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ORIGINAL PAPER

Landslide investigations in Russia and the former USSR

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Abstract Landslide hazard has always been a focus of research of scientific and industrial organizations in Russia, as well as the former Soviet Union . This research included a broad spectrum of studies of landslide processes based on monitoring data collected at specialized stations nationwide, as well as the data collected and analyzed by various government and academic research institutions. The current study summarizes a vast body of knowledge encompassing an inventory of landslide cases, overview of mechanisms of landslide development and monitoring and slope stability assessments. It presents a new mechanism-based landslide classification and proposes a practical method of increasing slope resistance. Partial findings have been previously presented in numerous publications. We believe these findings have a worldwide significance and can be applied in different regions of our planet.

Keywords Landslides · Russian landslide researchers · Landslide mechanisms · Landslide classifications

1 Introduction

First scientific publications dealing with landslide problem in Russia go back to the nineteenth century. However, major damage caused by large landslides has been historically documented even earlier. Landsliding caused significant destruction of historical structures. For example, catastrophic development of a deep landslide in the slope of Volga

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River in 1597 resulted in a destruction of Voznesensky–Pechersky monastery. This event was registered in the Chronicles. The signs of slope instability, such as deformations of a timber roadway, took place a week before the main landslide movement, with the subsequent development of cracks over 1 km in length in the “mountain” that housed subterranean monastic caves, and destruction of the buildings of the monastery.

Landslides research peaked after 1917. Theoretical and applied methods of slope stability assessment, as well as evaluations of efficiency of protective measures, have been a constant focus of specialized conferences, symposia and workshops on landslides, Landslide Committees of the Academy of Sciences and the USSR State Division of Buildings. The importance of landslide hazard was emphasized at these events, and steps were taken to increase landslide research to prevent negative consequences of their occurrence.

It is noteworthy that over 725 Russian cities are affected by landslides. Among them are such major cities as Moscow, Nizhny Novgorod, Kazan, Ulyanovsk, Volgograd, Cheboksary, Saratov, Saransk, Perm, Sochi, Rostov-on-Don, Tomsk and Barnaul. Known landslides that involved deformations of lower Cretaceous clays (i.e., observed depths of slip surfaces in excess of 100 m) occurred in Saratov on the slope of Sokolova Mountain in 1783, 1818, 1846, 1869, 1884, 1913, 1915, 1927, 1967, 1968, 1986 and caused destructive deformations of the city area and bulging of Volga riverbed. The volume of sliding mass was estimated as about 10 million m^3 (Tihvinsky 1988).

Significant contributions to landslide research were made at Moscow State University (by G.S. Zolotarev, V.S. Fedorenko, K.A. Gulakyan and others), Odessa State University (by L.B. Rozovskiy, I.P. Zelinskiy, V.M. Voskoboinikov and others), Armenia Academy of Sciences, Yerevan (by G.I. Ter-Stepanyan, A.P. Arakelyan and others), VSEGINGEO, Moscow (by E.P. Emelyanova, A.I. Sheko, V.V. Kuntsel and others), GIDROINGEO, Tashkent (R.A. Niyazov, G.L. Krukovsky, V.D. Minchenko and others), Institute of Mineral Resources, Simferopol (V.N. Salomatin, V.I. Kuznetsov and others), ISC SB RAS, Irkutsk (Y.B. Trzcinsky, N.I. Demjanovich, V.K. Laperdin and others), MGRI, Moscow (N.V. Kolomensky, G.K. Bondarik, I.S. Komarov and others), MIIT, Moscow (G.K. Shahunyanc, T.G. Yakovleva and others), DIIT, Dnepropetrovsk (M.G. Goldshtein, A.J. Turovskaya, S.S. Babitskaya and others), MGI, Moscow (A.M. Galperin, M.A. Revazov and others), MADI, Moscow (N.N. Maslov, Z.M. Karaulova and others), NIIOSP, Moscow (A.S. Stroganov, A.S. Snarsky and others), PNIIIS, Moscow (R.S. Ziangirov, I.O. Tikhvinskii, N.L. Sheshenya etc.), SOYUZDORNII, Moscow (V.D. Kazarnovskiy, E.M. Dobrov, Y.M. Lvovich and others), HYDROPROJECT, Moscow (E.G. Gaziev, Y.K. Zaretsky, L.A. Molokov and others), GIGHS, Moscow (M.E. Pevzner and others), VNIMI, St. Petersburg (G.L. Fisenko, E.L. Galustyan, A.M. Mochalov and others), LGI, Saint-Petersburg (V.D. Lomtadze, V.A. Mironenko, R.E. Dashko and others), KubSAU, Krasnodar (K.Sh. Shadunts, S.I. Matsiy and others), IEG RAS, Moscow (V.I. Osipov, G.P. Postoev, A.I. Kazeev).

Extensive research across different regions of the country was conducted at so-called landslide stations maintained by the industrial branches of governmental Department of Geology, which were tasked with landslide hazard assessments, monitoring and raising awareness of local and regional authorities about possible landslides in the area.

Overall, there have been fundamental studies of landslide hazard, including numerous field investigations, development of theoretical basis and methodology leading to a better understanding of the landsliding processes, mechanisms, risk assessments, modeling and development of preventative measures.

This article presents only some results of these studies which deal with main aspects of the landslide hazard that might have a worldwide significance, specially landslide mechanics and categorization based on mechanism of their formation, monitoring of their development and evaluations of stability of landslide massifs.

2 Landslide mechanics and mechanisms of development. Definitions

Landslide researchers have always been concerned with understanding of physical and mechanical causes leading to formation and development of the landslides. In Russia, major contributions to understanding the nature of landslide processes were made by I.V. Mushketov, A.P. Pavlov, A.V. Pavlov, N.F. Pogrebov, F.P. Savarenskii, I.S. Rogozin, N.Y. Denisov, A.M. Drannikov, G.M. Shahunyanc, N.N. Maslov, M.N. Goldshtein, E.P. Emelyanova, N.A. Ignatovich, K.A. Gulakyan, A.M. Demin, G.S. Zolotarev, I.P. Zelinsky, I.B. Korzhenevsky, V.V. Kuntsel, V.D. Lomtadze, P.N. Naumenko, R.A. Niyazov, N.F. Petrov, M.K. Rzaev, Z.G. Ter-Martirosyan, I.O. Tikhvinskiy, A.Y. Turovskaya, V.S. Fedorenko, G.L. Fisenko, K.S. Shadunts and many others.

Landsliding is a process of changes in stress–strain state of a slope ground mass leading to a mass separation and ground movement downslope, while maintaining a continuous contact between sliding mass and underlying undisturbed ground. This definition is similar to that given by Emelyanova (1972), Petrov (1987), Ter-Martirosyan (1986) and other authors. In accordance with this definition, the *mechanism* of a landslide is a systemic sequence of changes in stress–strain state of a slope groundmass under the influence of natural and anthropogenic factors. These factors lead to the formation and development of a landslide.

The formation of a landslide or other slope process is the result of a failure in the slope ground mass and loss of slope stability. The loss of soil strength and failure are preceded by a significant deformation. The initial stress–strain state of soil before the failure is determined by distribution of stresses in soil (gravity loading, pore water pressure, seismic forces, etc.). External forces may lead to the additional soil deformation that range from increased compactness of soil structural elements due to change of volume to a movement of soil mass caused by shear or mass wasting (Pevzner 1992).

