

Topic 2. Foundations in landslide areas

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GRAVITATIONAL 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.

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. 1, 2).
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. 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. 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 ($2\text{--}3^\circ$) slopes (Figure 5).



Fig. 1 The scree slopes of the high mountain zone of the Carpathians,
Dovbushanka mountain

a



b



c



d



e



Fig. 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



Fig.3 Landslide, Canada

a



b



Fig. 4 Floodplains on the slopes:
a - Rock formations on the slopes of Talgar settlement, Kazakhstan;
b - natural floating slope, Bukovyna

Fig. 5 Deluvial slope

TECHNOGENIC ARTIFICIAL SLOPES



Fig. 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



Fig.7 Kryvyi Rih iron ore quarries, Ukraine



a



b

Fig. 8. Man-made mountains in Ukraine:

a – terrikon, Donbass;

b – slag dumps, Zaporozhje

SLOPE PROCESSES

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. 10,11). 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.

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.

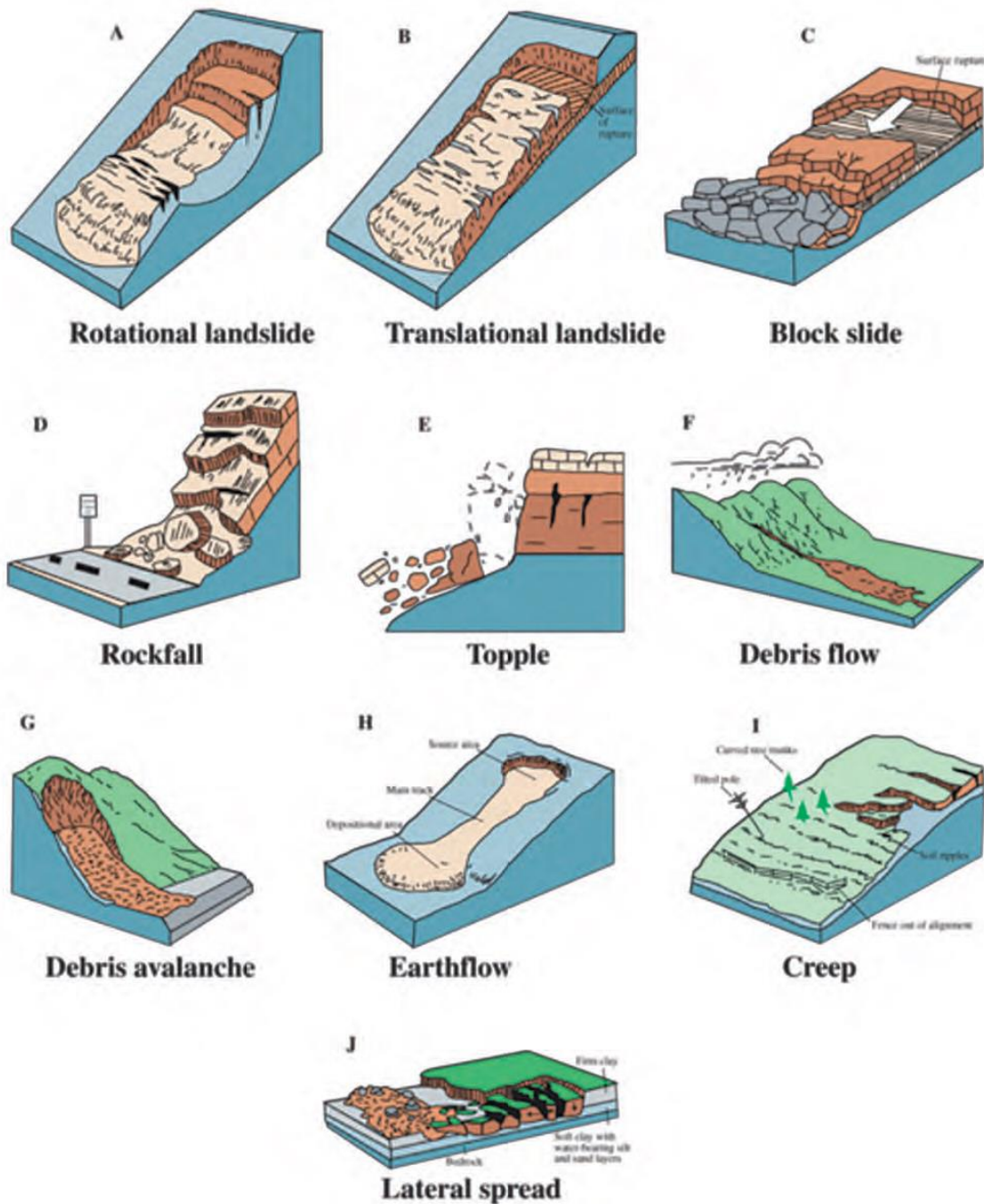


Fig. 9 Schemes of the main types of movement of soil masses on inclinations (according to the US Geological Survey):

- a** – rotational landslide;
- b** – translational landslide;
- c** – block slide;
- d** – rockfall;
- e** – collapse;
- f** – debris flow;
- g** – debris avalanche;
- h** – earthflow;
- i** – creep;
- j** – lateral spread



Fig.10 Rock outcrop



Fig.11 Collapse of blocks on highways in the mountains: Colorado, USA;



Fig.12 Sarez lake, formed as a result of a catastrophic gravitational displacement of rocks that blocked the river valley

PROTECTIVE MEASURES AGAINST 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. 13);
- hotcrete 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. 13 Protective anti-rockfalling gallery

SCREES OR TALUS



Fig. 14 Scree of various types: **a** – in Pakistan; **b** – in China



Fig. 15. Kurum – a slowly moving stone river from blocks



Fig. 16. Sweeping of a slope composed of loesslike loams

SOLIFLUCTION



Fig. 17. Solifluction – viscoplastic soil flow

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.

