving, to protect against freezing depth (or at least 0.5 m for one-story buildings), heaving soils are removed and replaced with non-porous soils (coarse sand, gravel and rock spalls).

4.7.1. Technical reclamation of rocky soils

The insufficient strength of rocky soils is associated with the presence of cracks of various origin and larger voids (for example, karst) in their massifs. Cracks are fastened with metal staples, sealed with cement or silicate mortar, which gives solidity and strength to rocky soils. In order to stop water filtration through cracks, they are filled with hot bitumen or clogged with clay. Similar methods are used for voids with a small volume and located close to the surface of the earth (anti-filtration methods, Lugeon and Packer test). Partially soluble rock and semi-rock soils, for example chemogenic limestones and dolomites, which have sufficiently high strength and deformation parameters, are protected by artificial layers of low-permeable clay or heavy loam (waterproof methods).

4.7.2. Technical reclamation of dispersed soils

Currently, two main techniques have been developed to improve the construction characteristics of dispersed soils: compaction and stabilisation of soils.

During compaction of dispersed soils, the porosity decreases and the contacts between individual particles in the soil increases. This leads to an increase in the total bearing capacity of the soil base and a decrease in its compressibility. Soils are compacted both from the surface of the earth (rollers, heavy rammers, vibration, soaking), and in the depth of the soil stratum (deep vibration compaction, soil piles, explosions, soaking).

Artificial soil stabilisation is a series of technical measures which improves contact strength between soil particles by cementation, gluing, sintering, and other methods. As a result, the soil becomes more durable, and in some cases waterproof. The main purpose of soil stabilisation is to increase the bearing capacity of foundations, as well as to create waterproof curtains around the excavation pits, underground mines and ground excavations. Depending on the physical and mechanical characteristics of the soil, its condition and the required degree of ground improvement, various methods are used: cementation, bitumen, chemical, electrochemical, freezing.

4.7.2.1. The main methods of compaction of soils

Mechanical methods are used to improve the quality of dispersed soils by using external loads (pressure, shock, vibration). The following methods of soil compaction are distinguished: 1) vibration compaction; 2) rolling 3) tamping; 4) soil piles and 5) the use of explosion energy. The essence of all these methods is of the same – compaction of soils by reducing its porosity. The natural structure of soils is generally modified and new mechanical structural bonds between the particles are formed. Typically, macro-porous compressible soils which are subject to compaction, include: loess subsiding soil, loose sandy, weak clay, bulk and some other types of soils. The depth of exposure distinguishes between surface and deep compaction of the soil formation.

Surface compaction. Surface compaction methods are used in the construction of roads, airfields, in the layering of loose, incoherent soils. The compaction is carried out with manual vibration compactors (Fig. 4.7.1), road vibratory rollers (Fig. 4.7.2), self-propelled dynamic rammers (Fig. 4.7.3), vibratory rammers and vibrating plates, the mass of which varies between 0.25–20 t at vibration frequency from 600 to 3000 per minute.



Fig. 4.7.1. Compaction of subsiding soil at the bottom of the pit with manual vibration methods
http://stroidom-mozhaisk.ru/photo/stroy_proc/011.jpg



Fig. 4.7.2. Compaction of an embankment with a road vibratory roller
<https://www.geosisp.ru/typy-issleduemyh-gruntov/>



Fig. 4.7.3. Dynamic self-propelled rammer compacts the soil base

<http://www.menard-russia.ru/images/dynamic-self-propelled-tamping-slider-1.png>

The dynamic self-propelled ramming equipment consists of a hydraulic pile-driving hammer mounted on an excavator. Depending on the size of the dynamic self-propelled ramming equipment, soil composition and its moisture content, the effective compacting depth varies from 4 to 5 m. Under certain favourable conditions, soil compaction can occur to a depth 7.5–8 m. Dynamic self-propelled rammer operates at a pace of 40–60 beats per minute, while the impact energy varies from 6 to 18 tons-m.

Ramming. In industrial and civil engineering, the most widely used method of mechanical compaction of dusty clay soils is realised by *ramming*. Reinforced concrete or metal ramming plates are used, which are dropped onto the ground from a given height. The efficiency depends on the mass of the rammer and the characteristics of the soil. So, with a ramming mass of 5–7 tons, the drop height should be at least 6–8 m, and with a mass of 10–15 tons – 12–15 m. The compaction depth of loess subsiding loams can reach 3–3.5 m. With a two-layer compaction, first, the bottom layer is rammed, then the second layer is placed onto the compacted layer and rammed. The total thickness of the soil compacted in this way can reach 5 m.

In recent years, heavy and super-heavy rammers have been developed, with a significantly greater depth of impact on soils (Fig. 4.7.4, 4.7.5).



Fig. 4.7.4. Heavy rammers

<http://www.menard-russia.ru/images/heavy-tamping-slider-3.png>

a



b



*Fig. 4.7.5 **a, b** –
Tamping soil on a grid
in a checkerboard
pattern*

<https://almaahadeng.com/product/dynamic-compaction/>

It is reported that super-heavy tampers weighing 40–50 tons have been used in England and Sweden, and in Japan the mass of such mechanisms reaches 150 tons. In Sweden, using compactors weighing 40 tons falling freely from a height of 40 m, successful compaction of crushed stone embankments to a depth of 40 m has been achieved.

In France, during the construction of an airport, the use of super-heavy rammers weighing 200 tons made it possible to compact embankments and water-saturated sands to a depth of 40 m. These rammers were dropped from a height of 20 m with a special jib crane.

Data on the effective depth of compaction of various types of soils, depending on the composition and moisture content, are shown in fig. 4.7.6.

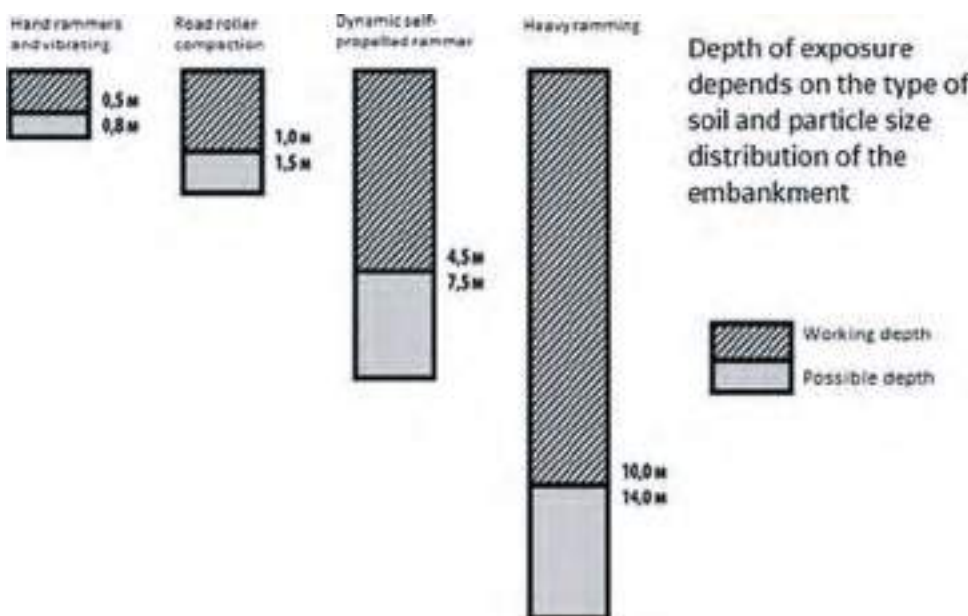


Fig 4.7.6. Depth of compaction of soils, compacted by various surface equipment
<http://www.menard-russia.ru/images/heavy-tamping-slider-4.png>

Deep vibratory compaction is one of the widely used methods that is commonly used for compaction of natural loose or washed sands to a depth of 70 meters.

The principle of operation of the vibration compaction is to increase the density of soils overlying construction sites with the help of vibration effects caused by a special vibrocone, which is immersed in the soil (Fig. 4.7.7 a). Fluctuations are accompanied by a constant supply of water through nozzles located along the entire length of the working body (Fig. 4.7.7 b, c), which

contributes to the repackaging of sand particles (Fig. 4.7.8), with the formation of a denser mass of base soil. Vibration compaction is usually used to increase the bearing capacity, improve soil properties, reduce soil liquefaction with possible seismic and dynamic effects on the soil at the base.

The degree of compaction is dictated by the main parameters of the site requirements (time of vibration, lifting speed of the working tool, distance between compaction points); soil reinforcement is performed locally, which allows to optimise the compaction of various soil layers to a considerable depth.



a

b



c

Fig. 4.7.7. Deep vibration compaction of soil: **a** – submersible cone;
b, c – water supply through nozzles in the working body
<http://www.menard-russia.ru/images/heavy-tamping-slider-5.png>

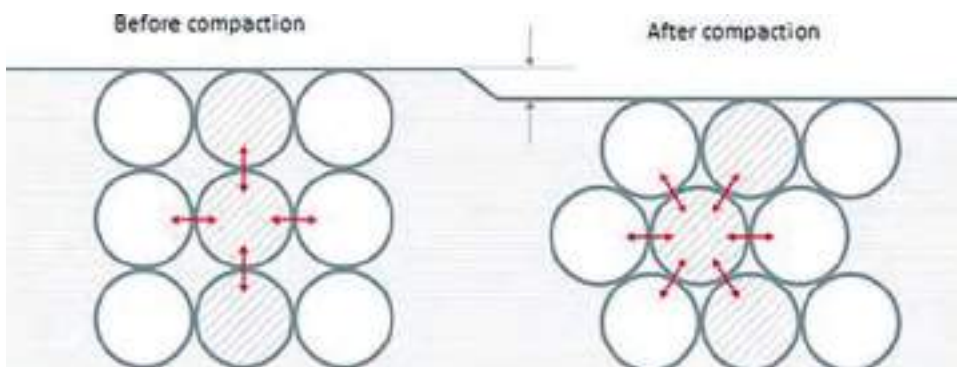


Fig. 4.7.8. Arrangement of soil particles before and after vibration compaction
<http://www.menard-russia.ru/images/heavy-tamping-slider-6.png>

Deep compaction with sand and soil piles is most often used for laying foundations in macro-porous loess soils, loose dusty and fine sands, as well as weak, highly compressible peat. For soil piles in macro-porous soils, local cohesive soil is most often used. For other types of soils, sand piles are used, which are manufactured using inventory pipes with a drop shoe. Inventory pipes are immersed in the ground using clogging or vibration immersion. After reaching the required mark, sand is placed in the pipe, followed by layer-by-layer tamping and the inventory pipe is gradually removed. When the vibrator is turned on, the pipe is removed, thereby compacting the sand.

Surface and deep compaction, as well as compaction using sand piles, are performed not only directly under the sole of the foundation under construction, but also in neighboring areas adjacent to the zones of maximum pressure.

For compaction of peaty sands saturated with water and weak water-saturated dusty-clay soils, lime piles are used, installed with the help of inventory pipes, into which slaked lime is poured. Extinguishing of lime occurs as a result of exposure to ground water. In the process of quenching, lime increases in volume and compacts the surrounding soil.

4.7.2.2. *The main types of soil consolidation*

Soil stabilisation in general is a targeted effect and transformation of soils through their chemical, physic-chemical, mechanical or thermal treatment, using appropriate technologies.

Depending on the method of soil treatment, which improves their properties, soil stabilisation is divided into the following types:

- chemical, based on physicochemical processes that occur in soils after the introduction of certain reagents;
- electrochemical, based on the secondary phenomena of electrolysis that occur in soils under the action of the created external field of direct electric current;
- thermal method: improvement of soil properties is achieved as a result of their calcination in wells with hot gases or electric heating;
- thermal stabilisation of clay water-saturated soils: improvement of engineering properties is achieved by self-compaction, when heated within a range of 50–80 °C.

Chemical stabilisation, depending on the method of introducing reagents into the soil, can be realised as follows:

1. chemical injection method, in which reagents in the form of solutions or gases are introduced into the soil by injection under pressure, without disturbing their natural composition;
2. soil mixing method, carried out by using mechanical mixing with cements or other chemical reagents and additives through large diameter wells.

Chemical injection method includes silicatization, resinization, cementation; the second method is realized by drilling and mixing of weak silted and peaty, as well as other associated soils. Each of the above methods has its own field of application, depending on the types of soils, permeability, chemical properties, moisture content and absorption capacity for clay soils.

The main ways of stabilising soils and the limitations of their practical application are given in table. 4.7.1.

Silicatization and soil resinization are applied using several specific methods that differ by chemical technology. These methods are purposefully applied to improve certain types of sandy and subsiding loess soils.

Silicatization is carried out according to the following schemes: two-solution or one-solution. A two-solution fixation consists in sequentially injecting into the ground first an aqueous solution of sodium silicate (water glass), and then calcium chloride (hardener). The solutions react and form a gel of silicic acid, which envelops the soil grains, over time, the gel gradually hardens and binds the dispersed soil into a continuous monolith.

With one-solution fixation, the solution itself hardens after a certain time. Two-solution silicatization is used in more permeable soils, with a filtration

coefficient from 0.2 to 80 m/day. The compressive strength of the resulting improved soil rises to 1.5–3 MPa.

One-solution fixation (a mixture of sodium silicate and hardener) is used for low permeability soils with coefficient of permeability less than 0.3 m/day. The strength of the improved soil is in the range of 0.3–0.6 MPa.

Table 4.7.1

The main methods of fixing soil

Method	Type of soil	Moisture content	Permeability, m/day
Silicatization	Subsiding loess, loesslike and cover loams	< 0,7	> 0.2
	Sandy soil	Regardless of moisture	0.5–80
Resinization	Sandy soil	Regardless of moisture	0.5–50
Thermal fixing	Subsiding loess and loesslike loam, non-subsiding loam and clay	< 0.5	Regardless of permeability
Cementation	Fissured rocky, coarse, gravelly and sandy. Large voids.	Regardless of moisture	For rocky 0.01. For non-rocking 50
Drilling and mixing	Silts, clay and loam accompanying them, soft plastic or liquid; loose and medium density sands	Regardless of moisture	Regardless of permeability
Freezing	Sands – Quicksand	1 or more	Regardless of permeability

Cementation and bituminization consist of injecting, respectively, cement mortar or heated bitumen into porous soils with a high coefficient of permeability, as well as into fractured rock formations. Soil stabilisation using cementation is often used to fill not too large underground karst voids and, generally, with the carbonate type of karst. In a number of cases, sands are cemented, in which suffusion processes may develop or may arise. In the same way, create anti-filter curtains to prevent the entry of groundwater into the pit within the contour of the structure.

Soil freezing is used in quicksand – sand saturated with water during the development of deep pits. For this, freezing column-pipes are connected around the perimeter of the foundation pit, connected by a pipeline, through which a special brine liquid (salt solutions with a low freezing temperature, for example, CaCl_2) is pumped, cooled by a refrigeration unit to

a temperature of minus 20–40° C. The soil surrounding the column freezes in the form of concentric cylinders, the diameters of which gradually increase. These cylinders freeze into a solid wall of frozen soil, which serves as a temporary fence.

The above fixing methods achieve a significant increase in the bearing capacity of soil bases, the strength and stability of many types of soils, while ensuring their water resistance, which makes it possible to build on soft soils. For all filtering soils without exception, stabilisation allows to reduce or almost completely eliminate their permeability, which makes it possible to use them as anti-filtration structures, as well as to increase the stability of these soils during underground construction works.

Test questions to chapter 4.7. Ground improvement techniques.

1. What is ground improvement?
2. What are the methods of soil compaction?
3. What are the main methods to stabilise soils?
4. What is silicatization?
5. What is cementation and bituminization?
6. What is soil freezing?

PART V. REGIONAL ENGINEERING GEOLOGY OF THE ISLAND OF MAURITIUS

Chapter 5.1. THE ISLAND OF MAURITIUS

Mauritius is located about 800 km east of Madagascar in the Indian Ocean. Its outlying territories are Rodrigues Island, situated about 550 km eastward, the Cargados Carajos Shoals, 400 km northeastward, and the Agalega Islands, 930 km northward from the main island (Fig. 5.1.1., 5.1.2).

It forms part of the Mascarene Islands (from french: Îles des Mascareignes), comprising the islands of Réunion, Mauritius, and Rodrigues, which are situated in a line along a submarine ridge, the Seychelles-Mauritius Plateau, 640 to 800 km northeast from southern Madagascar.



Fig. 5.1.1. Location of the island of Mauritius
<https://www.britannica.com/place/Mauritius>

PART V. REGIONAL ENGINEERING GEOLOGY OF THE ISLAND OF MAURITIUS

The island is of volcanic origin and is entirely surrounded by coral reefs. The northern part is a plain that rises to a central plateau, varying in elevation from about 270 to 730 metres, above sea level. The plateau is bordered by small mountains that have formed the rim of an ancient volcano; the highest point, 828 metres high, is the Piton de la Petite Rivière Noire in the southwest of the island. The scattering territory islands are mainly atolls, except Rodrigues.



Fig 5.1.2. Map of Mauritius
<https://www.britannica.com/place/Mauritius>

Chapter 5.2. GENERAL GEOLOGICAL CHARACTERISTICS

Formation of Mauritius Island (source: <https://www.yonature.com/formation-volcanic-island-mauritius/>)

There are some legends about the actual formation of Mauritius. While some scientists favour the hotspot theory that created the Mascarene islands, others believe the independent formation of the Mascarene islands by fracture zones on the sea floor.

Both lead to the same genetic history. Everything started 65 million years ago, during the breakup of Gondwana when India detached from Africa and moved upwards towards Asia. Flood basalts erupted along the volcanic hot spot where Reunion island is now located, as India crashed into Asia forming the Himalayas. It is at this point that ideas diverge.

Hotspot theory

A hotspot is a region in the mantle where magma rises to the surface. As it pushes through the crust, it initiates the formation of volcanoes. Since the crust is constantly in movement, the volcano created slides over the magmatic chamber, becomes inactive and can form an island. Another volcano is created in its place until the hotspot's activities decrease.

It is believed that to the east of Reunion, there is a volcanic hotspot that gave rise to the Mascarene Islands, the Chagos-Maldives Laccadive Islands, the Saya de Malha and the Nazareth Banks.

Reunion island itself started to form some 60 million years ago from an isolated volcano on an oceanic crust 3000 m deep^[1]. The island emerged 3 million years ago and volcanic activity has been continuous on Piton de la Fournaise.

Based on stratigraphic and potassium-argon dating, Mauritius emerged from this volcanic hotspot 10 million years ago; the volcano remained active until 25,000 years ago.

Fracture zone theory

The seafloor in the west Indian Ocean is undulated by fracture zones emerging from the mid-Indian ocean ridge. It is suggested that these fracture zones spewed up magma independently forming the Mascarene Islands. The main fissure was still active some 10 million years ago forming the initial volcanic shield of Mauritius and gradually building it up until its activity decreased.

Rodrigues, too, is suggested to have been formed by activities in the Rodrigues fault as the ridge adjusted its position over the years. Studies suggest that actually volcanic activities started approximately 10 million years

ago forming a flat base mount. This mount eventually eroded forming a plateau upon which the Rodrigues steep sided volcano emerged 2.5 million years ago.

Geologists began to conduct scientific research on the geological structure of the island mainly from the second half of the 20th century. Geological studies on Mauritius have been carried out by several scientists such as de Chazal (1949), Simpson (1951), Walker and Nicolaysen (1953), McDougall and Chamalaun (1968), Baxter (1972), Perroud (1982), and Williame (1984). Dr Proag, V., in his book clearly summarises the geology of Mauritius (*Ref: Proag V. The geology and water resources of Mauritius, analysis, Mahatma Gandhi Institute, 1995*). The following highlights the geology of Mauritius as described by Dr Proag.

5.2.1. Brief historical geology of the island

Mauritius has almost entirely volcanic origin. Exception are the small territories of beaches, the coral reefs formation and local alluvial extents.

The island is the result of several major activity periods. In the formation of the island, four volcanic phases are observed:

1. Emergence of the Island;
2. Older Volcanic Series;
3. Intermediate or Early Volcanic Series;
4. Younger volcanic or Late volcanic series.

A diagram of the stages of the island development is shown in Fig. 5.2.1.

Periods of Emergence and Older Series: 10–5 million years giving rise to the old lavas, Intermediate and Younger Series: 3.5 million years to 25 thousand years ago. We can also distinguish the period after the end of the volcanic eruptions from 25 thousand years to the present day.

Period of the Island Emergence

10–6.7 million years ago (late Miocene) the first volcanic emissions acted as an eruptive rift fissure. This process is characterized as a marine phreatomagmatic eruption, with large amount of water. The brecciated series or basic series consisted of volcanic products such as tuff, boulders and breccia flows. The island foundation is an accumulation of pillow-lava – lava that has solidified as rounded masses, characteristic of eruption under water. The accumulation of tuffs and breccia products was acted upon by ocean waves which disintegrated the lavas as they rose up. The lava flows separated by volcanic ash layers lie on top of these initial formations.

In the time period between about 7.8 and 6.8 million years ago, these massifs were the eroded remnants of a single, large, shield volcano built above sea level by the extrusion of lavas (Fig. 5.2.1 a).