Soil mechanics consider such mechanisms of soil deformation as compression, shear, tension and deformation of saturated soils (Goldstein 1979; Dalmatov 1988; Malyshev 1980; Osipov et al. 1999; Ter-Martirosyan 1986; Tsytovich and Ter-Martirosyan 1981, etc.).

At a present time, it is considered that one of the key objective of a landslide investigation is an identification of landsliding mechanism. However, the definition of the mechanism of a landslide process given by different researches often differs. This may be partly due to the complexity of the landslide processes and a great variety of geological conditions that may lead to landsliding. Based on the definition above, the mechanism of the landslide process involves the following:

- initiation stage (i.e., “preparatory stage” according to E.P. Emelyanova or a “phase of deep creep” according to G.I. Ter-Stepanyan) that involves physical separation of a sliding masses under the influence of gravitational volumetric forces, pore water pressure, seismic forces and factors associated with human activity;
- the development (i.e., mostly “displacement”) of a landslide after the separation under the influence of natural and anthropogenic factors.

Ter-Stepanyan (1978) emphasizes that key elements of the mechanism are stress, strain and time. Considering that a state of stress in the slope mass is realistically difficult to evaluate, G.I. Ter-Stepanyan recommends to focus on the kinematics of the process as the basis of understanding the mechanism, i.e., a relative movement of separate elements that constitute the landslide (Ter-Stepanyan 1978).

The majority of researchers reach the same conclusions, and as a result, majority of the landslide classifications are based on the mechanism of the landslide processes (Landslides 1984; Zolotarev 1983; Kuntsel 1980; Maslov 1977; Petrov 1987; Demin 1981; Fisenko 1965; Lomtadze 1977; Osipov et al. 1999; Postoev 2010, 2013; Tihvinsky 1988). Furthermore, the mechanism of landslide movement is the basis for the classification in the guidance document proposed for design and construction of buildings in landslide areas.

3 Mechanism-based landslide classification

There is a great number of landslide classifications, based on certain characteristics: landsliding mechanism (i.e., the process); planar shape; magnitude of an area or volume; landslide age; depth of a sliding plane; occurrence within a certain geologic formation, etc. Mechanism-based classifications are the most common (Petrov 1987; Fisenko 1965; Demin 1981, 2009, etc.). However, it is the mechanism of movement of a landslide mass (subsidence, uplift, sliding, rotation, translation or flow) that is the most frequently considered, neglecting the mechanism of landslide formation (preparation, losing stability of a soil mass and a separation of a landslide body). This often makes it difficult to correctly recognize a landslide type, because different landslide types may have a similar mechanism of *movement* in the intermediate stage of their development, i.e., movement of a landslide body along the slip surface.

For example, landslide classification based on a landslide mode of movement proposed by Cruden and Varnes (1996) is quite popular. But we think that the mechanism of landslide formation (i.e., all factors, processes leading to physical movement or slide) is more important, than the mechanism of displacement of the already separated part of the ground mass.

Accordingly, when classifying landslides, it is considered reasonable to take into account driving and resisting forces and a mode of deformation of the ground mass during initial (preparatory) stage of the landslide process, which would to a great degree determining the mechanism of formation and development of a landslide. Therefore, based on mechanism of formation, landslides may fall into three main categories (Postoev 2010, 2013):

- deep-seated compression–extrusion type;
- shear-sliding type;
- liquefaction-flow type.

The first category encompasses *relatively deep-seated block landslides of compression–extrusion* (Fig. 1). The loss of massif's stability and its progressive deformation take place in accordance with the compression scheme. The horizon with soil strength σ_{str} below compressive stress caused by the weight of overlying strata undergoes deformation, which leads to first subsidence and depression in the overlying mass upslope, then increase in tensile stresses in a zone of subsidence, then formation and downward propagation of a tension crack. Finally, a landslide block separates at this crack and moves down along a

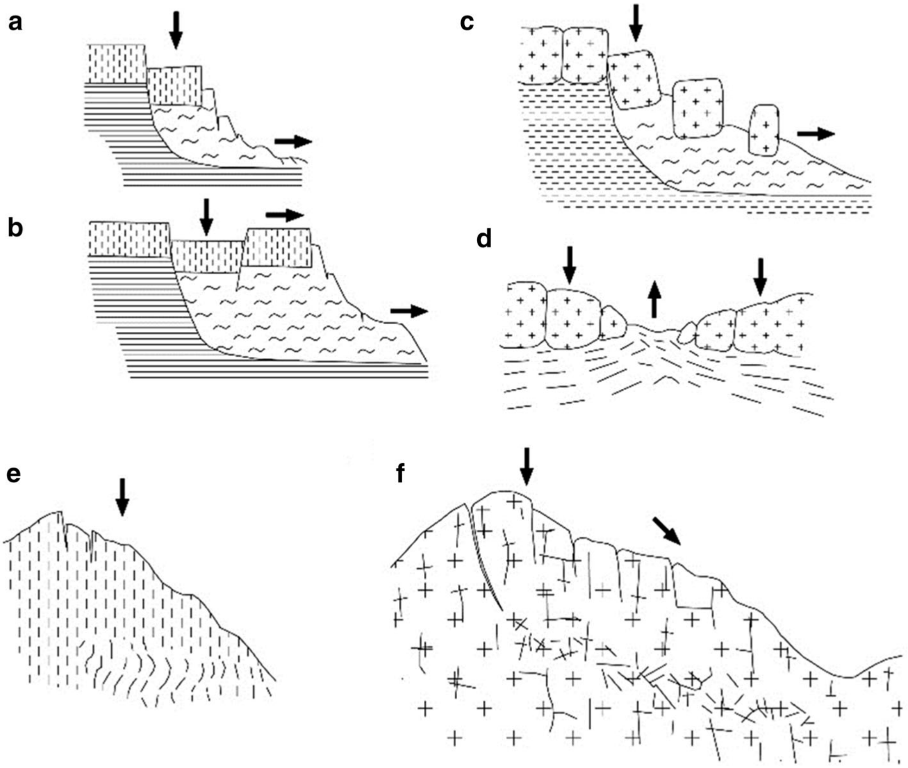

Fig. 1 Schemes of a landslide deformation with compression–extrusion mechanism: **a**, **b**—the compression landslide in cohesive soils; **c**—the subsidence and the spread of landslide blocks in rocks; **d**—bulging of the valley bottom; **e**—gravitational folds: deep creep with the S-shaped deformation of layers; **f**—gravitational deformation of ridges

steep curved slip surface. The angle of the slip surface flattens downslope and may become nearly horizontal. The displacement of a new sliding block triggers a displacement of the previously separated blocks located further downslope.

The block-type landslides of compression–extrusion mechanism are the most widespread. Their slip surfaces are typically formed in clayey soils. They occur in coastal, river and lake bluffs and may develop in slopes of excavations, embankments and in pit walls. Landslides in fractured, and/or weathered rock are less known. They occur in mountainous and foothill regions. They are characterized by slow development of deformations during the initial developmental stage that may take place for several hundreds of years.