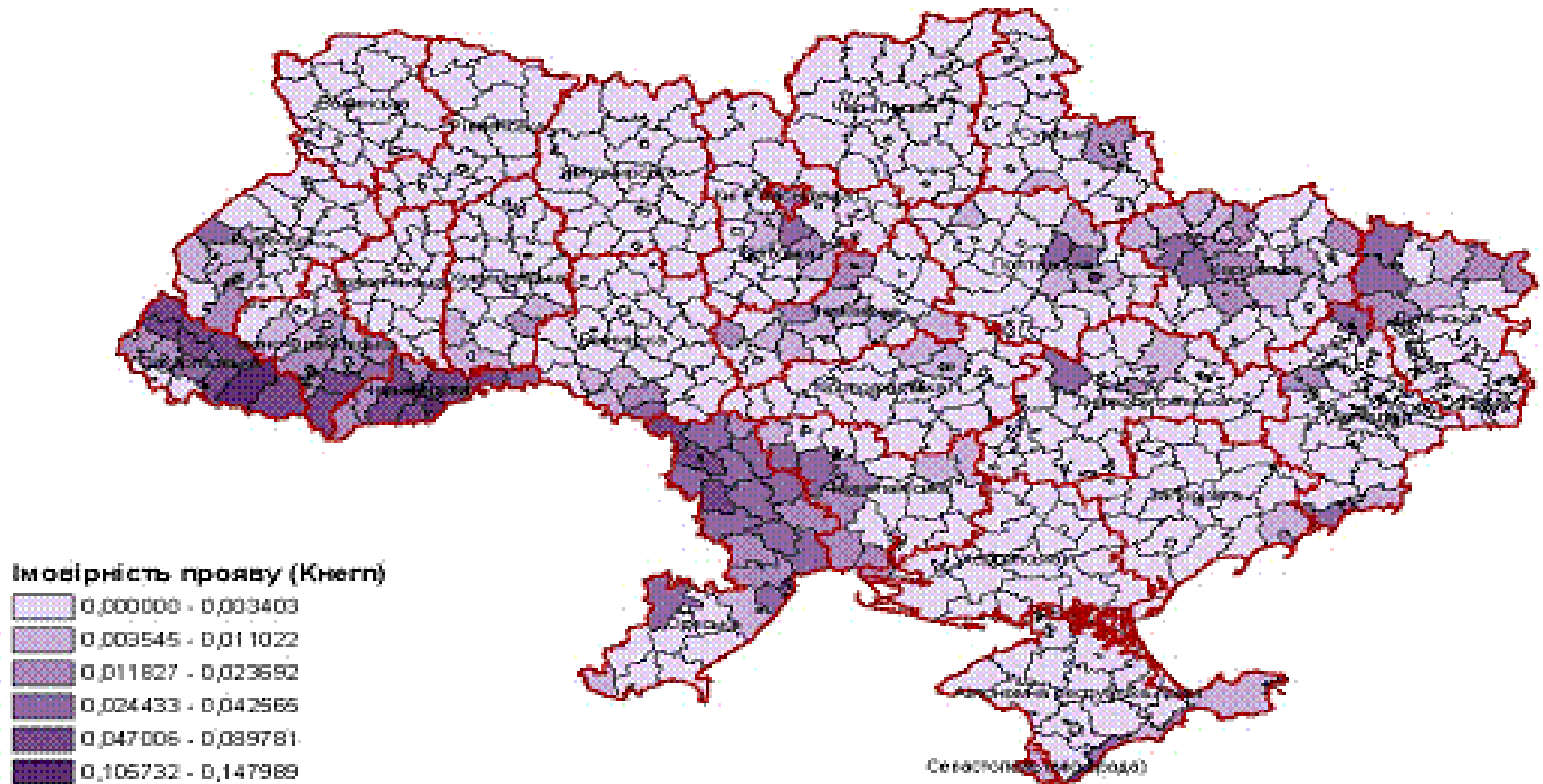


Fig. 18 Map-diagram of the probability of occurrence of landslides in Ukraine

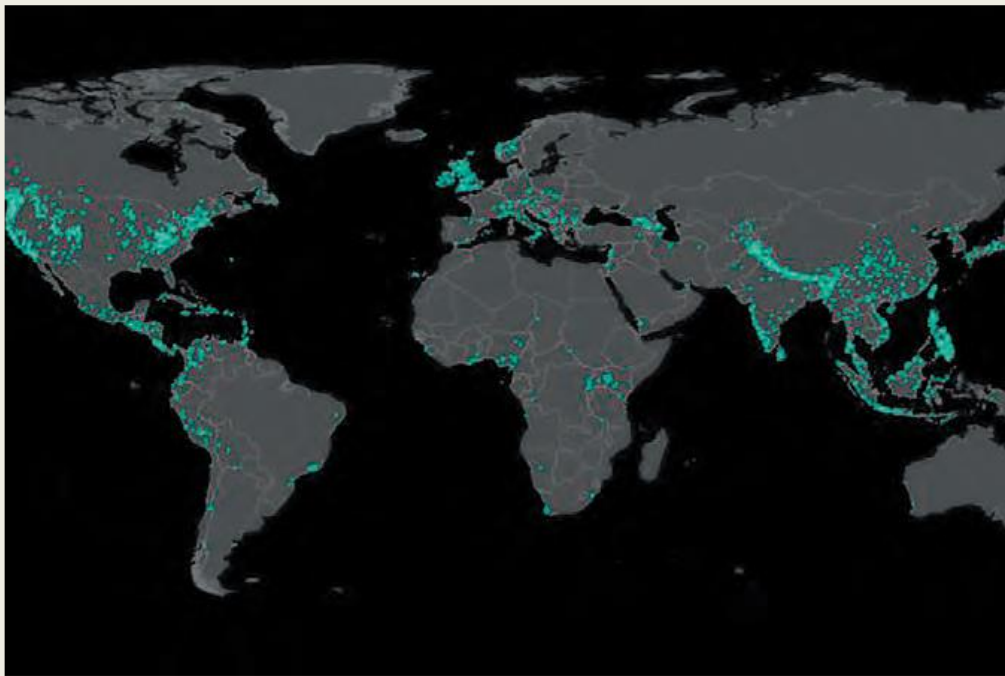


Fig.19. Using the Global Landslide Catalog, a map has been produced to show the location of 5741 rainfall-triggered landslides from 2007 till 2013



Fig. 20. 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

a



b



Fig. 21 a, b Landslides on the Black Sea coast, Illichivsk

Fig. 22. Landslide massifs in the region of Sevastopol, Crimea

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. 23).
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. 24 a).
3. Small landslide ledges or large terraces in the sliding massif (Fig. 24 b).
4. The surface of the slope is tuberous – the number of hillocks and their height increase towards the bottom of the slope due to the pressure of the sliding material.

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. 25).

6. An important sign of landslide movements is the so-called “drunken forest” – trees tilted in different directions (Fig. 26 a), as well as torn, twisted, saber-like tree trunks (Fig. 26 b), which are formed from for 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. 27 a, b).



Fig. 23 Cracks in the upper part of the landslide in Kupyansk, Kharkiv region

Fig. 24 a – landslide amphitheatre, b – landslide ledges

a



b





Fig. 25 Landslide Terraces, Groundwater Outcrops



Fig. 26. Vegetation on a landslide slope: a – “drunken forest” – trees are tilted at different angles; b – saber-shaped curvature of tree trunks



Fig. 27 a, b – Stages of destruction of a residential building during the slow movement of a landslide