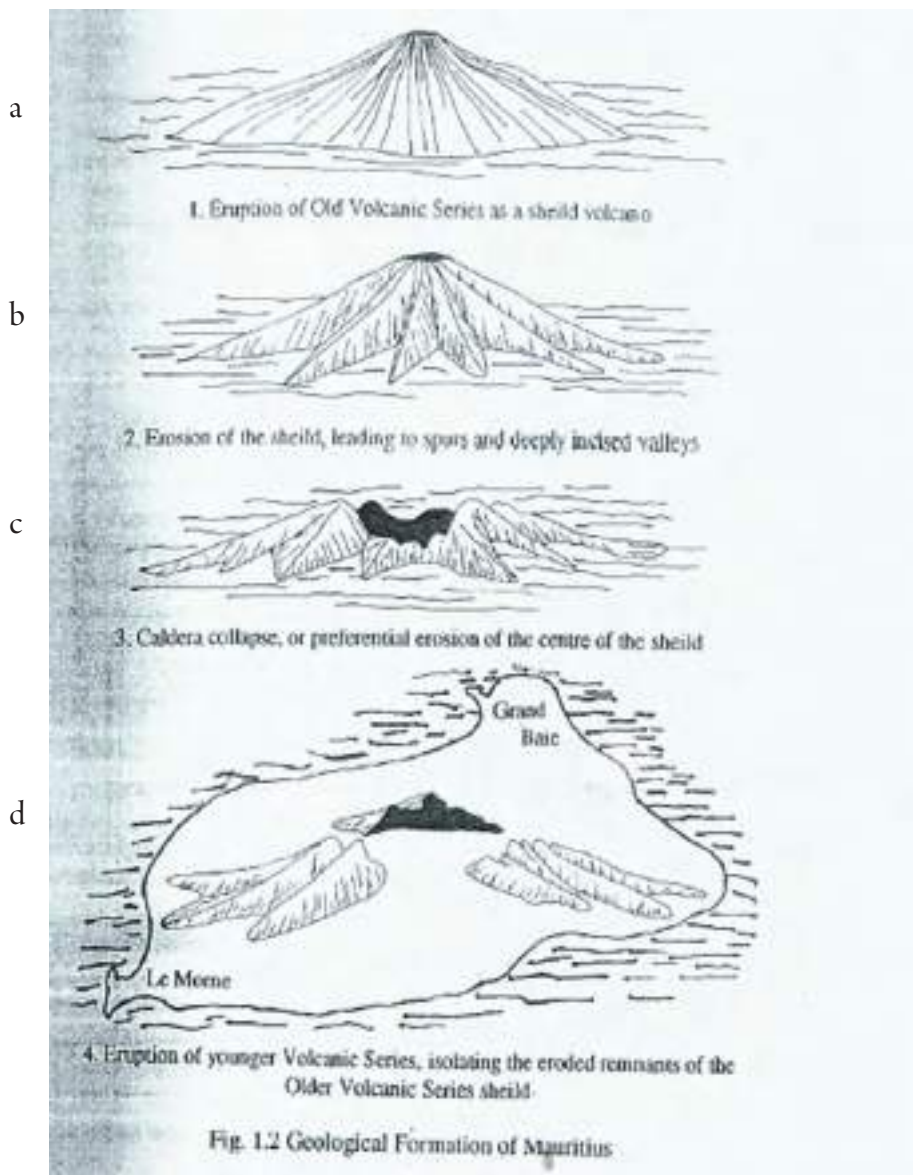


Fig. 5.2.1. Geological formation of Mauritius (Dr. Proag, 1995)

The Older Volcanic Series (Old Lavas)

The second phase of activity continued from 6.2 to 5 million years ago, and the island acquired a round shield (Fig. 5.2.1 b). The volcano that appeared was a huge dome with a diameter of 40 km and a height of about 900 m, with gentle

slopes (5°). In this series of lavas, basalts prevailed the flows of which sometimes reached a thickness of 50–100 m.

In a volcanic structure, a system of isolated cracks began to develop. The top of the elongated shield crumbled, forming a caldera with a diameter of 24 km. More differentiated lavas erupted about 5.5 million years ago. The rift weakened and began to show mainly hydrothermal activity.

The Intermediate Series (Early Lavas)

After the old lava series erupted, the island went through a relatively quiet period for about 1.5 million years. Intense erosion occurred during this period. And then (from 3.5 to 1.9 million years) the bottom of the caldera and secondary depressions was filled with volcanic lava flows (Fig. 5.2.1 c) of a subsequent eruption. During that period, activities were relatively intense, especially in the south western part of the island.

At the late Pliocene (about 3.5 million years ago), volcanic activity resumed, giving rise to a younger volcanic series of basalts. These eruptions continued intermittently until recently. Volcanism had a completely different character than before – during the formation of the shield volcano. Eruptions came from relatively small craters. Although younger volcanic lavas are very widespread, their total volume is relatively small compared to older ones. Early lavas were extruded from about 3.5 to 2.0 million years ago.

The Younger Volcanic Series (Late Lavas)

After the intermediate phase ended about 1.9 million years ago, a rest period followed by a duration of more than 1.2 million years.

The renewed eruptions in the Quaternary period of 700 thousand – 25 thousand years ago correspond to the latest volcanic events on the island. Eruptions associated with the reactivation of a secondary rift, came from 26 craters (Fig. 5.2.1 d). Hawaiian-type basalt flows with a thickness of 0.2 to 2 m, sometimes reaching 5 m, occurred. Empty tunnels are present in the lava horizons, sometimes locally connected. Often, lateritic soils lie between lava flows.

In general, the very deep weathering of the older series led to the formation of clay materials, which contributed to the filling of cracks in rock masses over the past 6.8 million years. And this caused the general impenetrability of these series. Early lavas are generally less permeable than late, fresh ones.

The effects of glaciation and sea level fluctuations

The consequences of the Quaternary glaciations are observed in the main formations of Mauritius. The “Earth icing” or glaciation of Mindel occurred between 700 thousand and 500 thousand years ago, the Riss glaciation between 300 and 250 thousand years ago, and the Wurm glaciation began about 100 thousand years ago and ended about 12 thousand years. Worldwide sea level fluctuations were due to these glaciations. Thus, the late volcanic rocks in Mauritius developed in the Pleistocene as sea level changed and ceased at the end of the Riss-Wurm interglacial period. The highest reefs of the island, ranging in height from 18 to 30 m near the Baie du Jacotet, are the result of a period of high sea level of the Riss-Wurm interglacial period. The resumption of erosion of old volcanoes and earlier series of younger volcanoes occurred at the same time. As Riss continued to freeze, coral reefs and sands arose at levels that are now well below current sea level. At the same time, streams and rivers washed away much deeper gorges and valleys in the old series and the earlier series of younger eruptions. The formation of new river terraces was also caused by significant fluctuations in sea level.

Since the late Pleistocene (300 thousand years), a relatively small increase in sea level – less than 15 m occurred only 3 times. And in the Holocene, there were two significant periods of sea level decline by more than 150 m: 80–40 thousand years and 30–5 thousand years ago.

Remains of coral and sand at levels that are actually 2–13 m above present sea level are likely to correspond to sea level rise since the end of the last ice age. Some parts of old reefs and beaches were buried under young lava flows. Other exits have been found in places where these flows have not reached: for example, in the two most important deposits of La Prairie in the southwest of the island, and Vieux Grand Port, north of Mahebourg in the southeast. They were protected from the invasion of late lava flows by the surrounding old masses.

5.2.2. Geomorphology

The modern relief of the island was formed under the influence of magmatic effusive activity and the subsequent transformation of the products of eruptions by processes on the surface of the earth: weathering, erosion, abrasion, biological processes, etc.

Mauritius Island consists of three main geomorphological elements: the central plateau – a wavy hill with an average height of about 300–400 m and

a maximum height of about 600 m in the south of the island: mountain ranges surrounding the plateau (700–800 m high), and low coastal plains (Fig. 5.2.2).



Fig 5.2.2. Geomorphology of Mauritius

<http://www.maphill.com/mauritius/3d-maps/satellite-map/physical-outside/>

Heavily eroded relics of the plateau edge are surrounded by a discontinuous ring of mountain ranges with sharp peaks. The plains surrounding the plateau and mountains on the outside formed on the surface of the frozen lava flows from small volcanoes located on a wide low middle ridge, passing through the island from the southwest to the northeast. Central elevations pass into the coastal plains without any clear boundary between them. The slopes as a whole gradually decrease towards the coast and are rarely steep at short distances. Mountains, as a rule, are very steep towards the plateau; their back slopes are less steep towards the plains.

The central highland plateau consists mainly of young volcanic formations that can form sharp rocks, and in some places they are very weathered, up to the state of clay, depending on the age of the rocks and climatic conditions. Laterites are often found, especially in marshy areas in the very humid and most elevated southwestern plateau region. The middle ridge, which lowers from southwest to northeast, is a wide mountain range with many low hills of young volcanic cones.

The mountains around the plateau are asymmetric and form the following mountain ranges:

- in the north-west – Port Louis – Nicolière range with Pieter Both peak, at 820 m;
- in the east – the Montagne Blanche – Montagne Fiennes massif;
- in the south – the Bambous mountain range;
- in the south-west – the Rivière Noire-Savanne range with the Piton peak and de la Rivière Noire peak (828 m).

There are also several hills or isolated peaks: St. Pierre – Corps de Garde (720 m), Piton du Milieu Candos, Motte a Therese, and Grand Malabar.

A very noticeable similarity of the forms of mountain ranges is noted. Almost correct central symmetry is observed – an amazing coincidence of the general relief lines, including the channel where recent lava flows occurred, and the location of two sections of lakes (Nicolière and Eau Bleue).

There is also a similarity between the Tamarin-Rempart massif and the Port Louis – Montagne Longue massif, which are symmetrical to each other with respect to the North-West – South-East axis. These two massifs are oriented in the same way and are relics of the same geological substrate.

The coastal plains

The island coastal plains include:

- in the North, plains spanning the regions of Pamplémousses and Rivière du Rempart;
- in the East, the Plaine des Roches region;
- in the South-East, the Plaisance – Mahebourg plain;
- in the West, the Petit Rivière, Rivière Noire and Tamarin plains.

The northern plain is the largest of the island's coastal plains. It also has the lowest surface slope – from 0 to 8.5 %. Its middle ridge is, as it were, the northern extension of the ridge of central uplands. Several volcanic cones of the younger series rise above the undulating relief of the plain.

The Flacq plain also has, as a rule, low slopes of the surface towards the sea. The gradient between the foot of Mount Fayence and Trou d'Eau Douce is on average about 11 %.

Other large plains of the island are steeper. For example, the gradient of the southeastern plain of Grand Port, between Rose Belle and the ocean, is about 20%, and in the western plain between the distribution channel of La Ferme and the sea, the gradient is about 30%. The rocks on these plains mostly exposed to less weathering, as the climate here is much drier than on higher lands.

Hydrography

A large number of streams and rivers on the island are distributed very unevenly. Significant territories of coastal plains do not have surface watercourses: almost the entire northern plain, the Plaine des Roches, the eastern plain between Centre de Flacq and Trou d'Eau Douce, the southwestern plain from Rose Belle to the sea, and the southern plain of Savanne.

In the two main regions of the Central Highlands, there are no rivers in the northeast, directly south of La Nicolière, and no zones from Cape Curepipe to Eau Bleue in the southeast. Erosive activity of surface water flows is observed during heavy rains, especially during storms and cyclones of the rainy season. In the two main regions of the Central Highlands, there are no rivers in the north-east, directly south of La Nicolière, and no zones from Curepipe Point to Eau Bleue in the south-east.

Erosive activity of surface water flows is observed during heavy rains, especially during storms and cyclones of the rainy season.

On the island, the largest are two natural lakes – Grand Bassin and Bassin Blanc. The existence of these lakes may be due to outflows of surrounding groundwater, or due to rainwater flowing down the slopes of the crater. The Trou-aux-Cerfs periodic crater pond is probably directly linked to the groundwater level in the Curepipe area.

There are several wetlands, mainly located in areas with low soil permeability, in the central highlands, for example, south of Mare aux Vacoas and on dark clay, for example, in the southern part of the west coast.

Aquifers of Mauritius

An aquifer is a wet underground layer of water-bearing permeable rock or unconsolidated materials (gravel, sand, or silt) from which groundwater can be usefully extracted using a water well.

There are five main aquifers in Mauritius, which were delineated by Giorgi et al. (1999) through extensive surveying with the help of local authorities. From the central recharge zone, water flows radially towards the sea. The different aquifers were demarcated using the sea as the outer boundary into which the aquifer drains. These aquifers are:

- I. Aquifer of Curepipe, Vacoas and Flic-en-Flac
- II. Aquifer of Phoenix, Beau Bassin, Albion/Moka, Coromandel
- II. Aquifer of Nouvelle France, Rose Belle, Plaisance
- IV. Aquifer of Nouvelle Decouverte, Plaine des Roches/Midlands, Trou d'Eau Douce
- V. Aquifer of the Northern Plains.

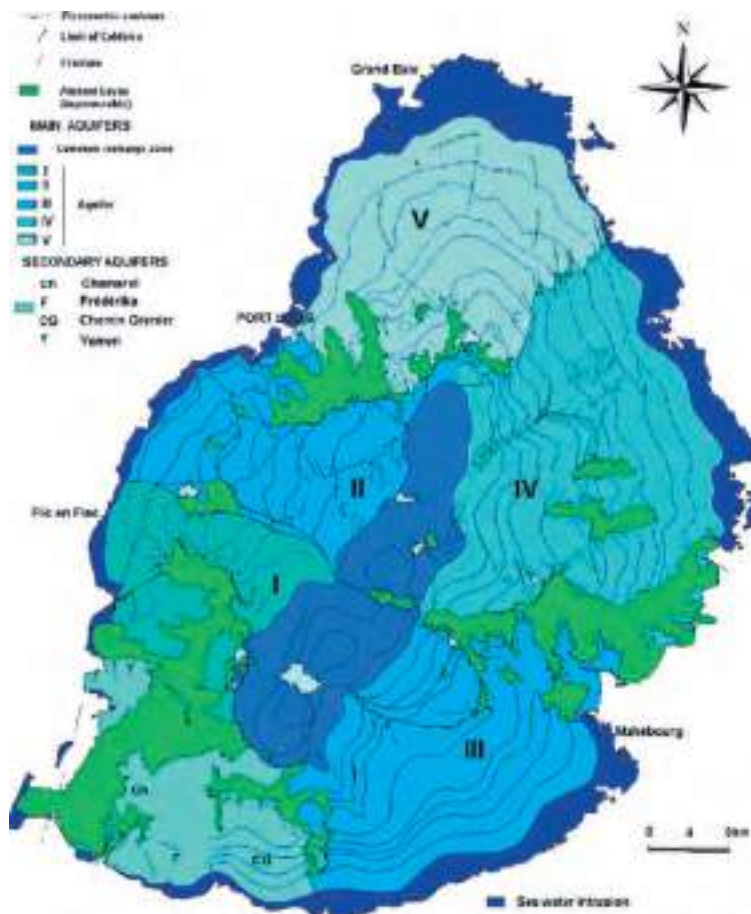


Fig. 5.2.3. Aquifers of Mauritius

source: <https://kth.diva-portal.org/smash/get/diva2:1205424/FULLTEXT01.pdf>

Aquifer I (Curepipe–Vacoas –Flic-en-Flac) is a multi-layered aquifer constituted by the superposition and juxtaposition of basaltic flows, healthy and weathered separated by clayish facies. The superficial layer of the aquifer consists of recent or intermediate basaltic flows. Lava tunnels and scoriaceous formations under the water table constitute channels where water flows very rapidly. Aquifer I comprises of:

5. The western part of the intracalderic groundwater reservoir
6. The median reservoir of Palma-Beaux-Songes
7. The coastal reservoir of Flic-en-Flac Tamarin

Aquifer II (Phoenix-Beau Bassin-Albion / Moka-Coromandel) comprises of:

8. The western part of the intracalderic reservoir
9. The median reservoir of Phoenix-Moka-Beau Bassin limited by ancient basaltic flow outcrops in the form of mountain ranges
10. The coastal reservoir of Coromandel-Pointe aux Sables-Albion

According to Giorgi et al. (1999), from borehole drilling it was found that there were two deep valleys made up of ancient basaltic flows and filled by intermediate and recent basalt flows. These two valleys guide groundwater circulations and particularly in levels of fossil alluvium located at the base some flows. The top of the aquifer is located within clayish semi-impermeable basalts which show some characteristics of semi-confined aquifers.

Aquifer III (Nouvelle France-Belle Rose-Plaisance) as described by Giorgi et al. (1999) has different hydraulic behaviour in different sectors: to the north the flow is conditioned by breaches that border the rims of the caldera, while to the south, groundwater of the superficial aquifer strengthens the recharge of the reservoir. Near the area of Mare Tabac, the variation of the static water level as observed until 1999 varied from 5 to 10 m at Nouvelle France and 20–30 metres at Mare Tabac. These fluctuations are considered to be conditioned by the presence of old basalt and at places covered by intermediate basalts that have channelled basaltic flows and subsequently groundwater flows.

Aquifer IV (Nouvelle Decouverte-Plaines des Roches / Midlands-Trou d'Éau Douce) comprises of three main reservoirs: the eastern part of the intracalderic reservoir, the median reservoirs of Camp Thorel, Pont Bon Dieu and Melrose-Belle Mare, and the coastal reservoirs of Plains des Roches and Trou d'eau Douce. The median reservoir of Camp Thorel-Pont Bon Dieu is limited to the north by the fault N20 that 2-21 affects the border of the caldera and to the south by the ridge of ancient basalt. The seasonal variation of water in the aquifers is high, between 10–20 m as of 1999, as described by Giorgi et al. (1999).

Aquifer V (northern plains) is located beyond the calderic rim. The principal refill is linked to discontinuities which constitute permeable zones allowing groundwater to flow to the north. The limits of the northern plains can be made up of vertical or horizontal dykes of intrusive rock which are the results from the collapse of the caldera. When these rocks are obstructed by the products of weathering they can become obstacles for free groundwater circulation. The aquifer consists of various zones of recharge.

5.2.3. Geology

The geology of Mauritius is fairly simple. Compared to the wide variety of igneous, metamorphic and sedimentary rocks that are found on the continents, basalts are found everywhere on the island. However, basalt formations are also diverse, ranging from very solid basalt with a massive texture and high density up to 2900–3000 kg / m³ (Fig. 5.2.5 a) to very porous basalt with a slag structure, which can be a groundwater reservoir (Fig. 5.2.5 b). According to geological history, there were three main stages of volcanic activity, which gave rise to three different types of effusive rocks. Over time, the rocks were subjected to varying degrees of weathering, and some sedimentary formations arose.

Old Volcanic Series

The most noticeable mountain ranges on the island are the old volcanic series, the cliffs of which rise high above the plateau and the plains of the young series (Fig 5.2.6).

There are three main groups of exposures on the earth's surface of volcanic rocks of the old series. One of them is located in the south-west of the island, making up most of the Rivière Noire and Savanne ranges. The second, in the east-southeast, is represented by the Bambous ridge and some other smaller outcrops, such as Montagne Blanche. The third forms the ridges of Port Louis and La Nicolière.

Some of the features of the course of eruptions that are common in these outlets are mainly related to the presence of dykes or lava plugs that have been cleaned by weather and erosion. The main dykes permeating the old row are subvertical or vertical and have a southwest-north-east orientation.

Basalt flows and agglomerate layers of the old series usually lie subhorizontal with a gentle slope to the sea, not exceeding 15–20 degrees, and from the inside of the mountains they are steep cliffs. The outcrops of the series are the remains of a shield volcano.