However, very often this stage of the new block formation (with deformation of the mass based on the compression scheme) is not analyzed during investigation of a landslide mechanism. The subsidence of the new block along a steep curved slip surface is mistakenly thought of as a shear process, and a landslide is considered to have a shear-sliding mechanism.

Formation of the long front of these landslide blocks and, moreover, of landslide cirques is an important feature in recognition of this landslide type. As rule, the relief is stepped, reflective of a blocky structure of a landslide mass. This stepped geomorphology may be barely recognized in the relief at the end of the landslide cycle, at which point, as a result of prolonged repeated displacements, the upper blocks, as well as the blocks further downslope, reach the lowest position on the slope and form nearly horizontal landslide terrace.

The appearance of long continuous cracks is a feature of active displacement of landslide blocks. Crown cracks usually occur at the top of the slope on the contact of the landslide with undisturbed ground mass, and also on the boundaries between landslide blocks. Cracks are also formed along the compressive bulges along the front of the blocks, as well as downslope at the toe. A scar wall of the cirque is steep, curved and has a maximum height in the central part of the cirque. The slip surface formed during the separation of a landslide block from the original mass is steep, curved and has nearly circular profile. It flattens out downslope and meets the nearly horizontal slip surface of previously displaced landslide blocks constituting the landslide body in the existing landslide cirque.

Landslide blocks of the compression–extrusion type can be formed practically in any type of soil or rock, if the following condition takes place in the ground mass:

$$\sigma_{\text{str}} < \gamma h, \tag{1}$$

σ_{str}—material strength of a layer in consideration; γ—unit weight of overburden material; h—depth of potentially deformable layer.

Displacement of a landslide body is caused by the pressure of the upslope blocks; therefore, a compressional bulge or ridge is formed at the toe. This geomorphic feature is especially prominent during the main displacement stage, when a new landslide block separates from the plateau. In coastal areas when the sliding surface extends into the submerged part of the slope this bulge often resembles an island. These characteristical bulges often occurs in front of each landslide block that comprises the landslide body.

The second category of the *shear-sliding landslides* is characterized by a concentration of shear stresses in certain zones of a soil mass during initial stage of landslide formation and may occur when the slope is in quasi-equilibrium at a natural angle of repose, or due to a surface creep of weathered near-surface slope sediments (shallow landslides). The movement is per infinite slope model, or a shear along a zone of weakness determined by geological structure, such as a contact of weathered soil and bedrock, or a weak layer between strong layers.

Slope deformation occurs as a progressive shear with a decrease in soil resistance with deformation, a reduction in soil strength from peak to residual strength and a gradual formation of a slip surface. On steep slopes, landsliding typically occurs along a curvilinear slip surface that extends into a toe of the slope or stops above it (Fig. 2a). Thus, a profile of equal-strength or equal-stability slope is being formed due to mass wasting (i.e., the displacement or fall) of weakened soil mass.

The slip surface may form along dipping boundaries of geological layers. This may involve significant geological strata (in accordance with Fig. 2b). The mechanism of displacement along polygonal subhorizontal slip surfaces is characteristical of sliding of eluvial-diluvial deposits over the bedrock (Fig. 2c). A frequent landslide case involves vegetated soil cover and is manifested by series of relatively small cracks (see Fig. 2d). A slow creep of a near–surface soils can be observed on relatively stable slopes with steeply dipping bedrock (see Fig. 2e).

As was discussed above, the landslides in this category are caused by the shear force acting along an inclined boundary, i.e., slip surface. They may have a well-defined landslide body and cirque, or a zone of slow soil creep extent which is difficult to define, or occur as a flow. They may be characterized by a hilly relief, or less often a stepped relief,

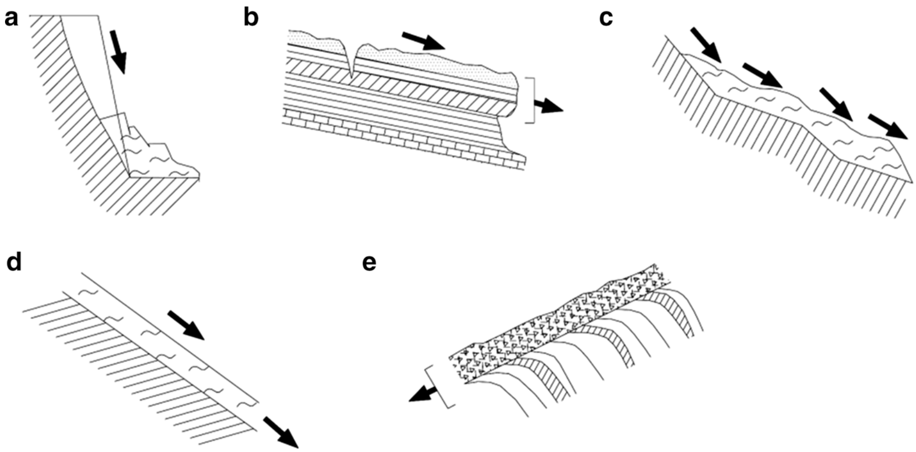

Fig. 2 Schemes of landslide deformation due to the *shear-sliding* mechanism: **a**—shear–cutting; **b**—shearing along layers; **c**—shear-sliding of shallow surface cover; **d**—shear of vegetated soil layer; **e**—bending of tops of steeply dipping layers

documented in cases of the landslide body 10 m thick or more. Landslide cracks are typically discontinuous, crescent-shaped, not extensive and may be better defined along the side borders. The scar wall (or headwall) often has a gentle slope and exposed subhorizontal slicken-sided bedrock surface.

Both the landslide surface and the slip surface are typically inclined. They may be curvilinear in case of steep slopes. Slided soil mass may form a bulge or ridge at the landslide toe.

The third landslide category represents *liquefaction-flow landslides*. A loss of slope stability is caused by liquefaction and predominant force is groundwater. Soil liquefaction is a result of the increase in pore water pressure and thus a decrease in effective stress. The pore water in saturated or partially saturated soils exerts pressure on the mineral skeleton of soil in form of hydrostatic and filtration pressures caused by filtration volumetric forces. The magnitude and direction of these forces depend on the external factors, such as static and dynamic loads on the slope, filtration flow rate and changes in the groundwater level, the water level fluctuations in reservoirs and surface streams and rainfall intensity.

This mechanism of landslide formation is especially typical for fine-grained soils with a weak structural skeleton and low filtration capacity, such as recently deposited silts, young water-saturated clays and loams, fine-grained water-saturated sands, topsoil, peat and clays of different ages that have reduced strength due to weathering disintegration and hydration.