The main elements of the landslide

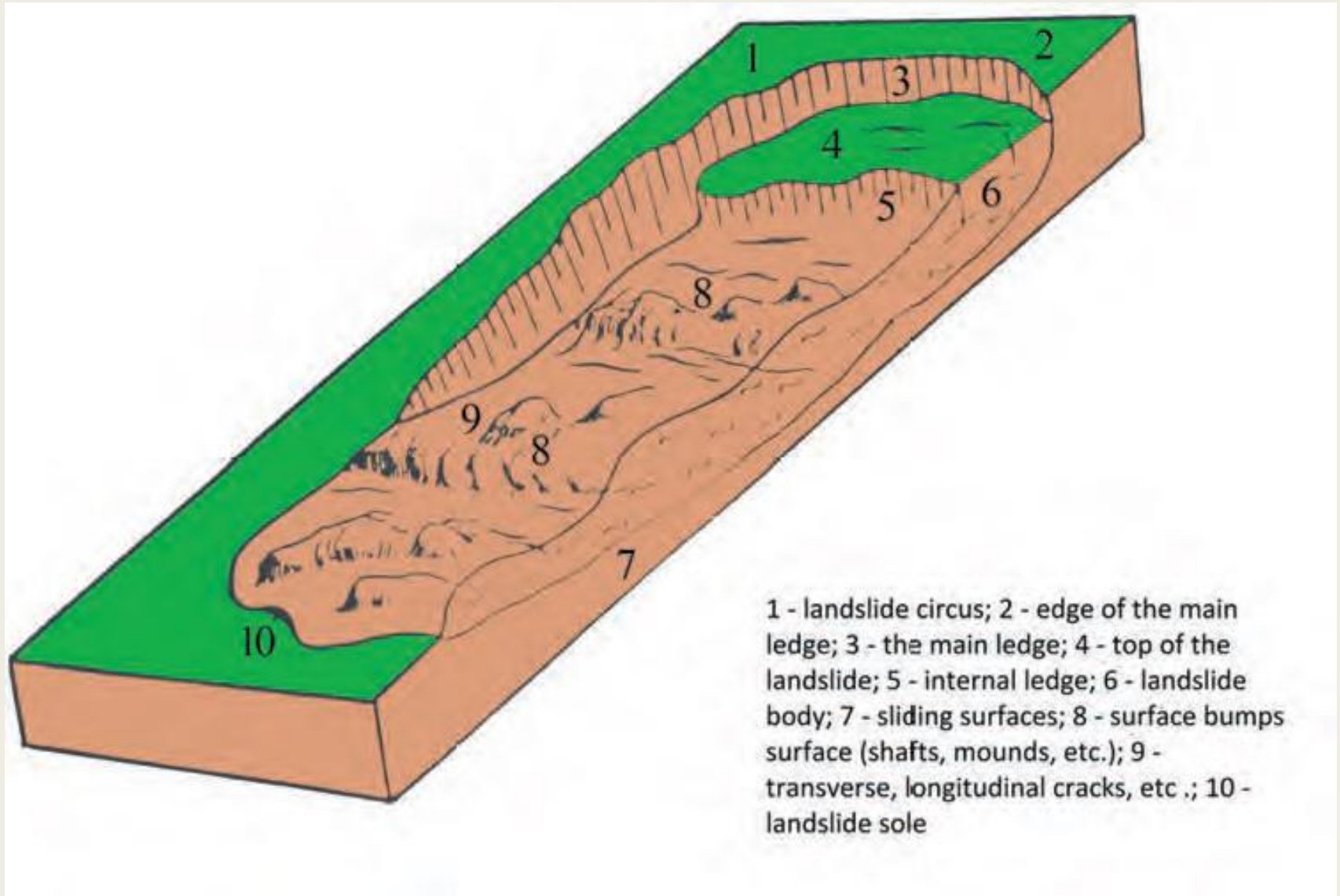


Fig. 28. Landslide Elements

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. 29. A huge landslide (sliding type) descended in Afghanistan to the village of Khobo Barik on May 5, 2014, causing about 300 deaths<http>

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.



Fig. 30. Modern landslide on an artificial dam, Kharkiv, Ukraine



Fig. 31. Ancient large landslide-stream, which filled the entire valley and is overgrown with forest, Colorado, USA

METHODS OF PROTECTION AGAINST LANDSLIDES

Landslide control includes passive and active measures.

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. 33).



Fig. 33 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

MUDFLOWS

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. 34). 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. 34. Mudflow



Fig. 35 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



a

Fig. 36 a – the road washed out by mudflow in the Carpathians; b, c – the consequences of mudflows

b



c



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 $\gamma = 1.1\text{--}1.5 \text{ t/m}^3$);
- • mud – a mixture of water and clay particles with occasional stones ($\gamma = 1.5\text{--}2 \text{ t/m}^3$);
- • mud-stone – a mixture of water, clay, sand, gravel, pebbles and cobbles ($\gamma = 2.1\text{--}2.5 \text{ t/m}^3$). In mountainous regions, the solid mass content predominates in the composition of mudflows.

MEASURES TO PROTECT AGAINST MUDFLOWS

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. 37).



Fig. 37. Gabion Type
Mudguard Dam



Fig. 38 Anti-mudflow dam in the
Medeo tract, Kazakhstan

AVALANCHE

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. 39. Descent of an avalanche, Alps

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. 40 a);