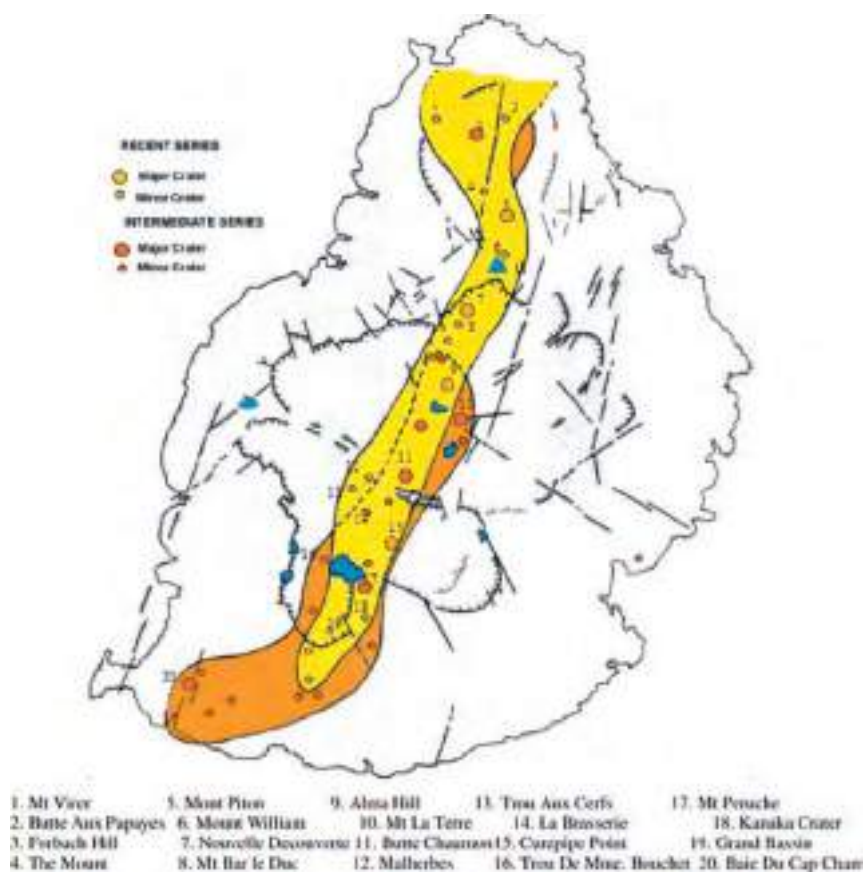
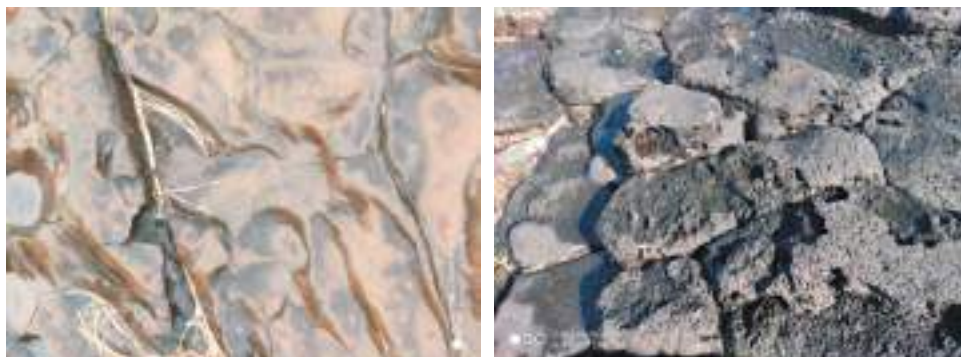


Fig 5.2.4. Main Craters of Mauritius

Nowbuth M. D et al. – Earth Science India, eISSN: 0974 – 8350 Vol. 5 (III),
July, 2012, pp. 79-91 <http://www.earthscienceindia.info/>



a

b

Fig 5.2.5 **a** – compact basalt with a massive texture;
b – vesicular weathered basalt Photo by V. Iegupov



Fig. 5.2.6. The highest mountain ranges of the island are composed of basalts of «Old Lavas» Photo by R. Goodary

The old volcanic series are mainly represented by flows of olivine basalts, which are fine-grained dark rocks, but in some places also have coarse-grained facies with large phenocrysts of olivine and pyroxenes.



Fig. 5.2.7. Alternation of basalts, agglomerates and volcanic tuffs at Maconde (South West of the Island) Photo by Krishun Dutt Goodary

Basalt flows, as a rule, are not expressed, massive and slightly fractured. In some places, flows alternate with layers of agglomerates and tuffs, and the thickness can vary from 3 to more than 30 meters (Fig. 5.2.7).

All these rocks, when weathered, have a grayish color, contrasting with the reddish appearance of the agglomerate or the darkish color of fresh basalts. Agglomerates consist of

scoria – ash matrix with inclusions of pebbles of olivine basalt, usually irregular or round. Tuffs are very similar to this agglomerate matrix.

The main intrusions consist of dykes, which in composition are very similar to the layers of the main extrusion that they cross. These are mainly olivine basalts of fine-grained type, compact and dark in color. The thickness of the dykes varies from a few centimeters to three meters. These major intrusions are contained in small clay hills near Saint Julien d'Hotman and Melrose.

Some older basalts turn into trachytes and may differ only from others in a lighter color.

Intermediate (Early) Volcanic Series

The intermediate row is represented by basalt flows that overlap the basalt agglomerate of lavas of the old series. Basalts are heterogeneous in composition, as their nature varies from place to place, but in general they are fine-grained rocks from gray to black, having an olivine composition. They are usually porous and often vesicular. They are also slightly cracked, and in some places the cracks and cavities are filled with montmorillonite clay.

Outcrops of columnar basalt are common, for example, at the Piton du Milieu and Rochester waterfalls. These layers are often very blurry, as is evident, for example, in the Chamarel region. In addition, they tend to form glandular laterites with very high iron content, as in the humid highlands of the Plaine-Champagne–Petrin region.

Agglomerates at the base of individual streams have the same characteristics as agglomerates of old series. The pebbles contained in the agglomerates with a diameter of several centimeters are bubble lava.

These volcanic series come to the surface mainly in the southwestern part of the island. They are more extensive and underlie the very common late lavas in many areas. Only one of the vents from which they were thrown out was relatively well preserved. Other craters are not known for the early series; they were either already destroyed by erosion or buried under later formations.

Radial runoff occurs in rivers that cut into strata deeper into older layers. The most impressive rapids, waterfalls, and gorges are mainly in the Old and Early Lavas of the southwestern Tamarind waterfall (300 m), Cascade Cecile (150 m), east of the Plaine Champagne (150 m), Chamarel Falls (100 m), Rochester Falls, Black River Gorges and Baie du Cap Gorges (Fig. 5.1.6).

Intermediate lavas are sometimes very heavily cut by rivers, for example, the Grand River North-West, Grand River South-East and Rivière des Anguilles.



Fig. 5.2.8. Waterfall at Chamarel. It is clearly seen that the bulk of the basalts are underlain by agglomerates. Photo by Krishun Dutt Goodary

Younger Volcanic Series

The late lavas are represented by a uniform dolerite facies. They are light gray in color and include many small olivine phenocrysts scattered among feldspars and pyroxenes. Lavas are often porous and vesicular and have many cracks.

Coriaceous textures are distributed mainly in the upper and lower parts of streams. The main openings are mainly located in these hilly areas between streams, and lava tunnels are not uncommon. This explains the very high permeability of late volcanic rocks. When weathering, cracks are not blocked by secondary filling with clay material.

The thickness of the flows varies from 0.5 to 13 m. With a large thickness, they have secondary cracks that form during cooling and divide the massif into parallel layers. These lavas are sometimes quite fresh, so you can often see loose structures, for example, in the Plaine des Roches region.

Some elevations from 1 to 8 m high and 22 m wide, are visible above the surface of some volcanic systems. In addition, many depressions in lava flows were due to phreatic explosions, and in some cases, tube-like openings are present.

The lavas filled the old hollows and now cover almost 70 percent of the island's modern surface. The central plateau and plains are formed from

this material, and their rather flat relief strongly contrasts with the prominent mountains of the old row.

Even their volcanic cones are low and have flat sides, and they are not as noticeable as the cones of older eruptions. In some cases, lava flows are probably of fissural origin, but in general, they come out of the vents. These holes are located inside the strip that crosses the island from southwest to northeast, which serves as a watershed for surface waters and is approximately parallel to the tectonic underwater fault that runs along the west coast of Mauritius.



Fig 5.2.9. Volcanic crater at Trou aux Cerfs

source: <https://i.pinimg.com/736x/5a/ab/05/5aab0580e4fd06fc2dac88eb86c0fffc.jpg>

There are approximately twenty-six of them, and many of them have lost their craters, while some of them are still very well-preserved, such as Trou aux Cerfs, Trou Kanaka, Bar le Duc, and Bassin Blanc. Some of the northern vents are surrounded by a layer of pyroclastic rocks ejected at the last stage of their activity.

There are many lava tunnels, and the most famous of them are Eau Coulée near Curepipe, Petite Rivière and Caverne des Hirondelles in the Western region. Sometimes streams flowed in the tunnel itself, for example, in Eau Coulée and Roches Noires.

Some of them are in very good condition with stalactites, loose structures on the floor and ledges on the walls, marking different levels of lava. Sometimes

they are almost 2 km long, and in many cases their roofs collapsed in some places, leaving natural bridges, the most famous of which is Pont Bondieu, located east of the Escalier volcano. These landslides also led to the appearance of caves, in many of which underground waters can be seen, for example, La Caverne (Vacoas) and Trois Cavernes.

The most well-known pipe-like holes are the Puit des Hollandais on the east coast and the Ile d'Ambre in the northeast. Other phreatic depressions are usually found along the coast, for example, between the Grand Bay and Cap Malheureux in the north and other places in the northeast and east. The main cone of the pyroclasts of the late series, consisting of bombs, clinkers, and lapilli, is located at the entrance to Mont Piton on the Northern Plain.

Pyroclasts are rare in the late series. They are represented by some: pozzolanic tuffs or a very rough scoria cone mixed with “bread-crust bombs”. Many volcanic cones have well-preserved craters. As a rule, they stand alone and have only one vent, but some of them are grouped into domes with several craters. The basaltic, very fluid lava that characterizes them is very similar to the lava in Hawaii.

Non-volcanic deposits

Non-volcanic formations are the youngest on the island. They are represented by deposits of modern beaches, elevated coral reefs and beaches, as well as deposits of ancient dunes. Modern beaches usually consist of fragments of coral reefs of various sizes (Fig. 5.2.10).



*Fig. 5.2.10. Reef fragments make up the bulk of the material of modern beaches
Photo by V. Iegupov*

The composition of elevated reefs is similar to the composition of underwater living corals with a large amount of secondary crystallization of calcite. The fossilized deposits of beaches and dunes are usually represented by coarse-grained sandstone, more or less loose, including fragments of coral and shells of various sizes. Sandstone cement consists of recrystallized calcite.

These sediments are located along the southwest, southeast, northwest and northeast coasts. Destroyed reef remains can be found at different heights: up to 3 m, from 9 to 12 m, at 18 m and even at an altitude of about 30 m above sea level. Many small islands (Flat and Gabriel islands in the north and Fortier in the west) consist of elevated reefs and beaches, especially in the Mahebourg region (Ile de Deux Cocos and Aigrettes islands), and they often have a height of more than 6 meters. Two isolated peaks are located inside the island, between Bel Ombre and Beau-Champ and 500 m southeast of Souillac. Elevated consolidated sandstone beaches often appear along the coast at low tide.

Old dunes are represented by the sand of varying degrees of fineness and compaction. Sand dunes are also common along the coast: Morne – Ilot Benitier in the southwest, Petite Rivière–Tamarin in the west, Mont Choisy in the north and along the east coast between Flacq and Trou d'Eau Douce. They are usually fixed by vegetation, especially Casuarina plantations. Some of them are exploited as sand pits.

Alluvial deposits are developed to a very small extent on the island, they are mainly located off the west coast in the Tamarin – Rivière-Noire region.

Test questions to chapter 5.2:

1. How was the island of Mauritius formed?
2. Give a geochronology of the island.
3. What are the main volcanic deposits encountered?
4. Give a brief description of the types of volcanic deposits.
5. Describe the volcanic deposits underlying the capital Port Louis.
6. What are pyroclasts and where they can be encountered?
7. What are the non-volcanic deposits and how they are spread over the island?
8. Name and describe the aquifers of Mauritius.

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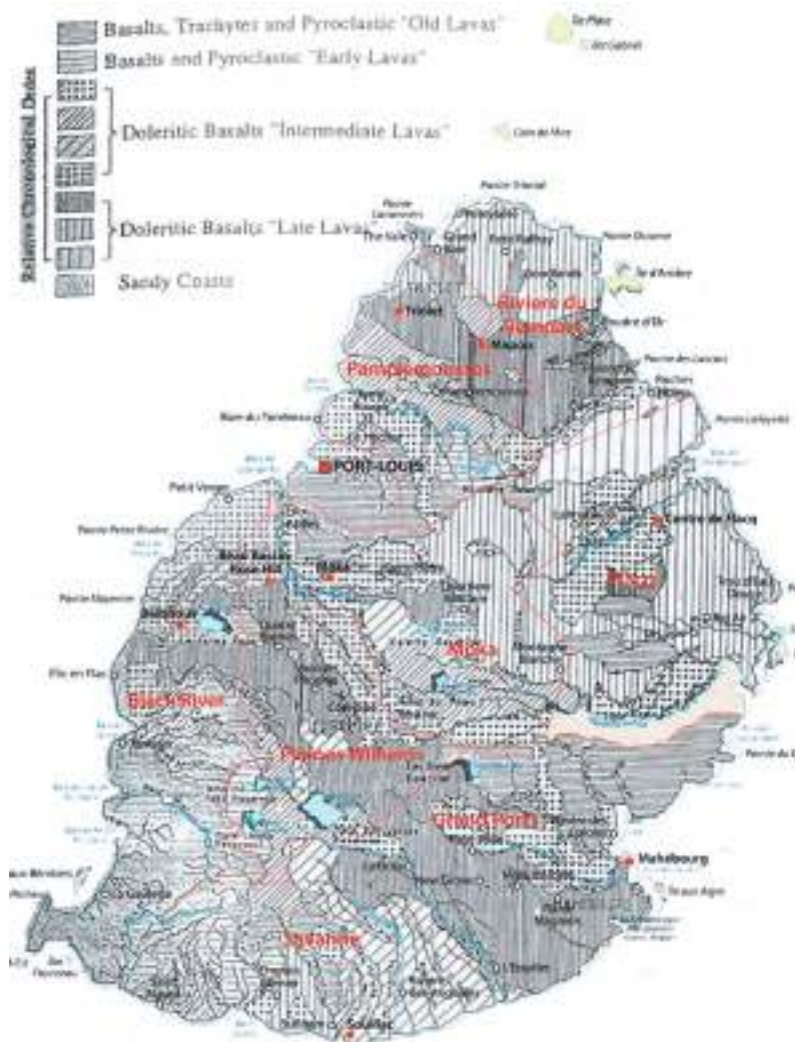


Fig. 5.2.11. Geological map of Mauritius

Chapter 5.3 ENGINEERING GEODINAMICS OF MAURITIUS

Engineering geodynamics as part of regional engineering geology studies the mechanisms, stages of development, local patterns of natural and anthropogenic geological (engineering-geological) processes in the upper horizons of the earth's crust and on the earth's surface in connection with human activities. The main attention in engineering geodynamics is given to the study of geological processes that occur or can occur in the uppermost near-surface soils horizons both in the natural environment in the form of natural geological processes and in territories developed by humans, as geotechnical anthropogenic processes.

This chapter provides information on the main natural and technogenic engineering-geological processes characteristic of the island of Mauritius, which have a direct impact on the territory, buildings, structures, utilities and can often pose a danger to human life and health. Characteristics and examples of these processes in various areas of the island are given.

Particular attention is paid to dangerous processes and disasters, their causes and methods of prevention.

According to experts from the Japan International Cooperation Agency (JICA), who worked in Mauritius on a disaster mitigation program for Small Island Developing States (SIDS), most attention should be focused on the phenomena of landslide hazards: destruction of slopes, rock falls and debris flows. Thus, the main dangerous slope processes are considered in this chapter.

5.3.1. Types of slope disasters in Mauritius

Landslide hazard areas, based on the «Cyclone and Other Natural Disasters Scheme 2011–2012», include several disaster forms besides landslides. Therefore landslide hazard areas are classified into six (6) types of disasters, given in Table 5.3.1.

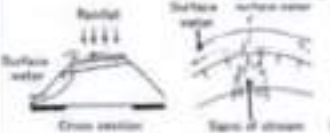
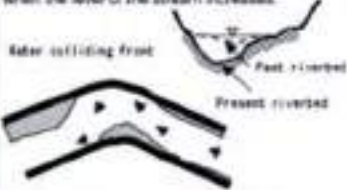
The term “Landslide” is defined as «the movement of a mass of rock, debris, or earth down a slope» (Cruden, 1991). Landslides are a type of «mass wasting» which denotes any down slope movement of soil and rock under the direct influence of gravity. The term «landslide» encompasses events such as rock falls, topples, slides, spreads, and flows, such as debris flows, commonly referred to as mudflows or mudslides (Varnes, 1996). Landslides can be initiated by rainfall, earthquakes, volcanic activity, changes in groundwater, disturbance and change of a slope by man-made construction activities, or any combination of these factors.

The following summarises the geodynamics of Mauritius as described by the Japan International Cooperation Agency, JICA, Ministry of Public Infrastructure and Land Transportation, MPI, in the “Manual for Survey and Countermeasure of Slope Failure, Rock Fall and Debris Flow, 2017”.

General classification: Landslide hazard areas, based on the “Cyclone and Other Natural Disasters Scheme 2011–2012”, are classified into two kinds of disaster, slope disasters and other disasters.

Table 5.3.1.

Description of the Slope Disaster Types in Mauritius (source: JET)

Slope disasters		Other disasters	
Slope failure	A slope failure is a mass detaching from a steep slope/cliff along surface with little or no shear displacement. Compared to landslides, slope failure is rapid and small-scaled, the inclination angle is relatively high (over 30 degrees). 	Damage of embankment	Collapse of road embankment is often triggered by rainfall, infiltration of underground water, erosion by surface water, or a partial catchment. It can be caused by weak embankment material or by lack of soil compaction. 
	A Rock Fall is a phenomenon where foliated rocks and gravel start to fall down a slope as a result of enlarged cracks in the bedrock or outcropped rocks. 		The disaster of a retaining wall doesn't occur suddenly as with Rock Falls etc., the deformation rather occurs over a comparatively long time. The survey should investigate - position around the retaining wall - main body of the retaining wall - history of the retaining wall 
Debris flow	A debris flow is a phenomenon where soil and boulders are liquefied by surface water or groundwater and tend to flow downwards rapidly through a mountain torrent. 	Stream erosion	Stream erosion is the phenomenon where the soil of the bank is removed by the flow of the river. It occurs in riverbanks where the flow of the river hits with the most power. Water might overflow when the level of the stream increases. 

Sub classification: Slope disasters are classified into slope failure, rock fall and debris flow. Other disasters occurred in Mauritius are classified as damage of embankment, damage of wall and stream erosion.

A *slope failure* is equivalent to the “FALLS” or movement of debris and earth material, however it does not include “rock fall”. The slope failure mass detaches from a steep slope/cliff along a surface with little or no shear displacement. It may be called

a “surface failure”. Compared to landslides, the slope failure moves quickly on a small-scale and the inclination angle is relatively high (over 20 degrees).

A *rock fall* is equivalent to the “FALLS” and the “TOPPLES”. Fall is a phenomenon where foliated rocks and gravel start to fall down a slope, due to enlarged cracks in the bedrock or outcropped rocks.

A *debris flow* is equivalent to the “FLOWS” of debris and earth material. A debris flow is a phenomenon where soil and boulders are liquefied by surface water or groundwater and tend to flow downwards rapidly through a mountain torrent. It usually has huge energy and destructive force. Debris flows tend to occur in places where there is massive amount of unstable sediment along a steep torrent, or a large risk of slope failure due to heavy rain in the catchment basin.

There are three types of slope disasters within the six slope disaster types described in the Table 5.3.1. Those which are most serious in Mauritius have been focused and selected (Tab. 5.3.2).

Table 5.3.2

**Description of the Slope Failure,
Rock Fall and Debris Flow in Mauritius (source: JET)**

Table 1.3 Description of slope failure, Rock Fall and debris flow in Mauritius (source: JET)

Items	Slope failure	Rock Fall	Debris flow
Image			
Photograph	 Petite's, cut slope along the motorway	 Macoré	 Belle du Cap
Points of the characteristics and the mechanism	• Failure of slope surface material • Prone area: Slopes with slope angle from 30 to 50 degrees and cut slopes • Higher velocity than landslide • Close relationship with rainfall and subsurface water	• Fall of rocks from steep slope • Prone area: Rock cliffs, cut rock slopes and steep slopes • Very high velocity: non-bouncing to free fall • Instability and weak contact with the ground by weathering and erosion	• Flow of debris from slopes and valleys with water • Prone area: Stream and valley in mountain slope and piedmont • High velocity: 5m/sec to 15m/sec at maximum • Close relationship with short-term rainfall and surface water
Effectiveness of the structural countermeasure works	• Planting (Vegetation) works: Seeding, Hydro-seeding, Planting, etc. • Slope failure prevention by structure: construction: Wire-netting, Retaining walls, Reinforced earth, etc.	• Rock Fall prevention works: Removal works, Girding works, Retaining wall, etc. • Rock Fall protection works: Protection net, Protection fence, Protection wall, etc.	• Source countermeasures: Check dam, Mountainside reinforcement, ground sill, etc. • Countermeasures in the flowing/sedimentation area: Silt-dam, channel work, training dike, etc.

Recognized issues from both technical side and administrative side	• Because there are many target dangerous slopes, it is difficult to carry out a countermeasure for all • Land use control by slope zonal map based on PPG • The construction of all countermeasures will not be possible in Mauritius. • Enforcement of regular check and maintenance • Administrative organizations in charge of natural slopes, road slopes and land development slopes are different. • There are differences between measures taken in public land and private land	• Because there are many target dangerous slopes, it is difficult to carry out countermeasures for all • Hazard map of Rock Falls • Construction of all countermeasures will not be possible in Mauritius. • Enforcement of regular check and maintenance • Administrative organizations in charge of natural slopes, road slopes and land development slopes are different. • Balance between landscape and countermeasure constructions (most of the Rock Fall site are in scenic spots)	• Debris flow is the slope disaster that is less recognized in Mauritius. • Hazard maps of debris flows • Construction of all countermeasures will not be possible in Mauritius. • Enforcement of regular check and maintenance • Administrative organizations in charge of mountains and rivers (mountain stream) are probably different. • There are differences between measures taken in public land and private land

Thirty eight percent (38%) of the land area in Mauritius is considered as environmentally-sensitive to slope disasters. Nearly four – fifth of this area being attributable to moderate and steep slopes.

The map of Mauritius Dangerous Landslides Zones is given in Fig. 5.3.1.