Where groundwater exits onto ground surface of the slope, a landslide cirque with an hourglass shape and a narrow «neck» is usually formed (Fig. 3a). Liquefied soil masses (the product of destruction of the headwall and its sides) move from the «neck» to the slope in the form of a viscoplastic flow with formation of cones of deposition at the toe. Elevated groundwater levels due to heavy rains and abundant snowmelt and, as a result, upward seepage force, can reduce internal friction in the soil to zero. The soil softening at low loads induced by surface layers may result in loss of cohesion between soil particles. In this case liquefaction of sandy and clayey soil may occur even at low slope gradients (1:10 or

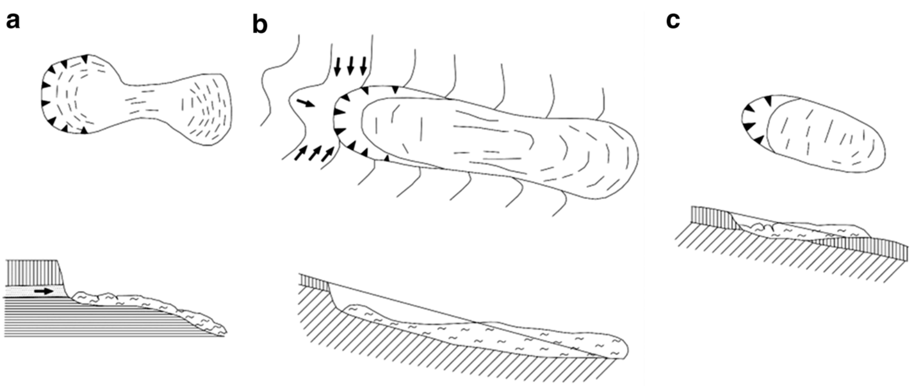

Fig. 3 Schemes of landslide deformation in accordance with liquefaction mechanism (plan and cross section): **a**—landslide cirque with a narrow neck formed at groundwater exit site; **b**—landslide-flow (earthflow); **c**—local flow

less) (see Fig. 3b). Local slope instability often occurs in areas of excessive moisture, resulting in soil deformation in the form of local flows (see Fig. 3c).

This type of landslide is often recognizable by the following indicative signs of the groundwater action: springs, low-relief depressions, temporary and permanent water courses, erosion undercuts, as well as numerous cracks, low hilly relief, etc.

4 The limit state of a ground mass during the formation of a landslide

Reliable determination of the limit state of slope groundmass and landslide hazard assessment are essential during site exploration and development, as well as design safety of the adjacent buildings and structures. The landslide processes include: (1) the landslide initiation stage, (2) general downslope movement of the landslide body and (3) distinctive phases of this movement during the landslide cycle, including the most important phase of catastrophic activization, when additional groundmass becomes separated from stable ground and joins with previously formed landslide body. Landslide movement becomes progressive and destructive during this phase (Gulakyan et al. 1977; Emelyanova 1972; Maslov 1977; Osipov et al. 1999; Landslides 1984; Tihvinsky 1988).

Institute of Environmental Geosciences of Russian Academy of Sciences (IEG RAS) has developed the criteria for limit state of the soil mass, and the methodology of the limit-state calculations (Postoev 2013). These numerical solutions received three patents in the Russian Federation: No. 2340729 (V.I. Osipov, G.P. Postoev), No. 2412305 (G.P. Postoev, A.I. Kazeev), No. 2413056 (G.P. Postoev, A.I. Kazeev).

For the 2D case, considering landslide–prone slope mass with landslide deformation on *i*th horizon (Postoev 2013) and assuming long, i.e., semi-infinite, slope with a curvature of slip plane approaching zero, utilizing the Mohr–Coulomb theory (for localized zone in a ground mass), the equation for limit state was developed as:

$$\gamma_i Z_{ai} - \sigma_{\mathrm{str},i} = \frac{\pi}{2}\gamma_i Z_{p,\mathrm{cr}} \tag{2}$$

γ_{i}—average unit weight of soils above the *i*th horizon in a landslide–prone undisturbed mass (Fig. 4); Z_{ai}—the depth of the *i*th horizon in the undisturbed mass, $\sigma_{1a} = \gamma_{\mathrm{i}} Z_a$; $\sigma_{\mathrm{str},i}$—

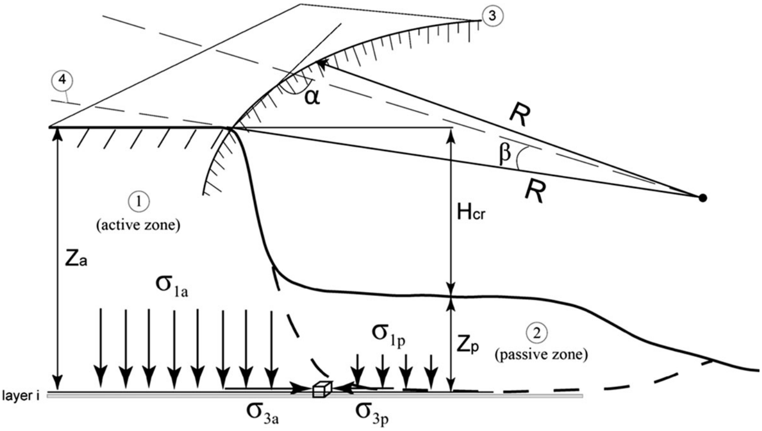

Fig. 4 Scheme for assessment for the stress–strain state of the soil at depth Z_a: *1*—mass in consideration (active zone); *2*—landslide mass deposited downslope (passive zone); *3*—edge of cirque headwall; *4*—central axis of the cirque; α—the angle between the front of active horizontal stress σ_{3a} (extent of the general outline of the cliff) and the direction to the considered section in the cirque; β—the angle between cross section in consideration and central vertical section in the cirque; *R*—radius of the cirque

the soil structural strength of the *i*th horizon of the undisturbed mass; $Z_{p,\mathrm{cr}}$—critical (calculated) depth to the *i*th horizon of potential deformation with soil gravity loading considered as $\sigma_{1pi} = \gamma_i Z_{pi}$; a and p indexes indicate active and passive horizontal earth pressures at the *i*th horizon.

The results of the theoretical calculations were calibrated against a large number of real events where limit state of landslide-prone soil masses and subsequent developments of massive landslide blocks were documented (Fig. 5).

Considering the radius of the cirque *R* the limit state of the mass may be described by the following equation (Postoev 2013):

$$\gamma \cdot Z_a - \sigma_{\mathrm{str}} = \frac{\pi}{2}\gamma Z_{p\mathrm{cr}} \frac{1 + \frac{1}{R}}{1 - \frac{1}{R}}, \tag{3}$$

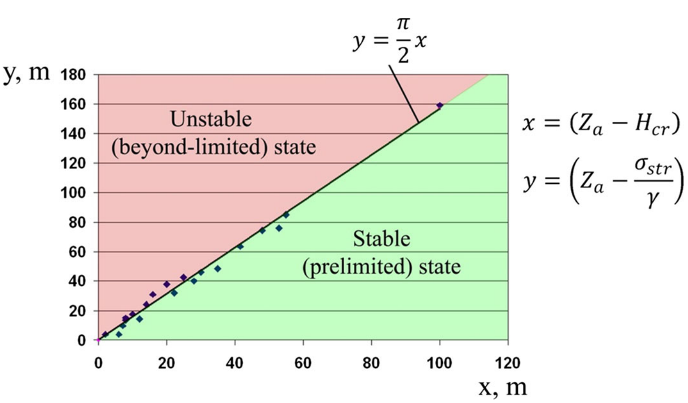

Fig. 5 Depth to the sliding surface versus thickness of the landslide body for documented landslide cases, where limit state was reached prior to catastrophic failure with the development of deep-seated block landslides of compression–extrusion type (Postoev 2013). Refer to Fig. 4 for definitions

where $1/R$ is numerically equal to the curvature of the curved edge of active headwall cliff (1 and R in meters).