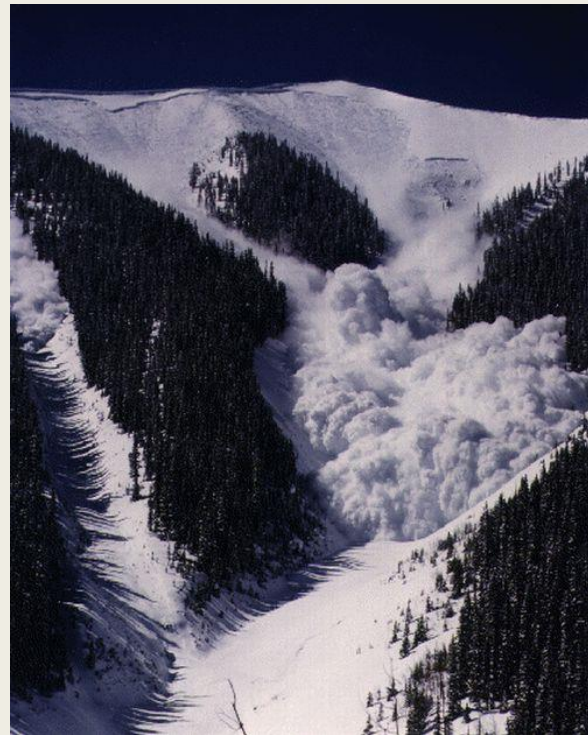
“Channel avalanches” – moving along ravines, channels and rivers; after the descent of such avalanches, a large drift cone is formed at their toe (Fig. 40 b).

“Jumping avalanches” – arising high in the mountains, and then freely falling down from the mountain ledges, sometimes directly into the underlying valley (Fig. 40 c).

a



b



c



Fig. 40 a – snow slide; b – channel avalanche; c – jumping avalanche

a



b



c



d



Fig. 41. Consequences of avalanches: a – international climbers camp at the foot of Everest; b, c, d – snow-covered buildings and cars

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 $\alpha = 15\text{--}22^\circ$; firn $\alpha = 30\text{--}55^\circ$ 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. 42).



Fig. 42. Skier on an avalanche slope

Types of anti-avalanche measures and facilities (DBN B.1.1-24: 2009)

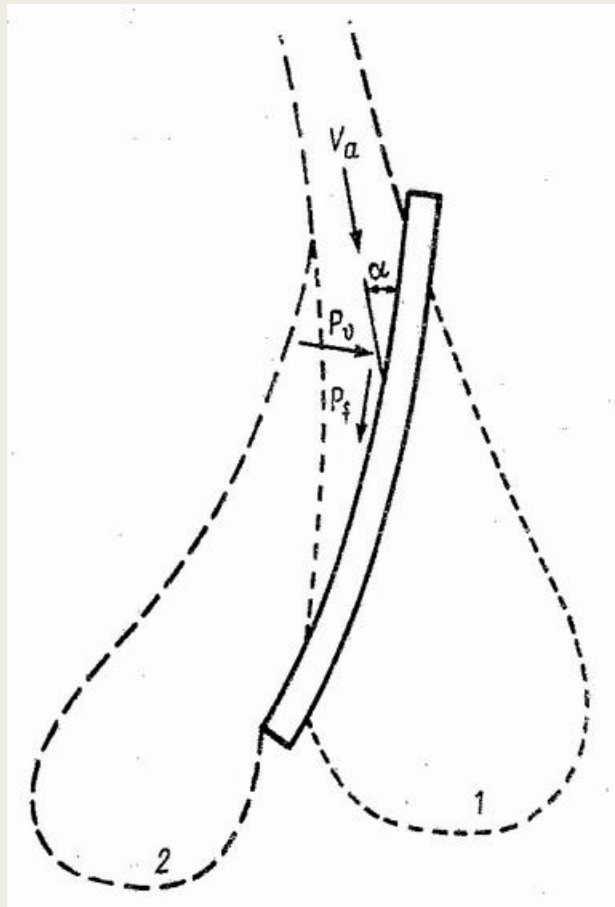
Types of events and facilities	Purpose of structures and events, conditions for their use
<i>I. Preventive:</i> Organization of a monitoring, forecast and alert service. Artificially adjustable avalanche discharge	The forecast avalanches. Termination of work and access of people to avalanche-hazardous 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



Fig. 43. Snow retention nets



Fig. 44. Anti-avalanche gallery



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. 45. Scheme of the guide wall: 1 – avalanche in the absence of a wall; 2 – allotted avalanchehttp



Fig. 46. The main part of the Gazex Exploder 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