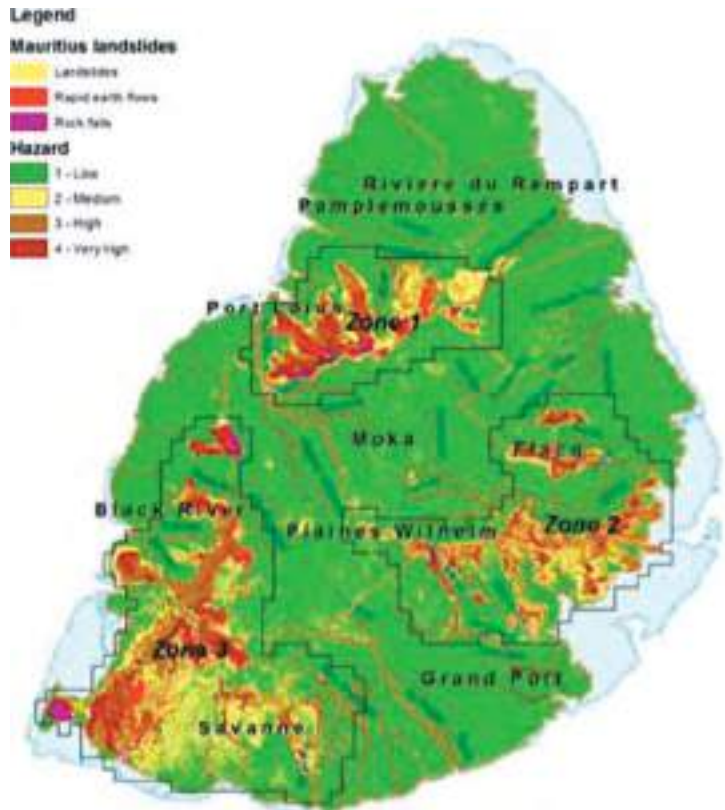


Fig 5.3.1. Mauritius Landslides Zones (Source: Japan International Cooperation Agency, JICA, Ministry of Public Infrastructure and Land Transportation, MPI. Manual for Survey and Countermeasure of Slope Failure, Rock Fall and Debris Flow, 2017)

Maps of three landslide hazard zones are given in Figures 5.3.2, 5.3.3, 5.3.4.

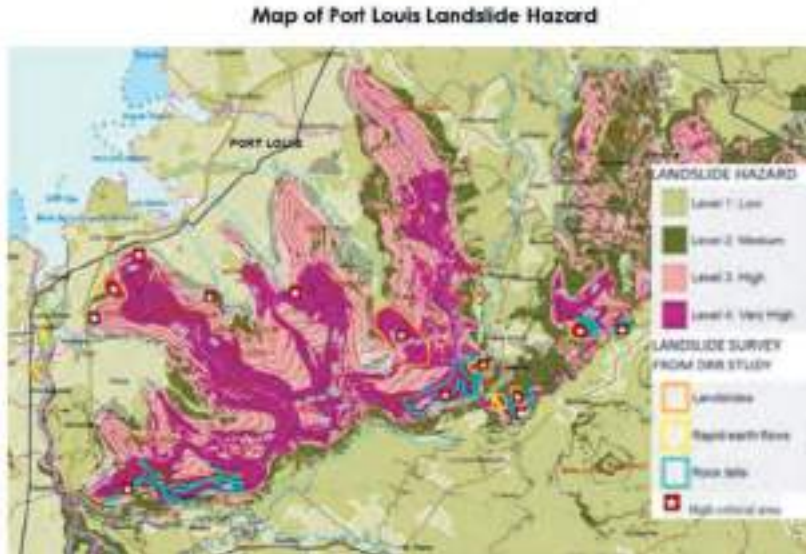


Fig 5.3.2. Landslide zone 1



Fig 5.3.3. Landslide zone 2

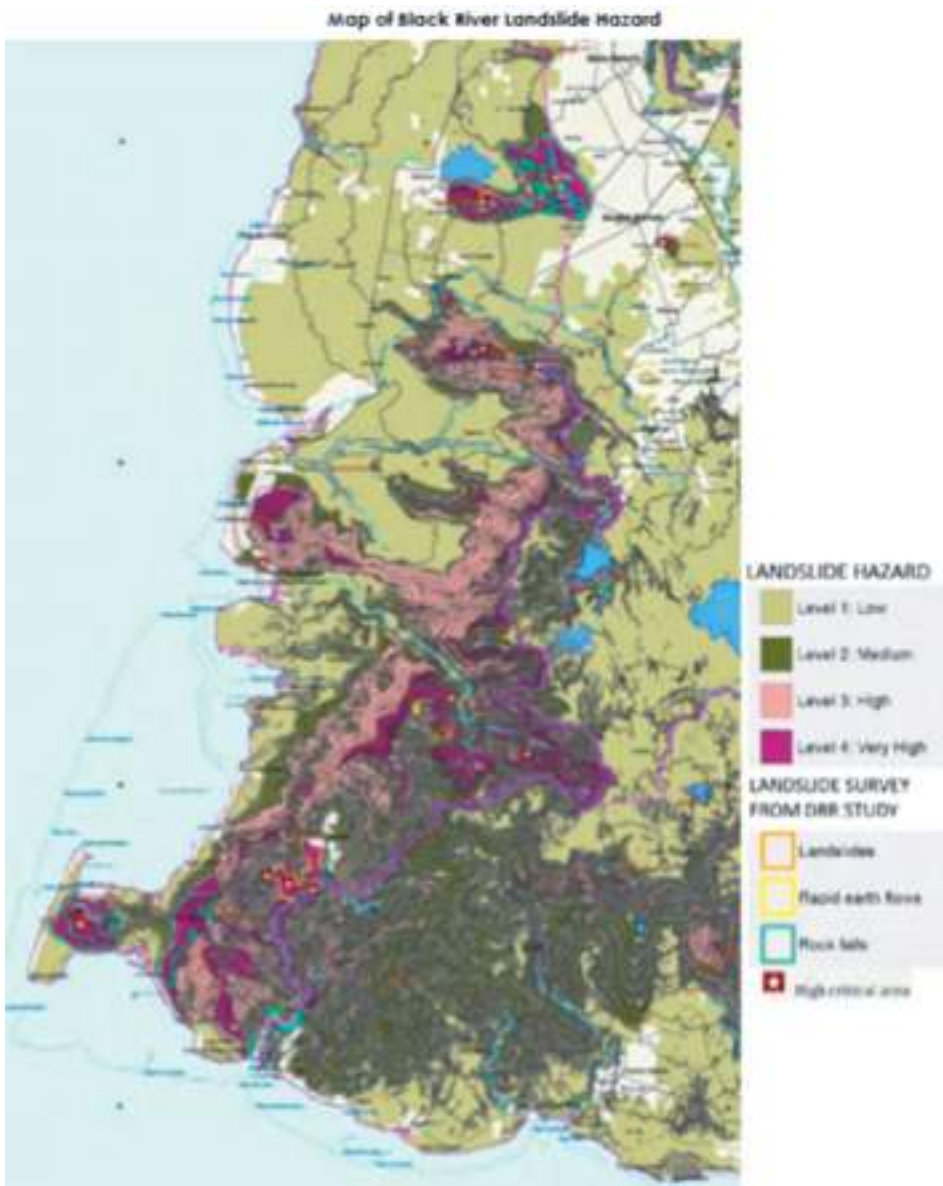


Fig 5.3.4. Landslide zone 3

5.3.2. Cut Slope and Natural Slope Failures

Cut slope and natural slope failures have different shapes based on their principal conditions, i.e. soil, geological structure and groundwater conditions, etc., and the secondary conditions, i.e. width of the cutting, shape of the slope, rainfall, etc. Slope failures can be roughly classified into the following types as shown in Fig. 5.3.5.

The survey is performed to study the actual condition of the existing slopes, to judge the presence or absence of slope failure, debris flow and rock fall hysteresis, and also to determine the groundwater conditions, based upon a survey on geology, soils and their structures.

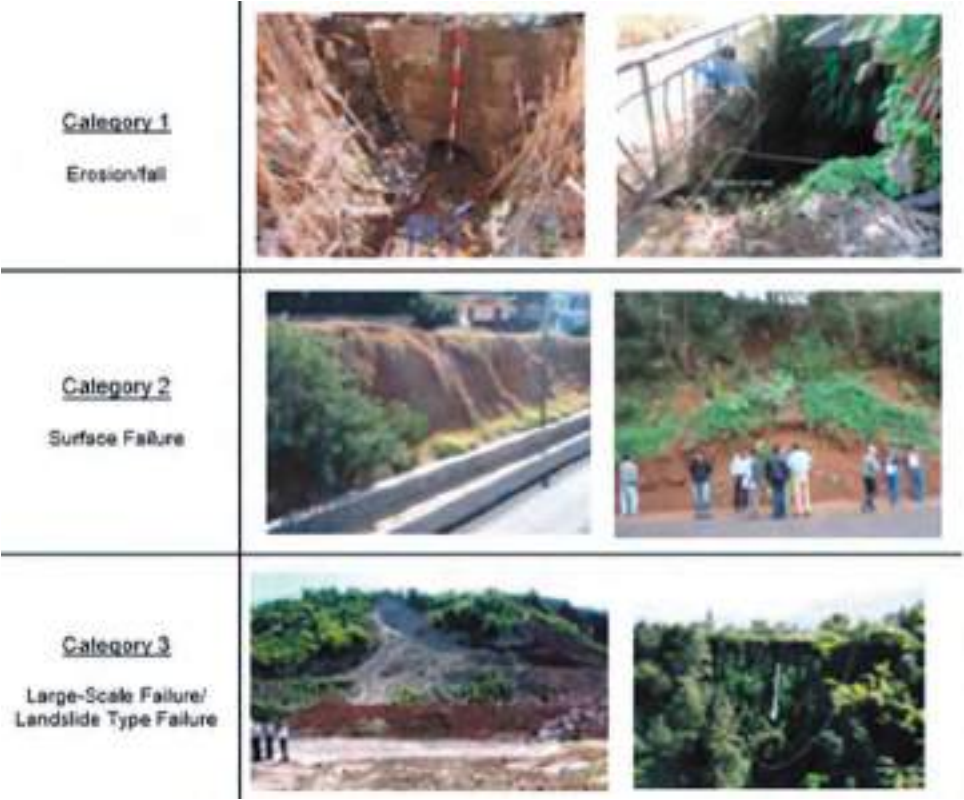


Fig. 5.3.5. Classification of slope failures (source JET)

Survey on Slope Failures Requiring Extra Precautions

Cuts in Colluvial Deposits and Highly-Weathered Rock Slopes

In the case of cutting unstable ground such as talus which has a low degree of solidification, weathered rock slope, volcanic mudflow deposit, and zones where slope failure has occurred previously, the site reconnaissance should be performed in the first place. It is required to determine the groundwater level and the Standard Penetration Test (SPT) N-values during drilling, the grain size distribution (condition of the matrix) from the results of a soil test, and the state of stratification from the elastic wave exploration. In addition, it is required to fully survey the main factors which may control the stability of slope such as

the relation between the depth of cutting and groundwater level, the state of solidification of the matrix and the grading, dip of bedrock, and the presence or absence of hysteresis of slope failures in the past. The results of this survey should be reflected in the design.

Cuts in Erodible Soils

Sandy soils are easily eroded by the surface water, and sometimes resulting in rock falls, slope failures or outflow of soil. In order to determine the slope gradients for such soils or to design slope protection works, it is necessary to make a comprehensive review of the degree of solidification and the erosion resistance by considering the SPT value, and the sand and silt content by grain size analysis. It is also necessary to analyze the results of the erosion resistance testing and the survey of the actual condition on the existing slopes.

Cuts in Easily Weathered Rock such as Mudstone

For slopes cut in rocks with a low endurance against weathering, the appropriate gradient of slope cut should be determined after comprehensively evaluating the velocity of elastic waves through the ground, the unconfined compressive strength of sampled cores, and the relation between the thickness of the weathered zone of existing slopes. Also, the period of time which has elapsed after the cut was made as well as the results of the dry-wet repeating test should be evaluated.

Cuts in Rocks with Numerous Fissures

The stability of slopes cut into rock is mainly controlled by faults or the degree of fracture, as well as by conditions of fissures having certain regularity, such as bedding stratification, foliation, and joints. The properties of rocks and the conditions of fissures should be fully studied through the detailed observation of the existing slopes and outcrops, and a comprehensive engineering evaluation should be made based upon the core recovery (RQD – Rock Quality Designation), and calculations of index of the degree of fissuring, in addition to the elastic wave exploration. If the direction of the fissure inclination has a regularity in a certain direction and coincides with the direction of the slope inclination (that is, if there is dip slope), then an extremely unstable slope may have formed, which requires a careful survey performance.

Cuts in Ground with a Large Amount of Groundwater

It can be said that most causes of slope failures are related directly or indirectly to groundwater. The groundwater can be evaluated by various methods such as

drillings, electric prospecting, and pumping tests. An appropriate type of survey should be selected and performed taking account of the field conditions.

Cuts with Large Slope

Large slopes are rarely composed of uniform and rigid soil and are more often composed of weak layers such as weathered layers, faults, and fractured layers. In particular, when cutting through cols (lowest points in ridges or saddlebacks), since cols are often fault fractured zones, the degree and direction of the fracture should be confirmed through drilling or elastic wave exploration. Moreover, rocks containing a large amount of montmorillonite that is said to be expansive rock may often be judged to be a relatively hard rock through in situ tests (SPT, elastic wave exploration) at points where the depth of the soil covering the rock is large. However, in large slopes, a large amount of stress is relieved and a significant secondary decline of strength occurs after the ground cutting.

In particular, for large slopes, since changes of a configuration of slope (re-cutting) during the cutting is disadvantageous from the perspective of construction cost and efficiency of work, a detailed survey of the soil property and condition of ground water is required.

Rock Falls and Slope Failures from Area above the Cut Slope

In order to prevent the Rock Fall and slope failure from the area above the cut slope, it is required to investigate the stratum, unembedded rocks and boulder stones with the potential of slope failure or Rock Fall. The history of such incidence should be understood from site reconnaissance, topographic map or aerial photograph interpretation, and appropriate countermeasures to be taken against possible incidence should be studied in advance.

Basic principles of slope protection design

A slope earthwork section must be capable of safely preserving the space required for land use and traffic. Slope earthworks consist of the construction of cut slopes by excavating the ground and of embankments by transporting and compacting excavated soil so that cutting and a banking area and section will have the important functions mentioned above. Construction of structures such as retaining walls introduced as auxiliary structures in cut slope to reinforce an earth structure and culverts buried in the ground to provide a passageway or water channel are usually included in the category of earthwork.

As the existing ground subject to cutting or excavation and the foundation ground above which an embankment is constructed, the soil and rocks used as materials for an embankment are all naturally generated, their properties are very complicated and diverse. As earthwork is carried out under natural weather conditions, it is strongly affected by the seasonal characteristics of the weather, rainfall and seepage water, etc. Accordingly, appropriate measures are required to ensure the sufficient bearing capacity of the foundation, to maintain the stability of slopes and to control the settlement of embankments so that cut slopes and embankments forming the main body of flat land and road and auxiliary structures of earthwork can be constructed to meet their objectives and to perform their expected functions for many years. As soil is liable to erosion by running water and also to a significant decline of its strength by water infiltration, it is essential to properly deal with surface water and groundwater.

Cut Slopes

As natural slope and ground are generally complicated and its properties are not uniform, the rock mass and soil layer forming the existing slope and ground must be classified from the viewpoints of the excavation difficulty and slope stability. Empirically established standard slope gradients are then applied to the classified ground, assuming non-treatment, sodding or simple protective work such as netting, to determine the slope gradient and shape corresponding to the soil and rock properties, and cutting height.

With time, a cut slope may experience progressive weathering or erosion, resulting in failure due to increased seepage water following a downpour, etc. Particularly when a large-scale slope is created, special attention is required to prevent an accident or disaster during or after the construction work.

Standard slope gradients

Natural soil is extremely complex and heterogeneous in its properties, and the inclined surface of the incline gradually becomes unstable after completion of work. A general judgment should be made by fully taking into account the stability requirements with reference to the standard gradient gradients listed in table 5.2.3. This table shows the standard values of the slopes, which were determined empirically based on protective work, such as turf, mesh or in the absence of protection.

Table 5.3.3

Standard Gradients of Cut Slope (source: PWRI, 2004)

Soil classification		Cut Slope Height	Gradient
Hard rock			1:0.3 to 1:0.8
Soft Rock			1:0.5 to 1:1.2
Sand	Not dense, and poorly graded		1:1.5 to
Sandy	Dense	Less than 5m	1:0.8 to 1:1.0
		5 to 10m	1:1.0 to 1:1.2
	Not Dense	Less than 5m	1:1.0 to 1:1.2
		5 to 10m	1:1.2 to 1:1.5
Sandy soil mixed with gravel or rock masses	Dense, or well graded	Less than 10m	1:0.8 to 1:1.0
		10 to 15m	1:1.0 to 1:1.2
	Not dense, or poorly graded	Less than 10m	1:1.0 to 1:1.2
		10 to 15m	1:1.2 to 1:1.5
Clayey soil		0 to 15m	1:0.8 to 1:1.2
Clayey soil mixed with rock masses or cobble-stone		Less than 5m	1:1.0 to 1:1.2
		5 to 10m	1:1.2 to 1:1.5

The differences between soft and hard rock are estimated based on the degree of complexity of the excavation and are mainly controlled by the shear strength of the rock and the number of cracks in the rock.

If the destruction of the trimmed slope can lead to damage to neighboring structures or requires a long recovery time, significant relocation of residents and impaired road functions, it is necessary to change the gradient of the slope along with the introduction of suitable measures, such as protecting slopes and drainage work on slopes, etc. Examples of slope gradient for weathered granite are given in table 5.2.4.

In the case where a cut slope with a steeper gradient than the standard slope gradient is necessary to reduce the earthwork volume, reinforcement of the cut slope with retaining walls and/or the reinforced soil method with a steel bar is required.

Slope Protection Works

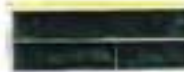
Slope protection works aim at preventing the erosion and weathering of a slope by covering a slope with vegetation or a structure or stabilizing a slope with drainage works or a retaining structure. The standard types of slope protection works are shown in Table 5.3.5 and these can principally be classified into those involving vegetation and those involving a structure.

Table 5.3.4

Standard Slope Gradient for Weathered Rocks (source: PWRI, 2004)

Category of Bedrock	Ground Conditions						Slope Height and Gradient (m)				
	Conventional Rock Category		Situation of Weathering		Condition of Drilling Core	Elastic Wave Velocity of Ground (P Wave)	0	10	20	30	50
Decomposed Weathered Rock	D	D ₁ D ₂	Sedimentary Soft Rock	Decomposed	Sandy	km/s 0.4 - 1.1	1.0 1.2	1.2 1.5	1.5 1.8		
Weathered Granite	C	C ₁	Extremely Soft Rock	Nearly decomposed rock with few cracks or concentration of cracks	Sandy to fine flakes	1.1 - 1.5	0.6 0.8	0.8 1.0	1.0 1.2	1.2 1.5	
Slightly Weathered Granite		C ₂	Soft Rock	Rock discoloured to a yellowish brown to the core and developed joints	Brecciated to short bar-like	1.5 - 2.3	0.4 0.6	0.6 0.8	0.8 1.0	1.0 1.2	1.2 1.5
Non-Weathered Granite		C ₃	Hard Rock	Mostly fresh rock mass with developed joints in a massive manner	Bar-Like	> 2.3	0.8 1.0	0.8 1.0		0.8 1.0	0.8 1.0
	B										
	A										

Decomposed Weathered Rock
Core: Sandy
Rock Category: D



Slightly Weathered Granite
Core: Brecciated to short bar-like
Rock Category: C₂



Weathered Granite
Core: Sandy to fine flakes
Rock Category: C₁



Non-Weathered Granite
Core: Bar-Like
Rock Category: C₃



Slope height and rock category
ha: slope height to rock category a
hb: slope height to rock category b
hc: slope height to rock category c

For the selection of suitable slope protection works, it is essential to consider such geological and soil conditions of the slope as the rock and soil properties and pH value, hydrogeological condition, and water catchment, weather conditions and size and gradient of the slope together with aspects such-as construction cost, working conditions, maintenance and conservation of the landscape/environment.

Vegetation works are performed to prevent erosion due to rainwater by growing plants on the faces of slopes, thus firmly binding the faces with roots of plants. Vegetation works are also performed to ease the temperature change on the ground surface and to provide aesthetical appearance by creating greenery. Vegetation is frequently used in places where the vegetation is possible and since the costs for vegetation are relatively low in most cases.

However, as the root system of such planting work remains relatively shallow, planting is not very effective for slopes liable to deep sliding. Moreover,

it is difficult to find the plants which grow under such structures as viaducts and bridges with little sunlight or rainwater or with a rock base with little soil. Even in the case of slopes of which the gradient is approximately 1:0.8 to 1:1.2, planting alone may not be sufficient to prevent surface erosion or failure depending on the soil properties. For these slopes, it is necessary to apply slope protection works with a structure.