In general form, equation of the limit state for potentially deformable horizon at the depth Z_a is as follows:

$$\sigma_{1a} - \sigma_{\mathrm{str}} = \frac{\alpha}{1 - \cos\alpha}\sigma_{1p}\frac{1 + \frac{1}{R}}{(1 - \frac{1}{R})} \tag{4}$$

or

$$\sigma_{1a} - \sigma_{\mathrm{str}} = \frac{\frac{\pi}{2} - \beta}{1 - \sin\beta}\sigma_{1p}\frac{1 + \frac{1}{R}}{1 - \frac{1}{R}}, \tag{5}$$

where $\beta = \pi/2 - \alpha$; α—the angle between the front of active horizontal stress σ_{3a} (extent of the general outline of the cliff) and the direction to the considered section in the ledge; B—the angle between considered cross section in the ledge and central vertical section in the cirque.

The general Eqs. (4) and (5) define limit state in considered zone of landslide–prone soil mass, where the principle vertical stresses in active zone σ_{1a} in undisturbed soil mass exceeds the soil structural strength σ_{str} (for existing R principle vertical stresses in passive zone σ_{1p}.

The coefficient of stability, or factor of safety of the cliff (K_{st}), may be used to characterize how close is the slope to reaching the critical state:

$$K_{\mathrm{st}} = \frac{\sigma_{1p_i,f}}{\sigma_{1p,\mathrm{cr}}} \tag{6}$$

where $\sigma_{1pi,f}$—observed vertical pressure of the landslide mass; $\sigma_{1p,\mathrm{cr}}$—critical (minimal) vertical pressure of the landslide mass on the slope.

Thus, the equilibrium of horizontal stresses in the soil landslide-prone mass at depth Z_a at $\sigma_{1a} > \sigma_{\mathrm{str}}$ is completely determined by the magnitude of horizontal stress σ_{3p} (resistance), which, in turn, is determined by the gravity load of slope deposits. When σ_{3p} reaches its critical value $\sigma_{3p,\mathrm{cr}}$ the soil is in limit state. The decrease in resisting pressure ($\sigma_{3pi} < \sigma_{3p,\mathrm{cr}}$) may cause development of vertical soil deformation and lateral spreading, and possibly formation of a sliding surface.

It should be noted that a concept of a limit state that precedes landslide deformations as discussed above may be valid not only for landslides of compression–extrusion type, but often for other types of landslides with similar mechanism of loss of slope stability and subsequent sliding or flow of the landslide mass.

Based on the above-presented methodology for limit-state analysis, a new practical method to increase slope resistance has been developed. It involves construction of artificial cuts similar to erosional downcuts of natural gully or ravine (patent for invention RF No 2413056, authors: Postoev G.P., Kazeev A.I.). These cuts break long continuous sloped fronts of cliffs or escarpments that have high potential for landslide hazard (Fig. 6).

The proposed method would result in a decrease in active earth pressure and a reduction in driving force in accordance with the equation of equilibrium (3), an increased resisting force at the base of the slope, improved drainage at the cut sidewalls and reduction in hydrostatic and hydrodynamic pressures. It should be noted that this leads to a general change of seepage path in cut sidewalls from original downslope direction (which results in increased hydrodynamic and static pressures in saturated landslide-prone zones) to a direction toward a thalweg of the artificial gully. Thus, stability of sidewalls, and the

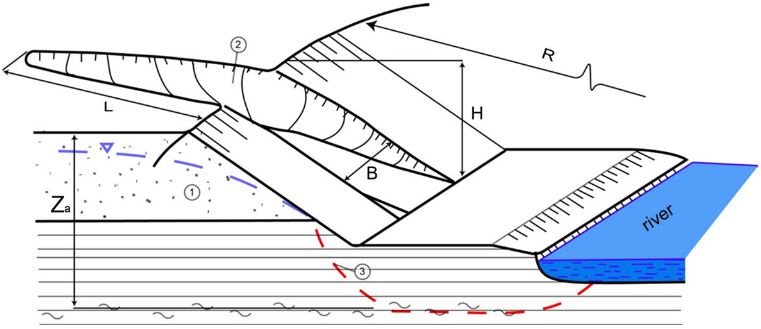

Fig. 6 Artificial "gully" cuts in a landslide-prone mass. *1*—landslide-prone ground mass; *2*—artificial local "gully" cut; *3*—slip surface; H—height of a scarp wall; L and B—length and width of a "gully" cut; R—radius of the scarp wall; Z_a—depth to potentially deformable horizon

overall slope stability is increased. This effect is not considered in the calculations, but it is believed that the actual slope stability may be higher than the calculated values. Therefore, limit state of the potentially landslide-prone slope with long continuous edge is altered by introducing artificial local "gully" cuts and creating local stable zones.

At each such site the calculated resistance is increased 1.5 times, as compared to an initial state of unmodified long slope that has a linear crown edge. The method is very effective in preventing huge massive landslides of compression–extrusion type, because the division of the ground mass into several discrete smaller bodies leads to elimination of one of the necessary conditions of their formation, i.e., a presence of the continuous slope front.

5 Peculiarities in the development of deep-seated landslides of the compression–extrusion type

The following characteristic features in the development of landslides of this type were observed (Fig. 7):

1. *The degree of activity and frequency of displacements of a landslide in a cirque is directly correlated with a high position of landslide blocks adjacent to the upper boundary (or scarp) on a slope* (Fig. 7a). As was shown above, the displacement of the landslide body is caused by block failure and stress increase in the remainder of the mass in the cirque. The magnitude of displacement depends on the size of sliding blocks, soil parameters and other influencing factors. On high slopes in hard bedrock this process can continue for many centuries. This is an important characteristic of deep displacements that needs to be taken into account when planning for construction in areas of known (or suspected) landslide hazard and adjacent water bodies, even when no visual deformations are apparent on the slope. This process leads to retreat of scarp wall and growth of landslide cirque.
2. *Translational and rotational movement of landslide blocks* is a specific feature of landslides of this type. It is caused to a great degree by the mechanism of formation of landslide blocks as a result of compression within the zone undergoing deformation, and soil squeeze into the slope, along with failure and rotation of the blocks (Fig. 7b). Based on the landslide research along Odessa coast of the Black Sea, Naumenko

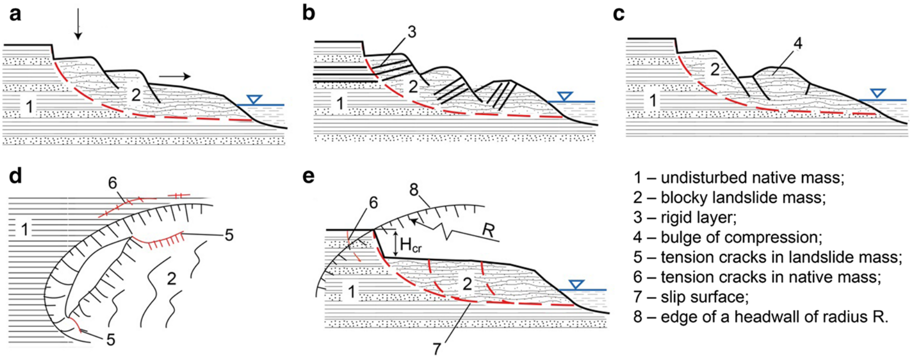

Fig. 7 Characteristic schemes of a landslide slope with deep-seated block-type landslide. **a** High position of the upper sliding block, regulating the displacement; **b** translation and rotary movements of blocks; **c** formation of a bulge of compression in a landslide body; **d** formation of a “cutting” failure at the bottom of a scarp wall and «main» (rear) failure in landslide native mass; **e** the limit state of the native mass at headwall, with preparation of a new landslide block

(1977) showed that the rotational movement of blocks occurs along nearly circular surfaces as they continue to move downslope. Inclination (i.e., angle of rotation) of a rigid marker layer (i.e., the 6–13-m-thick limestone layer of Pliocene, Pontik stage) increases with progressive translational movement of a landslide mass. Characteristical extrusional ridges form underneath the blocks, as soil mass continues to deform (Fig. 7b).

Therefore, it is necessary to take into account the complexity of movement of the blocks when considering building on any landslide-prone slope. Due to significant thickness and extent of landslide massif, significant continuous ground deformations need to be considered in structural design, as well as post-construction maintenance to provide building safety and functionality, which may be a difficult task.

3. *The formation of compressional ridge (bulge).* This element of relief can be found in landside local cirques, with landslide mass composed of a significant number of sliding blocks, which create a natural counterbanquet to any new block that has separated from a native ground mass (Fig. 7c). In this case, under pressure of a new block midpoint landslide compressional bulge may form in any part of a landslide slope (Postoev 2010). Landslide deformations below this bulge are insignificant.

   This peculiarity may influence the requirements for selecting the type and location of protective structures. The upper part of a slope may still have the potential for landslide development even after landsliding has occurred downslope. Moreover, a catastrophic activation of landslide deformations is possible, as will be shown below.
4. *The self-sustaining effect* is a specific feature of deep-seated block-type landslides. During its movement each new block pushes entire remainder of the landslide mass away from the surface of rupture and a scarp wall, leading to a development of a deep tension crack along its margins (Fig. 7d). This landslide crack undercuts a potential landslide ground mass, forming “heading” tension cracks in upper terrace which are tell-tales of the beginning of decrease in stability and initiation of a new landslide block.

This is a common occurrence for instance in landslide cirques that form long escarpments along coastal shorelines. Recorded instances of this phenomenon are repeated catastrophic activations in the same landslide amphitheater in Odessa. In 1964, a new block about 420 m in length formed along a coast. In 1965, the displacement of a new block with the length of 270 m occurred to the south of the 1964 location. The latter was attributed to the process of "self-development" and resulted in a significant magnitude of displacement (Naumenko 1977).

It is often believed that side erosion (abrasion) determines the intensity of the development of deep landslide movements. But the effect of "self-development" gives evidence that once the process of formation of landslide blocks and the development of landslide deformations has begun, it may continue even without influence of external factors, such as undercutting or removal of the downslope areas and the toe. Thus, consideration of the mechanism of self-development is necessary for designing of appropriate mitigation and protection measures.

The mechanism of a catastrophic activation. As was illustrated above, the development of landsliding processes, such as deep block-type movements dies out once a flat landslide terrace is formed (Fig. 7e), which represents the end of a landslide cycle. Near the axis of a landslide cirque, the height of a scarp wall reaches critical value H_{cr}. At this moment there are temporarily no deformations on a landslide slope. The landslide body is motionless, but the native massif is in a limit state. Transition from this temporary quasi-equilibrium to a catastrophic activation of a landslide process (with formation of new sliding blocks and destructive deformations involving entire landslide cirque) may occur as a gradual change in a strain–stress state of a landslide-prone mass, or as a sudden catastrophic event triggered by an external factor.

Thus, development of protective measures in areas with a potential for deep-seated block-type landsliding should include:

- timely characterization of landslide-prone native ground masses, which are at near limit state;
- analysis of a potential slip surfaces and lateral movements of blocks in a slope cross section;
- development of effective engineered controls to increase the stability of the sites approaching a limit state to prevent formation of new landslide blocks and development of destructive deformations.

6 The developmental features of shear-sliding type of landslides

The development of landslides formed by the shear-sliding mechanism is relatively well understood (Shahunyants 1953; Fisenko 1965; Goldstein et al. 1969; Emelyanova 1972; Demin 1981, 2009; Maslov 1977; Vyalov 1978; Ter-Stepanyan 1978; Tsytovich and Ter-Martirosyan 1981; Shadunts 1983; Tihvinsky 1988, etc.). Investigations of this type of landslides have shown that the translational movement of a landslide body usually occurs along a single main slip surface. This is consistent with geomechanical principles of the formation of shear zones and is confirmed by the instrumentation data (Postoev et al. 1982; Landslides 1984).

Formation and subsequent movement of the landslide mass is mainly by shear. The magnitude of deformations depends on the type of soil and can vary from a few millimeters for rocky soils to up to tens of centimeters for clays (Pevzner 1992). The mobilized shear resistance significantly changes in the process of the development of shear deformations due to changes in soil structure, fabric, deformations, particle reorientation, etc., on an interparticle level. The number of defects in interparticle contacts increases with the increase in magnitude of deformations. L. Bjerrum notes that “a macroscopic shear zone will develop once there developed a shear surface or network of shear surfaces of lowered resistance that make possible a progressive displacement” (General reports 1975).

As a shear deformation progresses, the shear stress increases until it reaches the peak value and then it decreases to residual value (Fig. 8a). The denser the clayey soil and the greater is its structural strength, the greater is the difference between the peak and the residual values. A.Y. Turovskaya (Goldstein et al. 1969; Turovskaya 1979) distinguishes four stages of the deformations (ε) of the clayey soil (see Fig. 8a). Phase I is a conventional equilibrium state of the soil. Phase II is characterized by a gradual development of plastic deformation and a mobilization of the internal forces of resistance, mainly due to the cohesion. The more important is the role of the coagulation bonds, the longer is the duration of Phase II. At the maximum shear resistance (S_p) there is still no discontinuity in the soil structure. Soil failure and a corresponding decrease in shear strength occur at the beginning of Phase III. The boundary between Phases II and III is called the critical state, and shear deformation at the moment of full mobilization of shear resistance is called the *critical deformation.*

The further development of the shear deformation leads to the soil reaching its residual strength, i.e., Phase IV. In this phase, the movement occurs along the shear surface and at nearly constant shear stress (S_e). It was established that under condition of moisture increase, a hydration layer may form, which will provide the least shear resistance. Turovskaya (1979) proposed to call this state a residual strength. It was established that different clays have the same residual strength (Fig. 9), regardless of their composition, age, origin, nature of the inter-particle bonds and initial strength (Goldstein et al. 1969; Turovskaya 1979):

$$S_e = 9 + 0,14\sigma \tag{7}$$

σ—normal stress.