Table 5.3.5

**Main Types of Slope Protection
Works and Their Purposes (source: PWRI, 2004)**

Category	Type of Work	Purpose and Characteristics
Planting	- Hydro-seeding - Borrow spraying - Planting ground spraying - Sodding - Sodding mat - Planting sheet	Erosion prevention; surface water flow; total planting cover
	- Simple seed matting works - Simple sodding works	Erosion prevention and partial planting of embankment slope
	Planting sandbags	Erosion prevention of slope surface made of poor soil or hard soil
	Spraying with planting of young trees	Erosion control and landscaping
	Planting	Landscaping
Slope Prevention by Structure	- Net harding - Gabion works	Control of sediment outflow at slope surface due to erosion or spring water
	Precast concrete crib works	Erosion prevention when filled up with soil or cobblesstones
	- Mortar/concrete spraying - Stone pitching - Block pitching	Prevention of weathering, erosion and seepage of surface water
	- Concrete pitching - Spray crib works - Cast-in-place concrete crib works	Prevention of collapse of slope surface; retaining at sites likely to face slight earth pressure; prevention of exfoliation of rock base
	- Stonemasonry retaining walls - Gabion works - Crib retaining walls - Concrete retaining walls	Resistance to a certain level of earth pressure
	- Reinforced earth (reinforced earth embankment, reinforced cut slope method) - Rock bolt works - Ground anchor works - Pile works	Resistance to sliding force of sliding soil mass

There are many types of slope protection works with a structure, ranging from relatively small-scale works aimed at stabilizing an embankment for effective planting to relatively large-scale works aimed at preventing the weathering, erosion or surface failure of a slope and further to very large-scale works designed to prevent large slope failure. Among the various types of slope protection works while retaining wall works, pile works, cast-in-place concrete crib works

complemented by anchor works and reinforced earthworks can be assumed to have a certain degree of resistance to earth pressure, other types of slope protection works are not essentially designed for use in unstable places subject to earth pressure. Accordingly, the application of different measures is necessary if these works are subject to earth pressure due to a change of circumstances in the future.

If spring water exists on a slope, the adoption of slope drainage works in addition to slope protection works is essential to prevent the scouring as well as destabilization of the slope. As the soil properties or the state of spring water are often not uniform even at a single slope, the types of works that are suitable for the specific conditions of different places must be selected. In this case, the primary principle of countermeasure work is to introduce heavy works at the lower part of the slope and lighter works at the upper part of the slope.

Several types of slope protection works are available for different types of failures and some examples are shown in Table 5.3.6.

Slope Protection Works with Structures

Various types of slope protection work with structures are carried out for slopes which are unstable without slope protection and that are unsuitable for vegetation, slopes where the long-term stability against erosion cannot be guaranteed by only vegetation or slopes which are liable to failure and/or rock fall.

Basic protective structures are listed below.

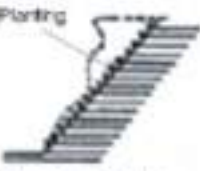
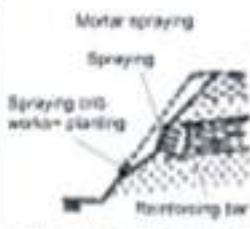
Stone pitching and concrete block pitching are mainly used to prevent slopes from being eroded and weathered and are employed for non-cohesive soil, mudstone or easily collapsible clay slope with a slope gradient gentler than 1:1.0.

Concrete pitching is used when concrete block crib work or mortar spraying is not considered appropriate for the slope of bedrock with many joints or loose talus cone layers. For large or steep slopes, it is desirable to reinforce the concrete with reinforcing bars or wire mesh and also to install non-slip anchor pins or anchor bolts.

Mortar and concrete spraying are used on easily weatherable rock and rock likely to be weathered and stripped off even though there is no spring water in slope and there is no danger for the time being as well as for mudstone not suited to vegetation.

Table 5.3.6

**Type of Failure of Cut and Natural Slopes and
Examples of Slope Protection (source: PWRI, 2004)**

Category	Description	Type of Failure	Example of Slope Protection
1. Erosion/fall	1) Separation of the surface or production of a gully by repeated drying and wetting; rain; could move to a deep failure if consolidated	 Gully erosion by surface water	 Precast concrete crib-work Nesting + planting or precast concrete crib-work + planting
	2) Fall of an overhanging section on a slope		 Planting Re-cutting + planting
	3) Fall of rocks with plenty of cracks and joints	 Loose stone type Rock Fall	 Removal of loose stones Mortar Reinforcing bar Mortar spraying (removal of loose stones) + reinforced rockfalls
2. Surface Failure	1) Slipping of the lower heavily weathered rock layer due to the slipping of top soil, often induced by spring water	 Failure caused by piping	 Precast concrete crib-work Spring water Lateral drilling Re-cutting + precast concrete works (filled with cobbles/stones) + lateral drilling
	2) Slipping of the surface layer as a result of weathering, etc.	 Surface failure with advancing weathering, etc.	 Mortar spraying Spraying Spraying crib-work + planting Reinforcing bar Cutting with different gradients + spraying crib-work + reinforced sandworks + planting + mortar spraying

	3) Slipping of rocks along a dip slope structure or cracks in the bedrock (joints, small fault and/or thin layer); frequently in the case of the latter		Removal of unstable rocks Mortar spraying Reinforced bar Mortar spraying + reinforced bar
3. Large-Scale Failure/ Landslide Type Failure	1) Large-scale slipping of a slope consisting of a soft layer with a low degree of consolidation or a slope with unstable factors in terms of the geological structure following a rise of the ground water level	Gravel layer  Groundwater level Slipping along surface of discontinuity in terms of permeability	Planting Colluvium Bedrock Pile works Re-cutting + pile works/lateral drilling + planting
	2) Large-scale slipping of a rock body which has such a geological structure as a dip slope, fault or fracture zone	Fracture Crack  Sliding along fault fracture zone	Spray crib works Reinforced bar Concrete lining Ground anchor works Pile works Pile works + spray crib works + ground anchor works + reinforced earth works + concrete lining
	3) Overturning of a dip slope or rocky slope with developed cracks	 Overturning of dip slope	Spray crib works Reinforcing bar Ground anchor Spray crib works + reinforced earth works + ground anchor works

Precast crib works are employed at cut slopes liable to erosion, sites where revegetation is unsuitable because of the specific conditions despite the slope having a standard slope gradient and sites where revegetation will not eradicate the possibility of surface failure. The target slopes are those with gradients that are gentler than 1:1.0. The use of anchor pins of some 50–100 cm in length at nodal

points of the frame is desirable to prevent sliding of the frame while protecting the inside of the frame, which is backfilled with good quality soil, with vegetation.

Cast-in-place concrete crib works is used when the long-term stability of the slope is questionable or when concrete block crib work is likely to collapse on a slope made of weathered rock accompanied with spring water or on a large slope.

Shotcrete crib works are used for slopes consisting of bedrock with many cracks or slopes where the protection is urgently required. While the standard function of spray crib works is the same as those of cast-in-place concrete crib works, the good workability means that spray crib works can be applied for slopes with an uneven slope surface. Moreover, the shape of crib works can be flexibly changed in accordance with the slope conditions (see Fig. 5.2.6).



Fig 5.3.6. Example of Spray Crib works (source: JET)

Net hurdling is often used to prevent an outflow of soil from the slope surface until the plants are fully grown. The net is made by fagot, bamboo, high polymer materials or others to wooden and fixed by stakes driven into the ground to retain the soil.

Gabions are used where there is spring water on a slope and soil is likely to run off, where a collapsed portion is to be restored. Ordinary wire cylinders and wire mat gabions are available as gabions, and ordinary cylinders are mainly used for the removal of spring water on the surface layer of a slope, for draining

surface water. Wire mat gabions are used for restoration work after failures in landslide zones and in places where spring water is present. In many cases, they are employed in retaining works rather than slope works.

Retaining walls are constructed for slopes where cutting or banking with a stable gradient is impossible due to the site conditions, topographical restraints or the presence of water channels and/or other adjacent structures or facilities.

Ground anchor works are usually used to provide suppressive force for slopes which are liable to failure due to joints and/or cracks in the bedrock and slopes which have relatively dense soil, but which also have a risk of failure. Ground anchor works can also be used as supporting works for temporary earth retaining walls.

Reinforced earthwork is defined as a construction method involving the use of various reinforcing materials to stabilize embankment slopes and cut slopes where the gradient is much steeper than slopes which have no reinforcing material. Reinforced earthworks are used for slopes requiring reinforcement because of the impossibility of securing a stable slope gradient for an embankment or cut slope, in turn, due to constraints posed by the topography and other factors as shown in the selection flow

5.3.3. Rock Falls

The types of Rock Falls are, as shown in Table 5.3.3, “uprooting type (boulder type)” and “flaking type”. These differ in their mechanism of occurrence and this categorization is fundamental to evaluating the possibility of Rock Fall occurrence or planning countermeasures for Rock Falls.

Survey on Rock Falls needs to be divided into “survey for planning and design” and “survey for undertaking countermeasures”, and implemented taking into consideration the following points:

1. Possibility of Rock Fall (frequency of occurrence, weather conditions, etc.);
2. Extent and type of Rock Fall (size and location of objects that originate Rock Falls, categorization into the uprooting type or flaking type);
3. Dynamics and path of the Rock Fall (sliding, rolling, bouncing, etc.);
4. Margin at the sides of the road or houses;
5. Extent and range of Rock Falls reaching the road and houses;
6. Condition.

Table 5.3.7

Classification of Rock Fall (source: PWRI, 2004)

Category	Description	Schematic Drawing	Typical Geological Features	Remarks
(1) Uprooting Type	1) Dropping of gravel located on a sandy slope containing gravel		Terrace and pyroclastic material, etc.	
	2) Sliding down of gravel contained in the sediment above the bedrock		Heavily weathered rock on talus, colluvial soil, hillside slope or cut slope	Loose stone type rock fall may occur depending on the relative positions of the bedrock and sediment.
(2) Flaking Type	1) Exfoliation along the surface of discontinuity in the bedrock		Bedrock with many cracks or continual cracks	Different forms, such as sliding, falling over and falling, take place depending on the directions of the slope and cracks; special attention is required in regard to the degree of loosening.
	2) Exfoliation of the surface of a highly weatherable or erodible bedrock		Weatherable soft rock or alternation of soft and hard rock layers from the Neogene onwards	The scale is generally small but the falling of large rocks may occur at an overhanging section of alternated soft and hard rock layers.
(3) Others	1) Increased instability of residual boulders, etc. on a ridge due to weathering or erosion		Weathered granite, etc.	Not frequent but tends to be on a large scale.

Countermeasures for Rock Fall

The important basic principles for countermeasures for Rock Fall are the minimization of damage due to Rock Fall by installing “Rock Fall prevention works” and “Rock Fall protection works”, taking the importance of the road, expected scale of Rock Fall, probability of Rock Fall occurrence, frequency and actual situation of damage and other relevant matters into consideration and also ensuring of the safety of the slopes using the available means, including road passage control.

The most basic requirements for the selection of countermeasures for Rock Fall are an accurate prediction of what type and scale of Rock Fall are likely to occur at which part of the slope in question and what form of movement the falling rocks are likely to follow and a decision on how to stop these falling rocks or how to let them pass the road and objects harmlessly.

Rock Fall Prevention Work

Although Rock Fall prevention work is a highly effective countermeasure for Rock Fall, the complete prevention of Rock Fall using only Rock Fall prevention work may be difficult. In reality, this type of work should be considered as a countermeasure to reduce the frequency of Rock Fall. Accordingly, it is preferable to employ this type of work in conjunction with a type of Rock Fall protection work in many cases. Many Rock Fall prevention works are identical to slope protection works. Examples of Rock Fall prevention works are shown in Fig. 5.3.7 and Fig. 5.3.8.

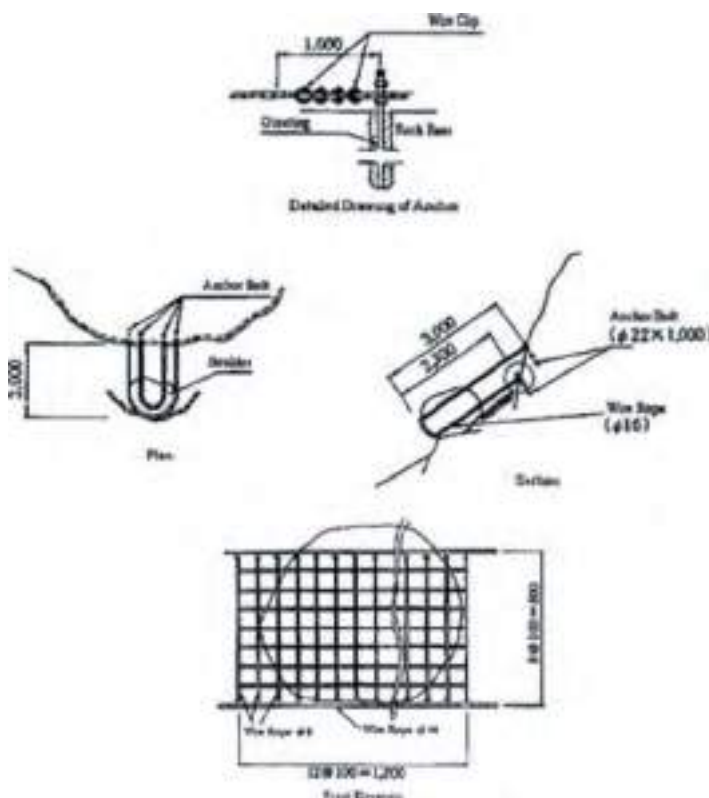


Fig. 5.3.7. Example of Wire Rope Works (source: PWRI, 2004)

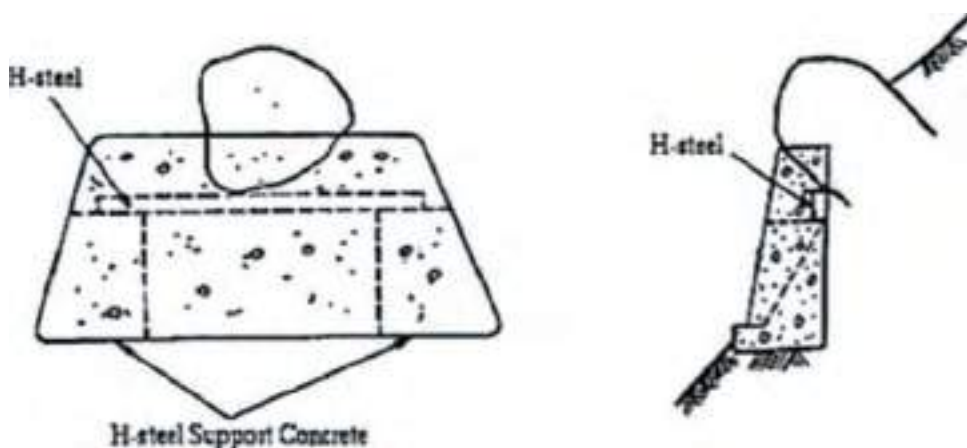


Fig. 5.3.8. Example of Concrete Foot Protection (source: PWRI, 2004)

Rock Fall Protection Work

For the design of Rock Fall protection work, it is firstly necessary for the external forces to be dealt with by a structure. In this context, it must be noted that the weight and velocity of falling rocks and the working direction and location of a Rock Fall protection works of falling rocks vary considerably depending on such factors as the topography, geology, degree of weathering of the slope, vegetation and the presence of any other Rock Fall prevention or protection works at the site. Accordingly, the most suitable values representing these factors must be estimated based on field investigation results and past experience of Rock Fall.

Rock Fall protection works can be designed by either the energy calculation method or the static strength calculation method. In the case of a Rock Fall protection net and a Rock Fall protection fence, design calculation at the time of their construction is not necessarily required. Instead, their specifications can be determined based on the specifications used for similar slopes.

Rock Fall Protection Net

A Rock Fall protection net uses such light materials as a wire net and wire ropes to entirely cover a slope which has a Rock Fall hazard and there are two types of such net as described below.

- ü Cover type Rock Fall protection net
- ü Pocket type Rock Fall protection net (Rock Fall curtain)

The former intends to confine rocks which have lost their binding power with the ground with friction between the net and the ground and the tensile force of the wire net, producing a function which is similar to that of Rock Fall

prevention work. In contrast, the latter consists of hanging ropes, posts, wire net and wire ropes. The upper part has an entrance for falling rocks, and it has the function of absorbing the energy of falling rocks through a collision between the net and the falling rocks.

The design of a pocket type Rock Fall protection net follows the following processes (Fig. 5.3.9).

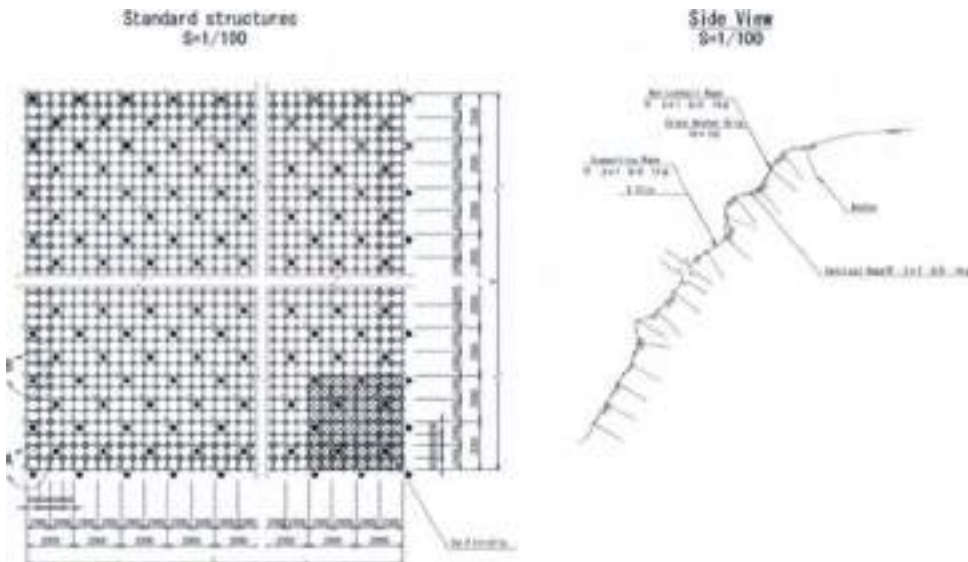


Fig. 5.3.9. Rock Fall Protection Net, Maconde (source: MPI)

Rock Fall Protection Fence



Fig. 5.3.10. Rock Fall Protection Fence, Maconde
Photo by Yeshvin Goodary

A Rock Fall protection fence is an effective countermeasure for relatively small-scale Rock Falls and the type and dimensions should be determined based on the slope conditions.

Two types of Rock Fall protection fences exist, i.e. wire rope and wire net type and

H-beam type (see Fig. 5.3.11). As the former uses wire ropes and wire net with excellent extensibility, the energy absorption capacity is relatively large. When the installation of a long Rock Fall protection fence is necessary, it is necessary to divide the entire length into suitable sections for the installation of the fence at each section. In this case, the end parts of the Rock Fall protection fence in each section should overlap to prevent falling rocks from passing through the gaps between neighboring fences.

Any design of a Rock Fall protection fence must examine the cross-section and positioning of the members and the stability of its foundations so that the fence can absorb the energy of falling rocks within its allowable displacement.

Only the load of falling rocks is considered for the design of a Rock Fall protection fence. The collision position with the falling rocks is assumed to be the central point between the posts and two-thirds of the height of the fence from the bottom. The remaining one-third of the height is considered to be the height margin. The collision direction of the falling rocks is set at a right angle to the fence.

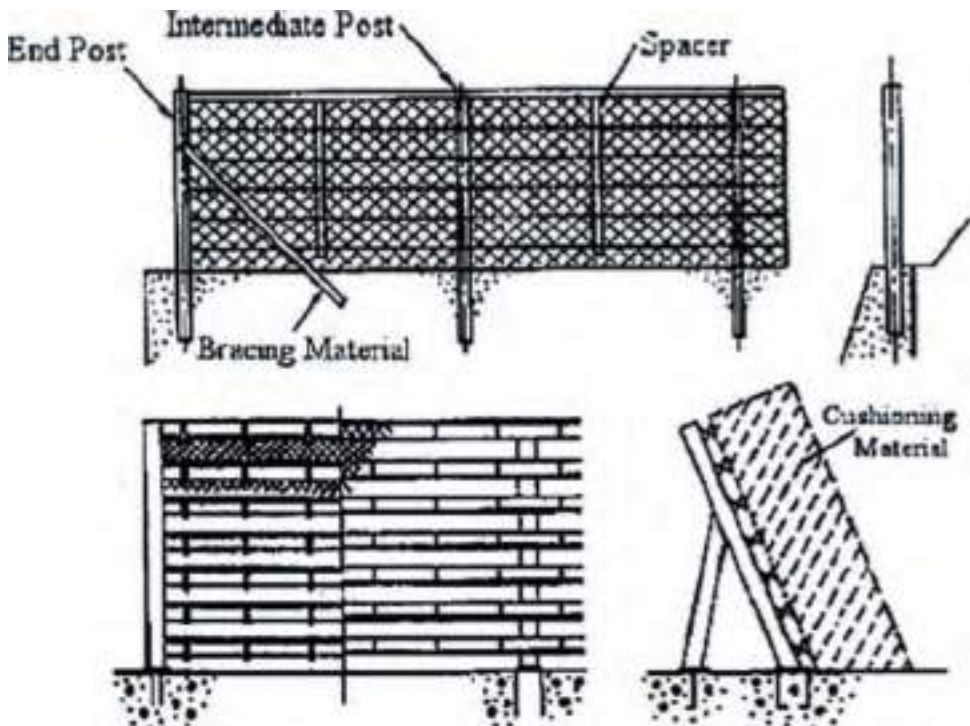


Fig. 5.3.11. Types of Rock Fall Protection Fences (source: PWRI, 2004)

Rock Shed

A rock shed is used where there is a series of steep slopes with a high Rock Fall hazard with little room at the roadside, where an expected large-scale Rock Fall cannot be prevented by a Rock Fall protection fence or where the high falling height suggests that falling rocks may well jump over a Rock Fall protection fence. The design is usually carried out using the allowable stress method by converting the impact load of falling rocks to the static load.

The primary objective of Rock Fall protection work, including a rock shed, is to absorb kinetic energy of falling rocks. However, it is essential to select a structural form, materials, and structural specifications to increase the energy absorbability. Sand and gravel are laid above the roof of the rock shed to act as a cushioning material (sand cushion) with a minimum thickness of 90 cm.

Rock Fall Protection Retaining Wall

A Rock Fall protection retaining wall is used as a protection work to prevent rocks from falling onto a road and is often used at sites where the slope gradient at the back is gentle or sites where there is ample room at the roadside. It should be designed to safely absorb the energy of falling rocks with deformation of the wall itself as well as the bearing stratum after calculating the value of such energy. In addition, it is desirable to establish a pocket at the back of this retaining wall so that fallen rocks, as well as fallen soil, can be deposited there to a certain extent.

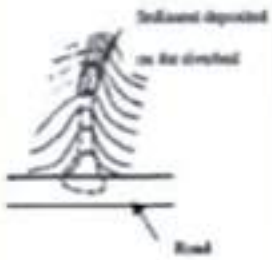
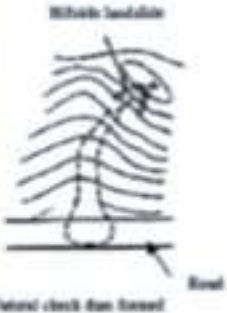
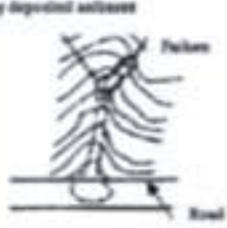
5.3.4. Debris Flow

A debris flow is a phenomenon in which soil, weathered base rock, valley deposit and colluvial deposit at the bottom of a valley or upstream moves as a result of heavy rain and flows in hydraulic jump out of the valley. There are four main types of debris flows as shown in Table 5.3.4. Survey on debris flow is focused on the following points and involves an investigation of materials on past damage, site reconnaissance and interpretation of aerial photographs.

1. Possibility of a debris flow occurrence (frequency of occurrence, weather conditions, etc.).
2. Scale and characteristics of the debris flow (peak amount of discharge, the flow velocity, height of flow, volume of deposits, maximum gravel diameter, etc.)
3. Area is likely to be inundated by the debris flow.
4. Presence of existing facilities for debris flow control and its configuration and size.

Table 5.3.8

Classification of Debris Flow (source: PWRI, 2004)

Category	Description	Schematic Drawing
(1) Fluidisation of deposited sediment and gravel on the riverbed	Fluidisation of sediment and gravel deposited on the bed of a steep stream due to the supply of a large quantity of water due to a downpour or rapid thawing	
(2) Fluidisation of sediment produced by a hillside failure	Fluidisation of sediment produced by a hillside failure as the structure is broken up while sliding down the slope and mixed with water	
(3) Collapse by natural check dam	Fluidisation of sediment forming a natural check dam(s) which is created by the blockage of a mountain stream by failed sediment and which is then eroded by overflow or which collapses	
(4) Fluidisation of landslide soil mass	Fluidisation of a cohesive soil mass with a high water content originally produced by a landslide	

In the event that a planned road or development area would cross over a mountain stream, where the occurrence of debris flow is anticipated, by a bridge, a culvert and/or a channel, the peak amount of discharge, the flow

velocity, the maximum wave height and the maximum gravel diameter of the estimated debris flow should be investigated, in order to provide a benchmark for reviewing whether or not the debris flow will cause damage to the bridge, culvert and/or channel.

Survey on Occurrence of Debris Flow

(1) Identification of Locations where Debris Flow may occur

In lowland topography to which rain water gathers, in mountain streams where water flow exists during rainfall, in mountain streams with 15 degrees or more gradient in the valley bed with more than 5 ha of catchment area upstream, from the point at which the gradient of the valley bed is superior to 15 degrees, and where there is sediment in the valley that could become debris flow, debris flow may occur, therefore, these areas need to be investigated.

Moreover, catchment areas of less than 5 ha upstream, where the gradient of the valley bed is more than 15 degrees and relatively large slope failures at the mountainside can be expected due to the soil properties, areas with spring water, and/or areas with a history of slope failure may be considered as areas where debris flow may occur. The above investigation should be undertaken through a rough interpretation of topographic maps and aerial photographs firstly and should be revised through site reconnaissance.

(2) Estimation of Frequency of Debris Flow

Existing materials on disaster records, interviewing, and site reconnaissance should be utilized to determine the times and frequency of occurrence of recent debris flow in the target mountain stream.

(3) Estimation of Rainfall Conditions Causing Debris Flow

Areas should be divided based on the similarity of rainfall conditions, and materials on rainfall that caused a debris flow in the past. Also, heavy rains that did not lead to debris flow occurrences should be collected in order to determine the distinction between rainfall conditions that lead to debris flow and those that do not.

In the event there has been no rainfall that has caused debris flow in the target area, the maximum amount of rainfall at which such debris flow did not occur shall be used as the temporary rainfall conditions on the occurrence of debris flow. Other information such as topography and soil properties should also be used in the determination of the threshold for debris flow occurrence.

Countermeasures for Debris Flow

When a planned road crosses a mountain stream where debris flow is predicted, it is desirable for its route to avoid an area flooded by debris flow. If

the crossing of such an area is unavoidable, a suitable countermeasure(s) should be selected and implemented, depending on the expected type and frequency of debris flow and the position and elevation of the road surface.

For the selection of a countermeasure for debris flow, the expected type (mud flow type debris flow or gravel type debris flow) and frequency of debris flow are first considered. In general, when a road crosses an originating or passing area of a debris flow along a mountain stream susceptible to debris flow, the crossing should, in principle, be provided by a culvert with a sufficient cross-sectional area or a bridge with sufficient clearance. In the case of a mountain stream where high-speed mud flow type debris flow is expected to occur at the mountain stream with a high debris flow frequency, a road crossing in the originating or passing area of debris flow should preferably be provided by a bridge with sufficient debris flow clearance, a debris flow shed or a tunnel.

At a site where the gradient of the upstream section of the debris flow sedimentation area is $3-10^\circ$, the occurrence of debris flow causes considerable fluctuation of the streambed. It is, therefore, desirable not to plan the route passing through such a site and the route should be shifted to either the upstream or downstream and a crossing provided by a bridge with sufficient clearance (see Fig. 5.3.12).

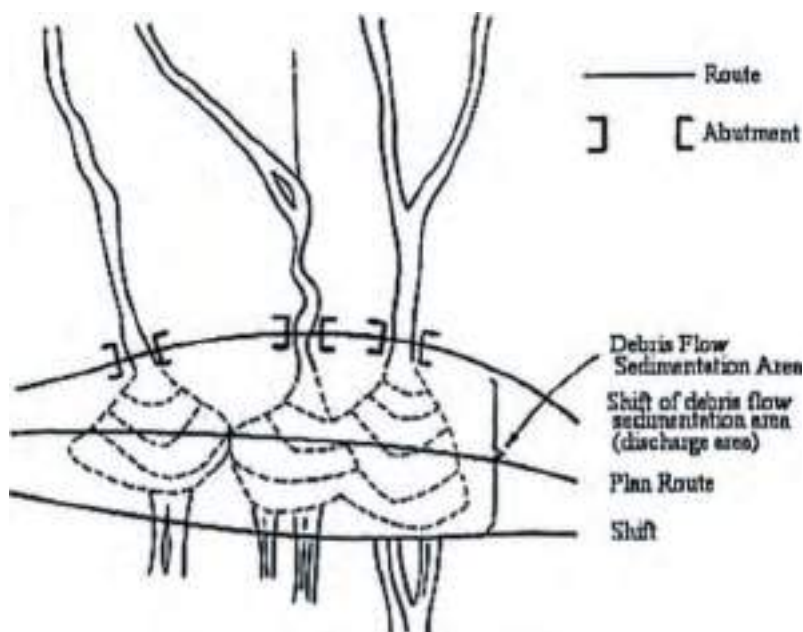


Fig. 5.3.12. Minor Shift in Debris Flow Sedimentation Area (source: PWRI, 2004)

When the road surface is not much higher than the stream bed, the introduction of a ford (low-level crossing) should be considered. When the road surface is lower than the streambed, the introduction of a debris flow shed should be considered. If a change of the route or countermeasure is not deemed to be sufficient, it may be necessary to consider the construction of a dam to control debris flow. For road sections which include an originating and/or passing area of debris flow, passage control should be introduced according to need if the level of rainfall which is high enough to cause debris flow is predicted.

Estimation of Scale of Debris Flow

For the design of debris flow countermeasures, the volume of sediment, peak discharge, the velocity of flow, water level (wave height), unit volume weight and maximum particle size of the anticipated debris flow should be estimated, if necessary, based on survey results for each mountain stream.

Bridge

The planned cross-section of a bridge should allow the passing of the peak debris flow discharge. The height of the bridge girders is determined by adding clearance to the debris flow wave height. It is preferable not to place the bridge piers on the streambed. Special attention must be paid to avoiding the narrowing of the channel width at the bridge site. Even if it is necessary to place piers on the stream bed, their positions should avoid the central section of the channel so that the piers are not destroyed by debris flow.

Culvert

The planned cross-section of a culvert should allow the passing of the peak debris flow discharge and both the height and horizontal width must exceed double the maximum particle size of the gravel contained in a debris flow. The axis of a culvert, including the water channel upstream, should be as straight as possible to coincide with the flow direction of debris flow. Careful attention should be paid to avoiding a smaller cross-sectional area and gradient of the water channel downstream than those at the culvert. Further attention must also be paid to the possible clogging of the culvert by driftwood. When the outflow of a large quantity driftwood is anticipated, it is desirable to set up a boom(s) in the upstream (Fig. 5.3.13).

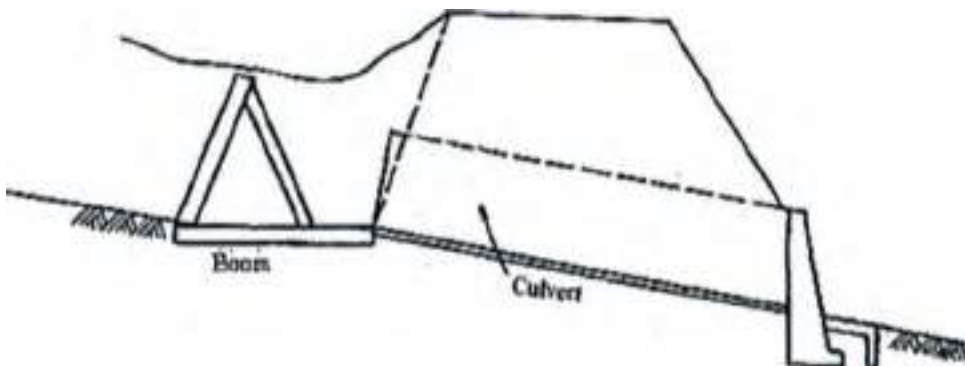


Fig. 5.3.13. Culvert and Boom (source: PWRI, 2004)

The capture of Discharged Soil by Dam and Fence

One or several dams or fences can be used to catch an entire debris flow or large gravel and driftwood so that only soil and water, which can be drained by road drainage facilities in the downstream, are allowed to flow further downwards. The design sedimentation gradient should be half of the current streambed gradient. Concrete or steel permeable dams and fences are used to reduce the sedimentation volume during ordinary floods. The size of the opening should be less than 1.5 times of the maximum diameter of large gravel to catch debris flow (Fig. 5.3.14).

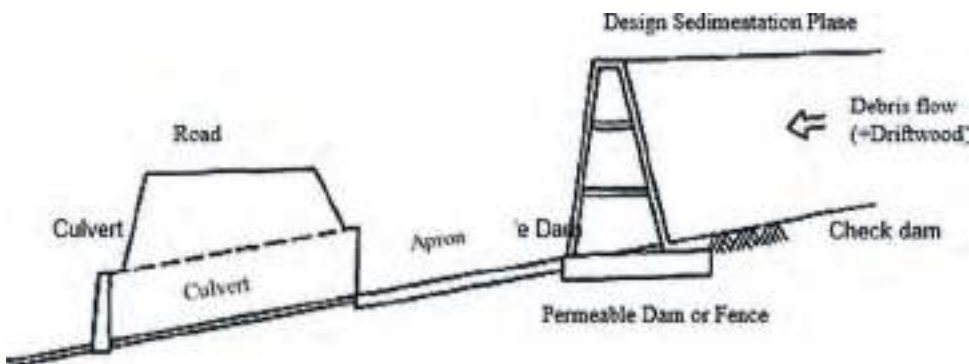


Fig. 5.3.14. Capture of Discharged Material by Permeable Dam or Fence (source: PWRI, 2004)

Test questions to Chapter 5.3:

1. Definition of Engineering Geodynamics.
2. What are the possible land disasters which can occur on the island?
3. Slope disasters which can be encountered?

4. Basic principles of slope protection and slope protection measures on the island.
5. Where are the landslide zones located on the island?
6. Precautionary measures for landslide.
7. Countermeasures for Rock Fall disaster.
8. Countermeasures for debris flow.

References to Chapter 5.3:

1. Japan International Cooperation Agency, JICA, Ministry of Public Infrastructure and Land Transportation, MPI. Manual for Survey and Countermeasure of Slope Failure, Rock Fall and Debris Flow, 2017).
2. Cruden, D. M., 1991. A Simple Definition of a Landslide. Bulletin of the International Association of Engineering Geology, No. 43, pp. 27–29.
3. Varnes, D. J., 1996. Landslide Types and Processes, in Turner, A. K., and R. L. Schuster, Landslides: Investigation and Mitigation, Transportation Research Board Special Report 247, National Research Council, Washington D.C.: National Academy Press.

Chapter 5.4. ENGINEERING PROPERTIES OF SOILS OCCURRING ON THE ISLAND

5.4.1. Ground Investigation

Geotechnical investigations are performed with an aim to have an insight of the characteristics of bearing soils such as the physical and mechanical properties of materials that exist underneath a building site. Geotechnical testing is vast in its own context and may start from a walk around on the surface of the delineated area and go as far as geophysical testing (non-destructive testing) to direct access of the bearing soil at various depths. Commonly soil testing may be realised by opening of trial pits, drilling of boreholes, laboratory investigation and in-situ testing.

Trial pits are much like one would expect, that is, a pit is dug either manually or with an excavator to the depth desired in order to reveal the sub-surface conditions. The profile of the trial pit walls are logged and the preliminary classification parameters and consistency of the underlying strata are assessed.

Drilling provides the opportunity to physically remove the soil or rock core samples for testing and inspection. The cores provide the advantage of physically seeing and visually assessing the actual materials, but for certain types of soils, the very act of boring can disturb the soil conditions and the samples extracted may not represent what the conditions will actually be for building and supporting structures. Generally, soil or rock samples from various depths of drilling are taken to a laboratory for further investigation.

In-situ, that is, in the actual location or on site, testing methods include penetration tests such as Standard Penetration Tests (SPT), which penetrate via drilling, and various Cone Penetration Tests, which penetrate via direct penetration of cones. These tests measure the physical and mechanical properties of the subsurface soil directly, without removal of cores. This provides the advantages of generating a more accurate reflection of conditions underground as well as avoiding the necessity of sending samples out for laboratory testing. In situ testing also includes plate load bearing tests, sand replacement, percolation tests among others – also meant to assess the actual nature of the prevailing materials.

The most important in soil testing campaign is to identify the right test for the right situation and for the right geology prevailing on site. Soil testing

methodology will vary in function of various parameters, likewise – equipment, normative regulations, working pressure underneath foundations and most importantly – varies with the type of soil being investigated. The types of soils encountered depend on numerous factors namely: genetics of the soil, geographical position, nature of weathering and also age of the formation. So when all these variables are put together, it becomes quite complicated to select the appropriate method to obtain reliable soil parameters for assessment of bearing properties of the strata under investigation.

This part presents the methods of soil investigation applicable to weathered volcanic basalt in the context of Mauritius.

Founding material

The identification and description (logging) of soil and rock strata, deposited as results the weathering of volcanic basalt (Goodary et al. 2012, 2014), are currently carried out following recommendations of British Standards (BS 5930, 1999) – Code of Practice for Site Investigations. Foundation materials encountered during logging of profiles depends on the degree of weathering of the parent material and are classified as – slightly, moderately, highly and completely weathered basalt or agglomerate as shown in Table 5.4.1 (Byrne G., and Berry A. D., 2008).

Table 5.4.1.

Rock mass weathering

Descriptive term	Fracture condition	Surface characteristics
Fresh Basalt	Closed	Unchanged
Slightly weathered Basalt	Discoloured and may contain thin filling	Partial discoloration/ not friable
Moderately weathered Basalt	Discoloured and may contain thin filling	Partial to complete discoloration/not friable
Highly weathered Basalt	Discoloured and may contain thin to medium thick filling	Friable
Completely weathered Basalt	---	Resembles soil

A scale of strength of rock material, based on the indicative uniaxial compressive strength, as per BS 5930, is used to classify the rock mass according to its strength (Fookes P. G., 1971) and is shown in Table 5.4.2.

Table 5.4.2.

Strength description of rock material

Term	Field description	Compressive strength (MPa)
Very weak	Gravel lumps can be crushed between finger and thumb.	< 1.25
Weak	Gravel lumps can be broken by heavy hand pressure.	1.25 to 5
Moderately weak	Only corners can be broken off with heavy hand pressure.	5 to 12.5
Moderately strong	Held in hand, rock can be broken by hammer blows	12.5 to 50
Strong	On a solid surface, rock can be broken by hammer blows	50 to 100
Very strong	Rock chipped by heavy hammer blows.	100 to 200
Extremely strong	Rock rings on hammer blows.	>200

The soil mass is then identified and classified as sand, silt and clay or a combination of all coexisting components (Little A., L., 1969). Its physical state is determined by the principles listed below.

Table 5.4.3.

Soil strength description for cohesive/fine soils

Consistency	Identification
Very soft	Easily moulded by fingers
Soft	Easily penetrated with thumb
Firm	Indent by thumb/moulded with strong pressure
Stiff	Indent by thumb
Very Stiff	Penetrated by thumbnail
Hard	Penetration by thumbnail difficult

Soils, hosting foundations, are normally end results of weathering process which occurred in the original parent basalt over millions of years and these are most likely gravels and cobbles in a matrix silty clay or sand (Fookes P. G., 1997). They may be encountered as:

1. Residual basalt or Completely weathered basalt
 2. Highly weathered basalt
 3. Moderately weathered basalt
 4. Slightly weathered basalt
- or as a combination.

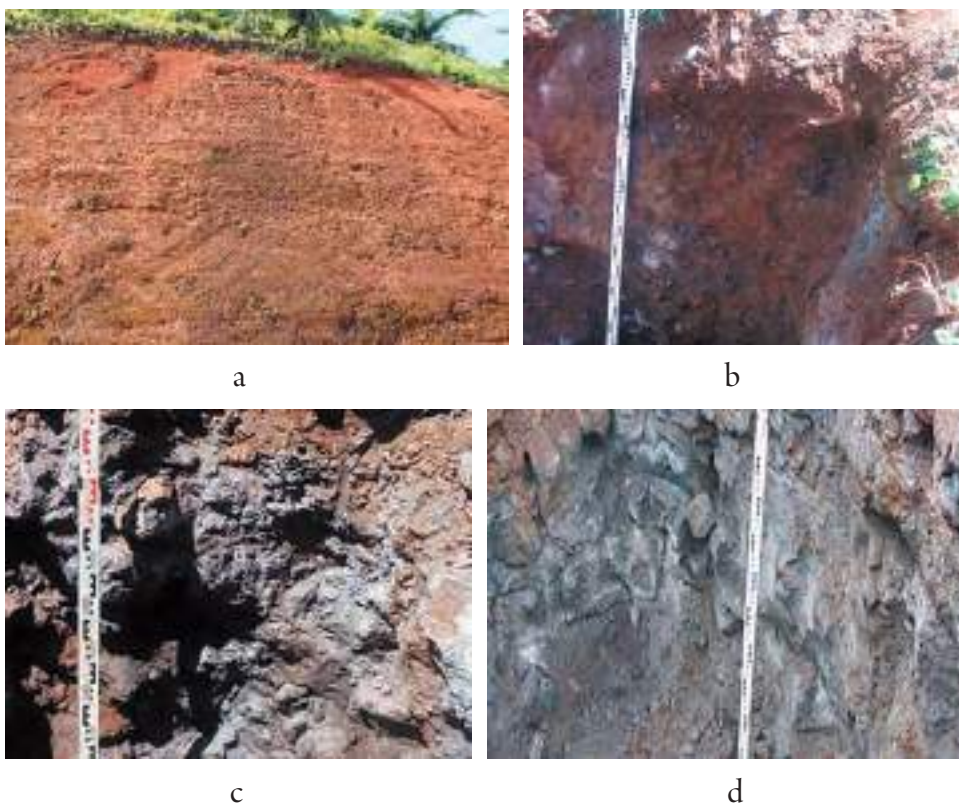


Fig 5.4.1. **a** – Residual basalt; **b** – Highly weathered basalt;
c – Moderately weathered basalt; **d** – Slightly weathered basalt
 Photos by K. D. Goodary and R. Goodary

Wherever possible, effort is made to seat foundations on weathered basalt, but it often happens that this formation is located deep down and shallow foundations have to be laid on encountered soil.