In the process of the soil deformation under constant shear stress (shear creep) there may be distinguished three qualitatively different phases (see Fig. 8b). Phase I is characterized by a deformation damping (not established creep). Phase II refers to the steady-state creep, i.e., the deformation is constant. Both Phases I and II correspond to the deformation in the pre-limit condition (Vyalov 1978). Similarly to a regular shear, when

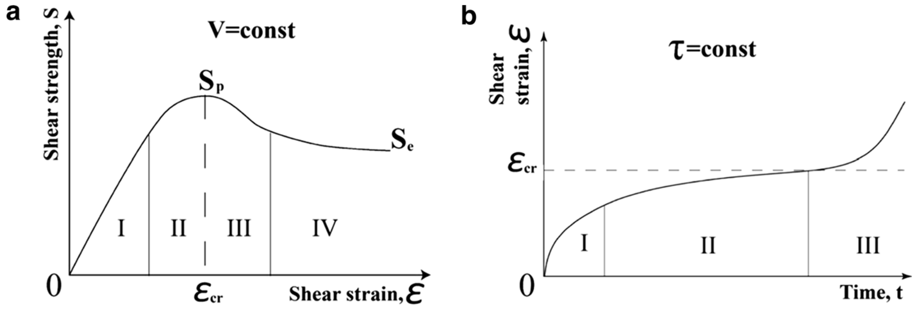

Fig. 8 Phases of shear deformation of soil (Turovskaya 1979). **a**—a short-time shear, **b**—a long-time shear (creep). S_p—peak shear strength; S_e—residual shear strength; τ—shear stress; ε_cr—critical shear strain: V—rate of shear deformation

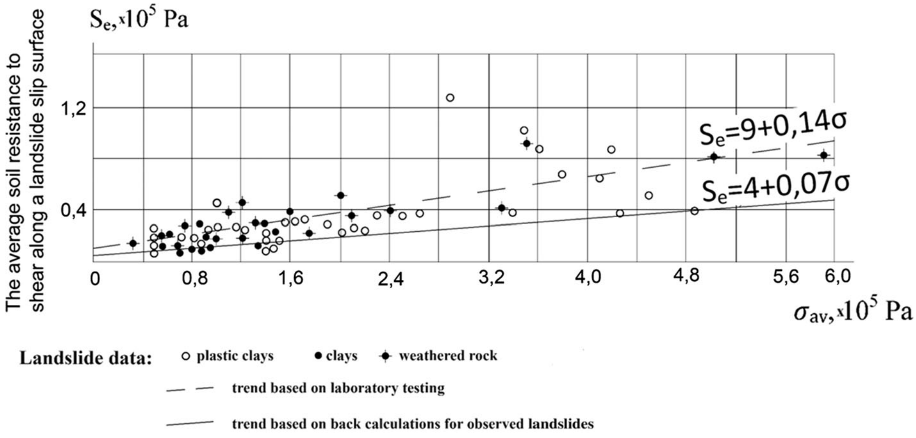

Fig. 9 Average shear resistance of clayey soils along landslide slip surfaces (Turovskaya 1979)

the critical state is reached, local sliding and soil failure are imminent. Phase III is a phase of progressive creep.

Analyzing the mechanism of shear creep deformations along the contacts between the soil particles in clays, L. Bjerrum noted that every contact point has a certain “lifetime.” If stresses are low, the “lifetime” is long—hundreds and thousands of years. If shear stresses are high, “lifetime” is short, only minutes or days. Therefore, the influence of the time on the mechanism of clay shear deformation comes down to a question of time required to achieve the critical shear strains to failure (Bjerrum in General reports 1975).

In Phases I and II of the deformation (Fig. 8), the initial strength of the soil stays constant. Only with beginning of Phase III and reaching the critical state, i.e., when structural bonds are broken and the particles in the shear zone are realigned, the strength of the soil drops to the residual value (Phase IV) (Turovskaya 1979).

According to G.I. Ter-Stepanyan (1976) and Vyalov (1978), the creep deformations in the pre-limit state are caused by shear forces and have possibly been developing for a long time. Their development may have an intermittent character. In rigid soils the period of the creep is much longer than in soft soils, and in bedrock it may last for millennia. Based on a study by Zhihovich (2007), in case of a long-term gradual change of stress state of a groundmass, such as typical for deep-seated landslide setting, there is no considerable change in stress–strain of soil mass, provided that shear stress does not exceed 80% of that at failure (Fig. 10).

Numerous experimental investigations (Demin 2009; Postoev et al. 1982; Osipov et al. 2015; Landslides 1984; Pevzner 1992, etc.) established the magnitude of a critical relative deformation (about 15%) when the creep process ends in shear failure and an abrupt increase in the rate of deformation. Shear failure is always preceded by a period of progressive creep.

The deformation in the shear zone can occur in the form of thrusting or creep without breaking the continuity, as well as in the form of a shear with creating a rupture surface. For instance, the former was observed in the Dzhizhikrutsky landslide (Gulakyan et al. 1970) with the thickness of the landslide body of 70 m, the length of 850 m and the width of 300–400 m. The contact between landslide body and bedrock (quartz–chlorite–sericite

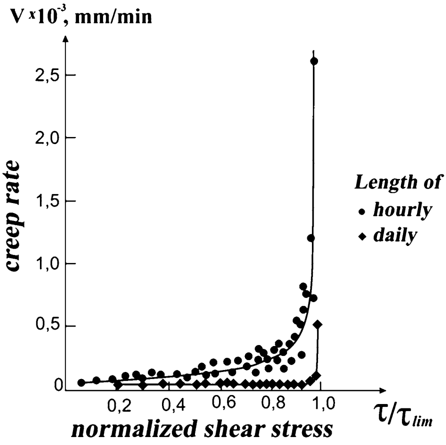

Fig. 10 Creep rate as a function of shear stress as measured in laboratory loading of clay samples with hourly and daily time steps (Zhihovich 2007). τ_{lim}—shear stress at failure

schist) consisted of a clay gouge layer only 5–20 cm thick, which was identified in all operational galleries of the mining company.

However, based on field studies, including artificial activation of a landslide of this type (Postoev et al. 1989), after the separation of a landslide body and repeated cycles of displacement, a slip surface is formed, along which the main landslide movement occurs during all subsequent stages of its development.

Kostomarov (1964) has proposed laboratory method of soil shear testing to be used for soil analysis that accounts for a slip surface in the mass. He proposed to use a new shear device "die on die" to perform the repeated shear on the prepared surface and then the third shear on the wetted surface. Such tests are routinely specified by the governing standards.

7 Features of development of liquefaction-flow type landslides

The formation of landslides as a result of soil liquefaction is particularly common for weak sandy-clayey, silts and organic soils. According to Abelev (1983), weak saturated clayey soils compose 11% of the total territory of the USSR. In addition, there is a significant part of slopes in various regions of the country underlain by clayey soils of various origin. This surface cover often consists of weak clayey soils formed as a result of disintegration, weathering and hydration. Investigating small local earthflows, Emelyanova (1982) noted that they can develop in any exposed formations and their appearance is often associated with water regime.

Special feature of the weak soils is that their natural structure is easily disturbed due to the additional changes in stress field; thus, they are often referred to as "structurally unstable." In undrained conditions an increase in shear stress causes a rapid increase in pore water pressure and soil liquefaction (General reports 1975; Goldstein 1979; Emelyanova 1972; Shadunts 1983). Soil liquefaction may be further aggravated by an increase in water pressure in the relief depressions and cause a separation of the landslide mass and its movement as an earthflow. Such landslides are observed on the banks of Volga River in the lower Cretaceous alluvial clay deposits (Volga region near Ulyanovsk).