Residual Soils

The island is overlain by several typical soils as shown on the soil map.

Zonal soils

The zonal soils, depending on the parent material, climate and location, may fall in one of the following categories (Proag V. 1995).

Low humic latosols

The Low Humic Latosols occur in regions with annual rainfall in the range 1,000 mm to 2,750 mm in areas with a distinct dry season. They are deep (over 100 cm) to moderately deep soils (over 60 cm) with good internal drainage.

They are from red to brown in color with kaolinite the dominant clay mineral.

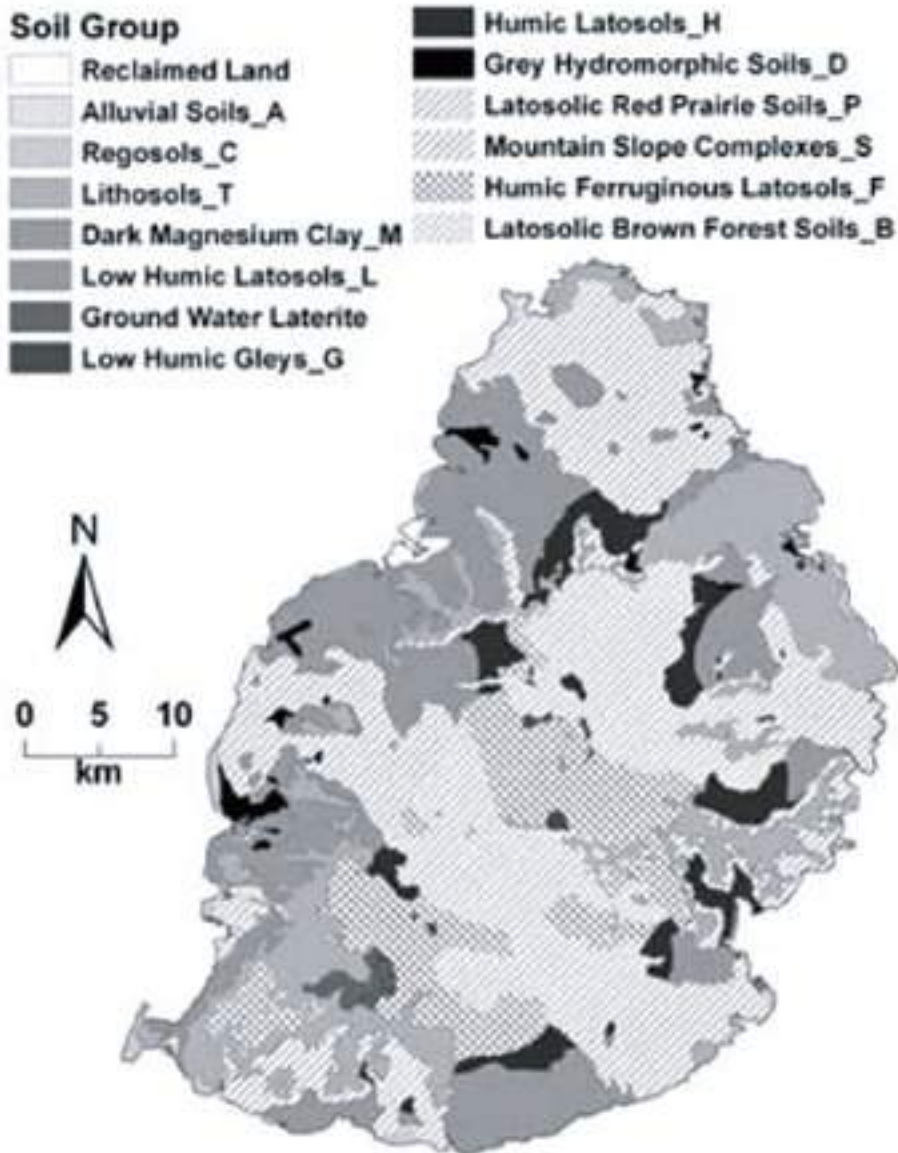


Fig. 5.4.2. Soil map of Mauritius

(<https://www.geospatialworld.net/article/a-landslide-potentiality-mapping-on-mauritius-island/>)

This group of soils has been subdivided into four families which reflect differences from variations in rainfall and age of material namely:

1. Richelieu
2. Reduit

3. Ebene
4. Bonne Mere

The soils of Richelieu family occur in the driest regions where the annual rainfall varies from less than 1,000mm to about 1,500mm; the Reduit family occurs above the 1,500mm isohyet as do the soils of Ebene family but these are comparatively less leached. Soils of Bonne Mere family are shallower and contain gravels which may certain areas, be the remains of very thin overflows of Late Lavas from Bar le Duc crater; since they occur in a higher rainfall zone, they represent soils which are transitional to Humic Latosols.

Humic Latosols

These occur in regions with annual rainfall ranging from less than 1,500mm to 3,750mm and it represents a transitional group between the Low Humic Latosols and the Low Humic Ferruginous Latosols.

The soils are dark brown to reddish brown silty clays, and friable throughout the solid although structural development is weak. They contain more organic matter (5–7%) than the Low Humic Latosols and the clay fraction consists of about equal proportions of Kaolinite, geothite and gibbsite

Two families have been classified:

- The Rosalie family which appears to be transitional to Low Humic Latosols and
- The Riche Bois family which is transitional to the Mimic Ferruginous Latosols

Humic Ferruginous Latosols

These occur within the rainfall zone 2,500 mm to over 5,000 mm annually on almost flat to sloping land and have been formed from Early and Intermediate Lavas of the Younger Volcanic series.

On flat areas, aluminium oxide concretions and permanently waterlogged gleyed soils may be formed.

Four Families have been identified:

1. Chamarel
2. Belle Rive
3. Sans Souci
4. Midlands

Intrazonal Soils

The soils have developed under conditions where the effects of climate and vegetation are masked by local factors of environment such as relief, drainage and composition of parent material.

The soils of the Late Lavas which have been classified as Latosolic Soils are subdivided into two Great Soil Groups as Latosolic Reddish Prairie in the dry areas and Latosolic Brown Forest in the wet areas.

The soils in the dry valleys of the Older Volcanic Series are Magnesium Clays. Grey Hydromorphic soils are formed when drainage is limiting on Intermediate Lavas in dry areas, while the Humic gleys are corresponding soils occurring in the humid and superhumid zones. The ground Water Laterites occur only in super humid zone. Mountain Slope Complex have been placed in, intrazonal order, although the two families of these soils were, separated on a rainfall basis; the dominant feature of these soils is strong erosion.

The Latasolic soils cover areas with mean annual rainfalls ranging from 1,000mm to 5,000mm and consequently they exhibit considerable variation in chemical properties and range from neutral soils with high base status to strongly acid soils low in exchangeable bases. All the soils have varying quantifies of boulders and gravels of relatively high (or moderately weathered basalt in their profiles. Bedrock exposure are frequent in many areas, their extent giving rise to phases rockiness. All soils have a high content of organic matter.

The Latosolic Reddish Prairie Soils

These soils have developed in areas of the Late Lavas below the 2,500mm isohyet.

The typical profile consists of a dark brown horizon, rich organic matter and containing variable but usually high amounts (to 50 per cent of volume) of gravels and stones, overlying a reddish-brown horizon. In many places the soils are shallow to very shall (less than 30 cm) With frequent bedrock exposures and many toe boulders.

Textures range from silty clays to clay loams; kaolinite is the dominant clay mineral.

Three families of the Latosolic Reddish Prairie soils have been mapped:

1. Medine
2. Labourdonnais
3. Mon Choisy

The Latasolic Brown Forest Soils

Although these soils have developed on Late Lavas, moderate strong weathering has occurred on account of the higher rainfall (greater than 2,000mm).

They may be dark brown in colour, high in organic matter and grades into a lighter coloured horizon over parent rock often at shallow depths.

The texture varies from clay loam to silty clay or clay. The clay fraction contains moderate to little kaolinite and rather more gibbsite than goethite.

Two families have been mapped on the basis of weathering intensity:

- The Rose Belle family occurring at lower elevations within the rainfall zone 2,000mm to 4,000mm and
- The bois Cheri family which receives over 3,000mm of rainfall.

The Dark Magnesium Clays

This group of intrazonal soils shows the dominant influence of montmorillonitic clay together with a high degree of saturation by magnesium.

They have developed under low rainfall conditions, less than 1,500mm, on the lower slopes and valleys of mountains of the Older Volcanic Series.

They are self-mulching black or dark grey clays. As they have been formed from colluvium and alluvium, their profiles in many instances contain gravels.

Two families have been identified:

- The Plaine Lauzun family with a horizon containing gypsum crystals and
- The Magenta family with no gypsum.

The Grey Hydromorphic Soils

The grey hydromorphic soils are plastic clays formed as a result of periodical waterlogging and have developed under low rainfall, below 1,250 mm annually.

They are characterised by grey, yellow or brown mottlings.

Two families have been mapped;

- The Balaclava family which is strongly hydromorphic
- The St. Andre family which is only moderately hydromorphic

The Low Humic Gleys

While the Grey Hydromorphic soils occur in a low rainfall area, Low Humic Gleys are corresponding hydromorphic soils under permanent waterlogging occurring in the high rainfall areas.

Two families have been mapped:

- Petrin

- Valetta

The Ground Water Laterites

These soils occur in the superhumid zone on the Early Lavas of Younger Volcanic Series; they have a permanently low water table. They occupy a relatively small area on the island.

The Mountain Slope Complexes

These soils have been mapped by taking the boundary of Intermediate and Late Lavas of the Younger Volcanic Series and Older Volcanic Series, which is always a well-defined break in slope and the 30% slope contour.

They occur under rainfall ranging from 1,500 mm to more 5,000 mm, producing two distinct types of weathering.

On the drier slopes, the soils are brown to grey clays, with good status while, as a result of intense weathering on the wetter slopes, the soils are reddish ferruginous silty clays, low in bases and in many cases with ferruginous concretions.

Two families have been mapped:

- The Nicolieri family occurring in the drier areas
- The Ferney family in the wetter areas

Azonal soil

Three main groups have been classified:

Alluvial and colluvium Soils

These are young soils developed from recent alluvium and colluvium. Depending upon the nature of the alluvium, they may be silty clays or silts, with or without pebbles. They occupy very small areas.

Regosols

These soils have little or no profile development and occur on deep unconsolidated coral sand around the coast line. They are highly permeable and well aerated with low water retention capacity.

Lithosols

These comprise the rough broken land of mountains and gorges and are made up of almost intact rocks.

The lithosols have been identified as rough broken land (mountain) or very steep slopes where soil development is offset by erosion and rough broken land (gorges).

5.4.2. Founding Materials encountered

As a general practice, foundations are seated on weathered basalt (or rocks) but in the absence of the latter, they are bound to laid on residual soils. In practice, two main types of residual soils are of interest to Engineers:

- non swelling soils with predominant kaolinite clay fraction
- swelling soils with predominant montmorillonite clay fraction.

Diffractograms of typical local swelling soil, sampled from the region of La Butte, Port-Louis and typical non swelling soil (LM1 and LM2 respectively) submitted to XRD analysis for overnight duration are shown in fig. 4.2.3 below. It is found that the swelling soil sample is a predominantly montmorillonite soil (with some derivatives) while the non-swelling is a kaolinite soil and its derivatives.

The Scanning Electron Microscope (SEM) observation of these soils reveals that the constitutive particles have a certain characteristic shape due to the high degree of alteration.

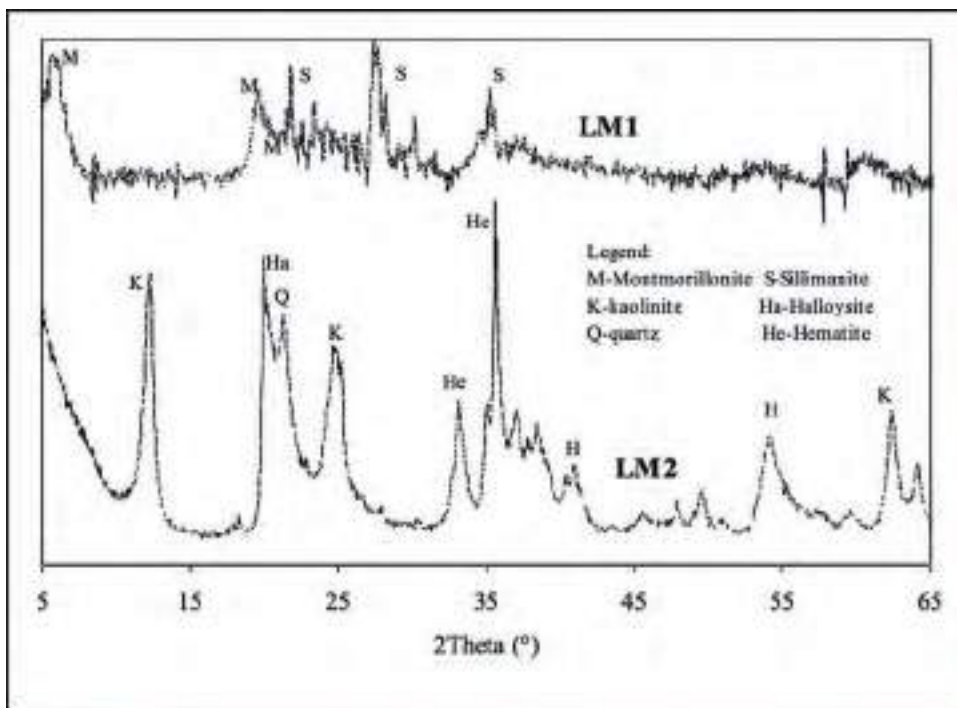


Fig. 5.4.3. Diffractograms of swelling (LM1) and non-swelling (LM2) soils
R. Goodary.

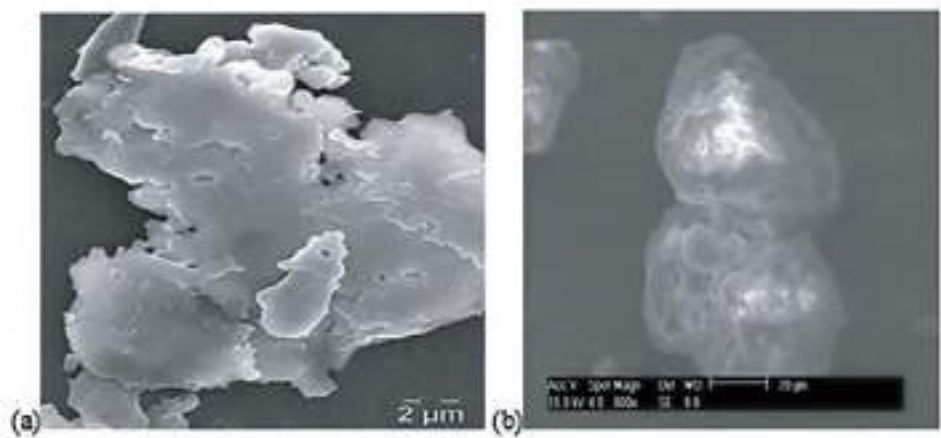


Fig 5.4.4. SEM micrographs of (a) swelling soil and (b) non-swelling soil. R. Goodary

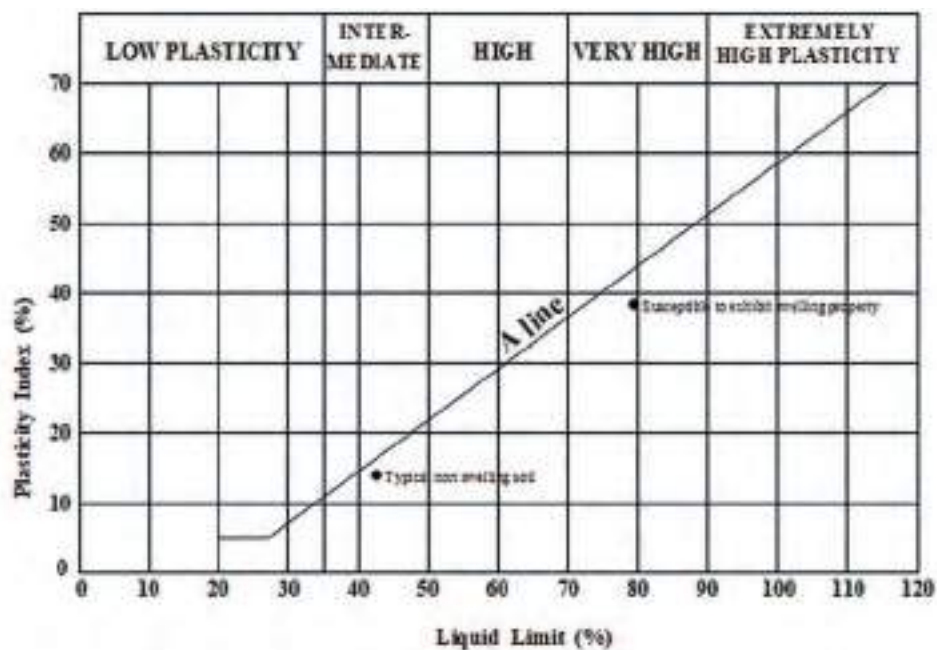


Fig. 5.4.5. Plasticity chart showing typical locations of soils on the Plasticity Chart

A typical particle size distribution curve is shown in Fig. 5.4.6.

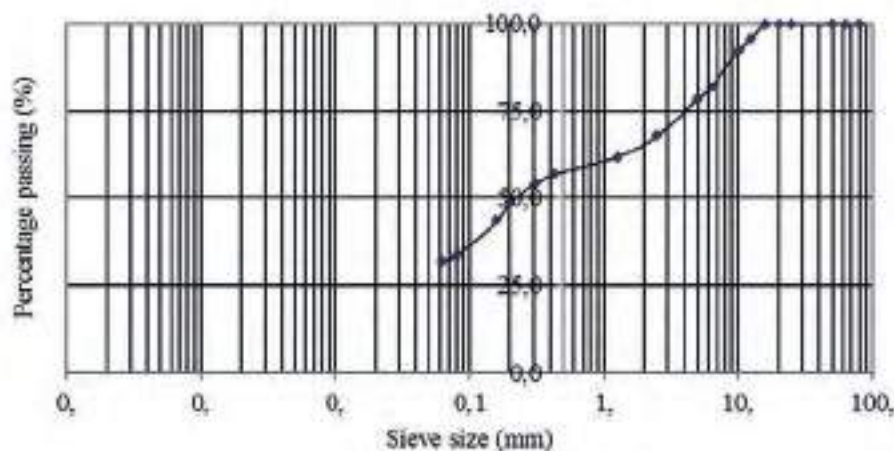


Fig. 5.4.6. Typical particle size distribution curve of typical highly to completely weathered basalt

Clay: 0-0.002mm Silt: 0.002-0.063mm Sand: 0.063–2.0mm Gravel: 2.0–60.0mm Cobbles: >60mm

From figure 5.4.6, it can be seen that for a typical soil encountered, and from the various components present, the material may thus be classified as a gravelly silt/sand (Vargas M., 1974). However, the sample below, contains 30 percent fines comprising silt and clay particles which also enables its appellation as gravelly silty clay. This is evidenced by the typical drilled core sample shown in the Fig. 5.4.7. In the figure, the plastified segments show depths at which Standard Penetration tests were carried out.



Fig. 5.4.7. Drilled coring in volcanic weathered basalt

Generally, the founding material underlies an organic top soil layer – as it can be seen between 0 to 0.55 m in Figure 5.4.7. It is obvious that the presence of gravels makes it difficult to extract undisturbed cylindrical samples for further laboratory investigation (Jennings J. E. et al, 1973). However, occasionally it becomes possible to retrieve undisturbed samples during site investigation, which are despatched to appropriate competent laboratories for testing.

As a matter of fact, tests namely: one dimensional consolidation oedometer test, direct/triaxial tests, permeability, unconsolidated unconfined tests and also classification and compaction tests, among others are performed on the sample. During site investigation the most appropriate and locally available in-situ tests realised are mainly plate load bearing test and dynamic standard penetration test. Geophysical investigation and pressuremeter tests are rather rare.

This paragraph aims at comparing some selective methodologies currently adopted on the island, along with an analysis of the some test results obtained.

Soil testing

The cost of an adequate investigation is very low in comparison to the budget put aside for a whole project. The consequences of not providing sufficient, accurate and reliable geotechnical data may have a significant effect on a project and can lead to delays and extra funding during construction. Consequently, a proper soil investigation campaign prior to start of construction is unavoidable.

The importance of obtaining adequate and reliable information and design mechanical data relevant to the subsurface conditions at a sufficiently early phase is vital when considering the choice and design of an economical and technically sound foundation. In quest of such information, a complete geotechnical investigation comprising the following is necessary: planning of the investigation, execution of fieldwork and management of laboratory testing and finally interpretation and reporting.

The soil investigation campaign aims to obtain the following parameters: description of the soil profile, consistency of the soil profile strata, in situ tests – dynamic cone penetration tests, plate load bearing test, SPT, location of ground water level from piezometers installed in boreholes. Laboratory investigation may include the following tests: drained and undrained shear strengths from undisturbed samples, compressibility characteristics from one dimensional consolidation and index properties of the encountered strata from bulk samples.

Physical and index properties of weathered volcanic basalt are generally found to be coherent with conventional soils as these are normally performed on selected samples with specified particle size, that is sand, silt and clay particles (BS 1377, Part 2). As regards the laboratory testing on undisturbed samples – a special attention is required as results show deviations from expected values and are not often coherent with information gathered during site investigation. For the purpose of this analysis, the one dimensional consolidation test has been set as an example.

5.4.3. Laboratory testing

One dimensional consolidation test

This method covers the determination of the magnitude and rate of the consolidation of a saturated specimen of soil in the form of a disc with specified diameter and height, confined laterally, subjected to vertical axial pressures and allowed to drain freely from the top and bottom surfaces (BS 1377, Part 5). The method is concerned mainly with the primary consolidation phase, but it can also be used to determine secondary compression characteristics. Data obtained from this type of consolidation test, if carried out on undisturbed samples of good quality, enable the amount of settlement under a structure to be estimated. Values of the coefficient of consolidation can also be calculated from which an indication of the theoretical rate of settlement can be derived. The very important aspect of the results is that the initial portion of the compression curve must indicate the virginity of the undisturbed sample, that is, its ability to resist the early phase of loading – indicating that the sample is familiar to such loadings and theoretically shall not react to it. This will prove the intactness of the sample and will be representative to the natural deposit on site.

For the purpose of this study, a typical one dimensional consolidation experiment with sample diameter 50 mm and height 20 mm is being considered. The material inside the consolidation ring is classified as highly to completely weathered basalt – possible residual basalt and was sampled from the north western part of the island.

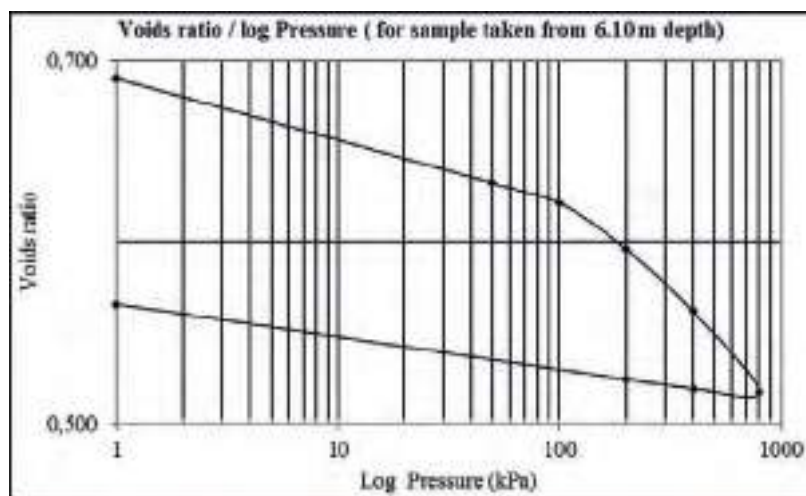


Fig 5.4.8. Typical laboratory compression curve for weathered basalt

An analysis of the compression curve shows that the soil started to react at the very early stage of loading, which is not conform to the real case. The soil has been sampled from a depth of 6.10 m, meaning that solely the overburden pressure p kPa should be equal to

$$p = h\rho g = 6.1 \times 1.6 \times 10 = 97.6 \text{ kPa (rounded to 100 kPa)}$$

where h is the depth, ρ – soil bulk density and g – gravity.

This implies that the soil sample should not react for the logarithm pressure value of 2 (logarithm of 100) which is not the case in the actual example. Contrary to the above said, void ratio e decreases from 0.69 to 0.68 which is quite significant, implying that the sample has settled, which should not be the case. It is to be noted that no surcharge added to the soil overburden pressure has been considered.

Discussion: The reason behind this anomaly is the existence of induced voids inside the consolidation cell. These voids might be residing at the extremities of the sample, between the sample wall and the metal ring, or within cracks or any other disturbance which might have given place to some amount of artificial voids. Theoretically, the sample should have fitted tightly inside the ring which might not be possible due to the coarse components within the soil structure. The original state of the material is compromised and consolidation parameters obtained from such samples will far not reflect the natural site conditions. It is now obvious that such samples will eventually not yield conclusive results in other experiments, likewise direct shear test or even triaxial compressive strength tests. Hence recourse to in situ testing is an ultimate option.

Conclusion: The quality of undisturbed sampled must be thoroughly controlled before testing.

5.4.4. In situ testing

Plate Load Bearing test

The plate load bearing test is usually carried out to determine the compressibility and bearing capacity of soils. The test is convenient and provides a direct method of obtaining these parameters. It is often used in soils which cannot be sampled with good quality sample or cannot be retrieved. In its simplest form, the plate load test comprises a rigid plate placed on the surface of the soil to be tested. The load is provided by a hydraulic jack, using a lorry to obtain the reaction. The plates used must be rigid and generally vary in diameter from 305 to 1200 mm. The procedure for the above test has been worked out

by the author with the collaboration of local consultants. The methodology was adopted to suit the local soil conditions and characteristics and was not altered much from prevailing standards (Terzaghi K. and Peck R. B., 1967; BS 1377 Part 9) in order to be coherent with the norms for which the plate load testing equipment has been designed. The following steps were adopted for the testing procedure (R. Goodary):

- Apply load to produce deflection between 0.25 mm and 0.51 mm.
- Record and release load.
- Apply $\frac{1}{2}$ seating load (seating load is the load required to produce deflection between 0.25 mm and 0.51 mm).
- Allow dial needles to come to rest.
- Set dial needles to zero.
- Apply load to produce 25 kPa above $\frac{1}{2}$ seating load. This will depend on plate diameter, for $d = 305$ mm, pressure = 34 kPa.
- Allow action of load to continue until rate of deflection of not more than 0.03 mm/min has been maintained for three consecutive minutes.
- Record load and deflection readings for applied load increment.
- Reload by applying 50, 100, 200, 300, 400, 500 kPa ... (if reaction load allows) and repeat steps above. The values of applied pressures will depend on plate diameter.

Unload in reverse sequence and release the load to load at which dial gages were set to zero.

Fig. 5.4.9 below illustrates results of plate load test carried out in the same family of soils as previously, that is, in weathered basalt

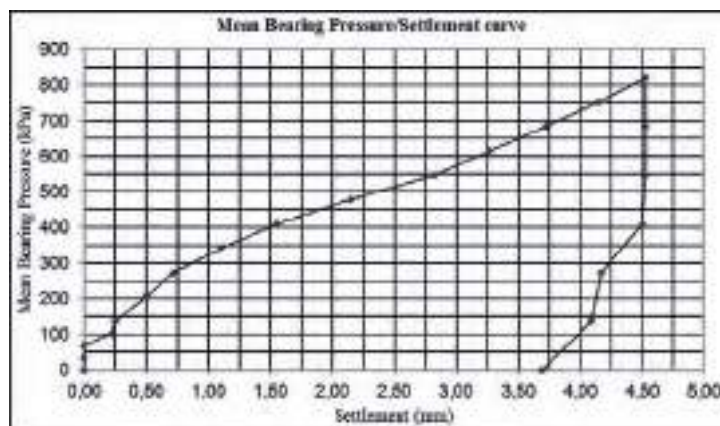


Fig. 5.4.9. Plate load bearing test result in weathered basalt

Assessment of ultimate bearing capacity: The value of q_{ult} for a proposed foundation is generally determined from a corresponding value of allowable settlement S of the foundation. A value for permissible settlement of 25 mm is being assumed for a presumed base of size 2 m x 2 m.

In this situation, settlement S_p (mm) of the plate (B_p of diameter 305 mm) corresponding to a settlement of 25 mm of the above mentioned base will be deduced. As such $S_p = (S \times B_p) / B = (25 \times 0.305) / 2 = 3.81$ mm, a value which has been achieved at mean pressure value of 700 kPa.

This allows to conclude that for an assumed allowable settlement of 25 mm, the value of the allowable bearing capacity is in the range of 233 kPa (assuming a factor of safety of 3), a value which corresponds to a very stiff soil consistency and is in agreement with site conditions as per available logs of borehole cores and trial pits.

Standard Penetration Test (SPT)

For the above site, Standard Penetration Tests (SPT) were conducted at various depths as per BS 1377, both in cohesive and granular/gravelly soils (Meyerhof G. G., 1956). The test was carried by using a thick walled sample tube, the outside diameter of which is 50 mm. This is driven into the ground at the bottom of the borehole by blows from a standard weight of 63.5 kg falling through a standard height of 760 mm. The number of blows required to drive the sampler at each 150 mm increment of a total of 450 mm penetration was recorded. The blow count for the first 150 mm increment was discarded and the sum of the blow counts for the second and third increments were recorded as the SPT "N" value. Results of Standard Penetration Tests carried out in boreholes at different levels are shown in Table 4 below.

Table 5.4.4

Standard Penetration tests results in highly to completely weathered basalt

SPT level (m)	SPT N value	Estimated UCS, kPa (Jennings et al, 1973)	Estimated shear strength C_u, kPa	Consistency
1.00	44	150–300	75–150	Very stiff
1.50	34	150–300	75–150	Very stiff
3.500	31	150–300	75–150	Very stiff
8.15	26	150–300	75–150	Very stiff

Standard penetration tests results reveal soil of a very stiff consistency which is in agreement with plate load test.

Closing remarks to Chapter 5.4:

It is noted that soil testing in weathered basalt of volcanic origin demands a special approach in the assessment of their geotechnical parameters as these soils may not submit themselves to conventional methods of soil testing, particularly in what laboratory testing is concerned. Laboratory testing results on undisturbed samples of weathered volcanic soils may often yield unreliable results. Likewise, the one dimensional consolidation test gives results typical to disturbed samples. The reason behind this anomaly is the existence of induced voids inside the consolidation cell. These voids might be residing at the extremities of the sample, between the soil sample wall and the metal ring or within cracks or any other disturbance which might have given place to some amount of artificial voids.

Plate load bearing test and SPT have been found to be appropriate for the type of soil under consideration.

Test questions to Chapter 5.4:

1. What is the purpose for a ground investigation?
2. Strength properties of soils and rocks encountered on site.
3. What are the common types of laboratory and in-situ tests on soils and rocks?
4. Which testing methods are more appropriate for volcanic residual soils?
5. Information provided in the soil map of the island.
6. Classify the soils encountered on the island?
7. Differentiate between geological map and soil map of the island.
8. What are the soil parameters which can be obtained from a Plate Load Bearing Test?
9. How is the Ground Water Table located during soil investigation?
10. What is Dark Magnesium Clay and why is it undesirable for construction purposes?

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Chapter 5.5. GEORISKS AND SUSTAINABILITY RESOURCE OF THE MASCARENE ISLANDS TERRITORIES TO EXTERNAL IMPACTS

5.5.1. Introduction

An analysis of the risks of natural hazards (georisks) occurring in a particular region is an important element in land use planning, as well as for the implementation of the region's sustainable development strategy. The increase in the number of emergencies observed in recent years throughout the world requires taking into account both individual events and the interaction of various types of dangerous phenomena with each other. Often there is a «synergistic effect» that can occur with the simultaneous action of these events and it becomes necessary to study the nature of the trigger mechanisms leading to these effects. The combined consequences of such events often exceed by far the damage from each event individually. For example, a strong earthquake with subsequent mountain landslides and rock falls can cause the closure of mountain rivers, or vice versa, the destruction of natural dams or artificial hydraulic structures, with flooding in foothill areas.

Georisks assessment is one of the primary tasks of geo-ecological investigation in order to ensure life safety, especially for urbanized areas – complex natural-technical systems together with their regulatory measures, due to natural and technogenic factors. The basis for assessing georisk at the initial stage is to determine the types of geological hazards, their spatial distributions and intensities. Then, an analysis of the stability of the territories should be carried out in terms of the geological structure, geomorphology, geotechnical and hydrogeological conditions. Particular attention is required to areas with residential development and large existing and prospected infrastructure projects which are obviously the most vulnerable to negative geological processes.

The study of georisks together with the analysis of the safety of the human environment is necessary for the development and implementation of preventive measures and codes of practice with an aim to save lives in cases of natural disasters, such as earthquakes, volcanic eruptions, tsunamis, landslides, flash floods, the effects of climate change and others.

These problems are especially relevant for low- and middle-income countries, as these countries often face a high risk of death and casualties in natural disasters. This is often due to the lack of mandatory building codes – their

poor quality or non-compliance, unsatisfactory urban planning, unauthorized community settlements and the lack of local technical management skills to handle high georisk disasters.

5.5.2. Multi-risk assessment approach

To solve these problems, the concept of «multi-risks» is currently being developed, including a group of more than one event that threatens a certain common region with an assessment of their interactions. This concept was first considered at the UN Conference on Sustainable Development in Rio de Janeiro and then introduced into the Johannesburg Plan. According to this concept, “multi-risk assessment should be understood as the process of determining the likelihood of various dangerous phenomena:

- occurring at the same time or soon after each other, since they depend on each other;
- or since they are caused by the same initiating event;
- or they threaten the same objects without a chronological coincidence”.

To assess the ability to withstand negative environmental impacts, the concept of “sustainability resource of territories” may be used. This concept includes a set of indicators of external influences on the system and the levels at which this particular system functions within acceptable parameters. After a certain threshold value of the degree of influence, the system ceases to function in a normal, predetermined or acceptable mode.

The concept of “sustainability resource (or resistance) to external influences” (SR) is quite universal and can be applied to various natural and natural-technogenic systems. For example, in geotechnics, one of the indicators of SR is the allowable settlement of loess soil mass caused by the initial applied pressure, after which the soil structure is destroyed and irreparable damage occurs, due to excessive settlement. The value of such pressure allows characterizing weak soils during surveys for design and construction purposes. In hydrogeology: at a certain critical value of the SR territory for the infiltration of atmospheric precipitation or domestic/industrial water is the rise in the groundwater level to a critical threshold value, beyond which unacceptable flooding occurs.

Georisks during earthquakes are significantly less for areas with rocky foundations for buildings and structures that have a high stability resource, in contrast to sandy, especially water-saturated soil foundations spread on low atolls. Seismic effects on sandy water-saturated soils can cause a phenomenon

such as liquefaction of soils, with the construction site plunging down causing their destruction. Such processes were observed in Indonesia and Japan. On the other hand, in the mountainous areas of volcanic origin, multi-risks arise with a “synergistic effect” during seismic impacts due to soil collapses, rockfalls, landslides that are practically inexistent on low islands.

The damage from tsunami, as well as from global sea-level rise, will be greatest for islands and coral atolls with low absolute elevations (low SR), in contrast to high volcanic islands.

This part aims to investigate and assess the georisks factors and sustainability resource for territories of the Mascarene Islands, located in the southern part of the Indian Ocean. The largest islands are Reunion with an area of 2512 km², Mauritius – 1865 km², Rodrigues – 104 km². There are also many small islands and atolls – Agalega, St. Brandon, and others.

The large islands are of volcanic origin and consist mainly of basaltic deposits of varying degrees of weathering. Among these islands, the island of Mauritius is the oldest with an ascension period of the island in the range of 6.7–10 million years. The islands of Reunion and Rodrigues were formed about 2 million years ago.

Mauritius was formed by the volcanic activities of the tectonic fault N100 along a crack periodically erupting basaltic lavas and other volcanic products. The last phase of volcanic activity on the island is between 700,000 and 25,000 years. Lava emissions occurred from 26 craters located along the NNE-SSW axis, that is, parallel to the fault, which is currently off the island. This fact, as well as the absence of volcanism over the past 25 thousand years, may indicate a displacement of the upper part of the earth's crust along with the island away from the active fault. The remains of volcanic cones are the highest mountains on the island. The highest is Mount Piton de la Rivière Noire, 826 m high. No significant earthquakes were observed on the island (Fig. 5.5.1).

Reunion island is characterized by modern intensive volcanic activity. The active volcano Piton de la Fournaise, located in the southeast of the island, is one of the most active in the world (Fig 5.5.2 a). There are also a number of volcanoes that are considered extinct. The highest of them, Piton des Neiges, has a height of 3069 m. Seismic activity is associated with volcanic activity. On 10 February, 2020, within twenty minutes in the bowels near the volcano, Piton de la Furnes, seismographs recorded more than two hundred volcanic earthquakes.

Rodrigues Island is located in the so-called “triple junction point”, where global mid-ocean ridges divide the bottom of the Indian Ocean into three sectors: African, Indo-Australian, and the Antarctic. Ridges are characterized by underwater volcanism, seismicity, and the rift structure of the axial zone. In the region of Rodrigues island, the system of ranges is divided northward into the Arabian-Indian ridge and southwest into the Central Indian Ridge. Despite the volcanic origin of the island of Rodrigues, the maximum height of its surface is only 398 meters above sea level. By the virtue of its location, seismic and volcanic activities are very likely on the island.



Fig 5.5.1. Extinct volcano on the island of Mauritius Photo by V. Iegupov and R. Goodary

Agaléga atoll consists of two coral sand islands in the western part of the Indian Ocean (North and South), located 1100 km north of the island of Mauritius. The total area of the islands, separated by a small strait, is 24 km². As in other tropical coral islands, soils are composed of bioclasts of calcareous organisms (material obtained from the skeletons of corals and many other animals and plants associated with corals) with an almost complete absence of silicon material. Beaches are developed all around and the wind accumulates lighter and thinner material in the dunes. Rainwater reach all this material, which, being almost completely made of calcium carbonate, is easily dissolved, and the dissolved lime re-precipitates around the bulk material, causing its cementation. The coastal dunes are located in the southeast of the South Island (Grande Montagne, rising to about 7 meters) and in the direction of the northeast of the North Island (Montagne d'Ernerez, rising to 15 meters). The interior of the beach and dunes is a very flat area, consisting of consolidated coral sand with a sandy surface and occasionally overlain by topsoil (Fig. 5.5.2 b).



a



b

Fig. 5.5.2 **a** – active volcano – Piton de La Fournaise, Reunion Island;
b – coral island beach Photo by V. Iegupov and R. Goodary

5.5.3. Assessment of Georisks and Resource of Stability for the Mascarene Islands

An assessment of the resource of stability of the territories of the Mascarene Islands to natural influences was performed from the geotechnical point of

view of the development and consequences of the most significant hazardous engineering and geological processes, with a prior expert qualitative assessment. The analysis was done, based on published data and recent reported information on geological and geotechnical surveys in these territories. When performing the assessment, georisks and sustainability resources were rated as “high”, “medium”, and “low”, depending on the gravity of the effects of their impact. The possibility of multi-risk occurrence has also been investigated and results of their evaluation are summarized in Table 5.5.1.

Table 5.5.1

**Main Georisks and Sustainability
Resource of the Mascarene Islands territories**

Georisks	Reunion	Mauritius	Rodrigues	Agalega and other coral islands
Seismic impacts*	High +++	Low +++	High +++	Depends on location +
Tsunami	Medium +++	Medim +++	High ++	High+
Volcanic eruptions**	High +++	Low+++	Medium +++	Unlikely
Landslides	Medium +++	Medim +++	Low +++	Unlikely
Rockfalls	High ++	High ++	Low ++	Unlikely
Mudflows	Medium ++	Medium ++	Low ++	Unlikely
Sea level rise	Possible +++	Possible +++	Possible ++	Posible +

Legend: Georisk level: high, medium, low, possible, unlikely

Sustainability resource: +++ – high, ++ – medium, + – low.

The * indicates multi-risks:

*Earthquakes often cause landslides, rockfalls in the mountains; dilution of water-saturated soils and tsunamis.

**Volcanic eruptions are often accompanied by volcanic eruptions and mild earthquakes.

Conclusion to Chapter 5.5.

The advantage of the proposed approach is the unification of the principles of assessment, the need to take into account the capabilities of the natural resource and regulate its increase through preventive measures, which is the basis for building harmonious and safe human relations with the environment. Further research on the quantitative assessment of the degree of impact of the listed

geo-risks on the territory, the development and implementation of necessary measures to protect against dangerous natural phenomena is deemed necessary for the Mascarene Islands territories.

Test questions to Part 5.5:

1. What is georisk and how it can be assessed?
2. What is multi-risk assessment?
3. Explain the concept of “sustainability resource to external influences”.
4. What are the georisk factors which may be a threat to the Mascarene islands.

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CONCLUSION

The elements of general geology and the main sections of engineering geology considered in this textbook, in our opinion, are the most important at the initial stages of the learning process for civil engineering students. Only after gaining an idea of the composition and structure of the earth's crust, the types of rocks and their properties, the main endogenous and exogenous natural, as well as technogenic processes, and the properties of soils, we can proceed to the study of more specialized disciplines.

Mastering the course "Engineering Geology" provides general theoretical and engineering knowledge, allowing to move on to the study of more complex scientific and applied areas, such as "Geotechnics". The knowledge and skills of students obtained in the study of "Engineering Geology" will serve as the basis for such disciplines as "Soil Mechanics", "Rock Mechanics", "Construction in complex geotechnical conditions", "Geo-ecology", as well as for final year graduate projects.

In the process of training specialists in construction specialties, questions of "Engineering Hydrogeology", concerning a very significant effect of groundwater in construction sites and in a developed territory as a whole — the conditions of their occurrence, movement, composition, require additional study. Subjects like Construction Climatology, Engineering Surveys, necessary for construction specialists, remain outside the scope of this textbook. With further training, students are also required to master the basic issues of "Geo-ecology".

Thus, only comprehensive professional training of specialists will reliably, economically and environmentally secure and ensure both the construction industry and life of people in general.

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