In the loesses of Central Asia, the liquefied landslide masses not only reach, but also continue moving along riverbeds as mudflows for up to 7–8 km distance (Niyazov 1974).

It is known that under certain dynamic conditions, the water-saturated clayey and fine-grained soils may suddenly become liquefied and lose their structural strength (Osipov 1988, Osipov et al. 1999). During an earthquake, an excessive pore water pressure may develop in water-saturated sandy–clayey mass and lead to an upward flow of water from the underlying aquifers. Liquefaction of the subsurface layers particularly occurs when the less permeable upper layers are underlain by more permeable strata, leading to a formation of viscous flows of landslide masses even in the areas with low gradients (Osipov et al. 1999). Moreover, earthflows in the lower part of the slope may cause the undercutting and the change in the stress–strain state of the entire slope ground mass. Specifically the reduction in lateral stress leads to increased deformability of soils, especially in layers with structural strength below overburden pressure.

The subsidence of the soil mass that lies above the zone of deformation of the liquefied masses eventually leads to the formation of the front block-type landslides of compression–extrusion with a relatively deep deformation of the mass. There are known landslide cirques that start off with landslides of liquefaction-flow type forming bowl with a narrow neck. After reaching a certain size, they transform into block-type landslides of compression–extrusion. Such landslides occur for example along shoreline of Ovechka River near Cherkessk in the Caucasus, on the banks of the river Tom‘ near Tomsk, or on the banks of the Sura River (Postoev et al. 2015) transition of landsliding from liquefaction-flow to compression–extrusion mechanism may be characterized qualitatively.

8 Landslide monitoring

Monitoring of landslide process is an important part of any landslide investigation. The purpose of the monitoring is observation of landslide response to natural and anthropogenic factors as necessary for the assessment of a state of a landslide, predicting stability and development of its stabilization and building protection measures. Observations on natural landslide slopes have been performed by specialized industrial geological organizations for many years.

Notably, significant contributions to the development of the methodology and studies of mechanism and dynamics of landslides were made by Emelyanova (1956). With the advancement of the landslide science, the methods of observation and monitoring were furthered by work of VSEGINGEO (Kuntsel 1980; Postoev et al. 1982; Sheko et al. 1988; Landslides 1984). The analysis of the accumulated information on the development of landslides in the different regions of the country leads to a deeper understanding of the landslide processes and further advancement of methods of landslide hazard assessment, prediction and development of protective measures. Landslide monitoring is regularly presented in the reports of Russian scientists at numerous international forums (General reports 1975; Goldstein et al. 1969, etc.).

In recent years, there has been a shift toward the use of modern remote-control devices and automated systems of landslide monitoring (Postoev et al. 1982; Landslides 1984). The techniques of controlling the sidewall stability and deformation of open-mining pits are being continuously developed and improved (Pevzner 1992; Fisenko 1965). In order to ensure the safety of the transportation systems, the methodological guidelines are prepared and the monitoring of the state and deformations of the landslide slopes, as well as excavations, roadway cuts and railway embankments, is carried out (Ashpiz 2002).

Geotechnical investigations on the landslide slopes include the monitoring of a landslide development in accordance with the regulatory documents (Emelyanova 1956; Postoev et al. 1982; Sheko et al. 1988; Landslides 1984). The main goal of these field investigations is the assessment of a landslide hazard potential, slope stability and the prediction of possible landslide movements.

Review of monitoring data of landslide investigations has shown that periodic assessments of the slope stability-based solely on geophysical parameters are not sufficient to adequately characterize critical changes in the development of a landslide and the beginning of its dangerous activation phase. Likewise, the monitoring of landslide deformations only by displacement rates cannot always detect a dangerous condition. In some cases, the rate of displacement of 75 mm per day was observed during the period of a full-scale experiment on artificial activation of a landslide, but did not lead to a catastrophic development (Postoev et al. 1989). In other cases, the lower rates have led to the destructive displacements in the open pit walls (Osipov et al. 2015).

Institute of Environmental Geoscience of Russian Academy of Sciences performed numerous studies leading to a development of effective technologies of automated monitoring. It was established that the most important parameters for characterization of the state of an active landslide and its dynamics (including the phase of a progressive hazardous activation) are: the magnitude and the rate of a soil deformation and displacement, the depth of a slip surface and the areal distribution of active displacements on the monitored slope. Extensometer lines of control, remote wireless monitoring systems of displacement on the slope and inclinometer measurements in boreholes are considered to constitute minimal requirements for the system of automated monitoring, based on the conducted research (Osipov et al. 2015).

Influence of other factors, such as precipitation, changes of groundwater levels, anthropogenic and other factors is reflected in the deformational behavior of the landslide body and thus is also monitored using high-accuracy instrumentation.

For example, one of the most important transportation projects for the 2014 Winter Olympics in Sochi involved design and construction of a new transit corridor that connected Adler and Krasnaya Polyana and combined a highway with light rail. It passed along the valley of the river Mzymta, and landslide hazard potential had to be evaluated. Landslide slopes were heavily instrumented with primarily horizontal extensometers and inclinometers that provided the necessary monitoring data to develop landslide hazard criteria. Based on the rate of a displacement at the monitoring points (V), the following criteria and for landslide warning signals were developed and implemented: $V < 4$ mm/day—non-hazardous condition (green signal); $4 \leq V < 24$ mm/day—moderately hazardous condition (yellow signal); $V \geq 24$ mm/day—very hazardous condition (red signal) (Osipov et al. 2015).

9 Slope stability analysis

Quantitative characterization of static and dynamic factors that influence slope stability and landslide processes is required for reliable evaluations of landslide hazard and design of protective measures.

Slope stability analysis is typically required for any proposed development of slope and thus it is the most widespread among the methods of local forecasting of a landslide process. A great variety of methods of slope stability analysis has been developed (Tihvinsky 1988; Matsiy and Bezuglova 2010). The existing analytical models are applicable for a variety of types of landslides. They include assumptions, such as soil mechanics models, failure criteria, simple slope geometry or the shape of the slip surface and come with limitations of limit-state analytical methods being used. The most popular are 2D models.

The experience shows that the reliability of numeric analysis is not as much determined by use of "correct" soil and analytical models (though they matter), but to a greater degree by taking into account numerical simulation of the deformation mechanism of a landslide, and ground behavior, such as realistic modeling of the soil shear resistance along sliding surface. Also, the actual influence of various natural and human factors that cause the change in the water saturation of the slope, the mass balance and the soil properties on the stability of the existing slope needs to be correctly modeled (Kazeev et al. 2009).

The majority of Russian software for slope stability analysis includes calculation methods of K. Terzaghi–Fellenius, method of horizontal forces of Maslov-Berrer and methods of G.M. Shahunyants (Ginzburg 1986; Kazeev et al. 2009; Maslov 1977; Shahunyants 1953).

Often shallow landsliding by liquefaction-flow and shear-sliding mechanisms leads to a stress reduction at the toe of steep slopes. This factor is modeled by a removal of the downslope slices in a numerical simulation. The sequence of removal of vertical slices within a landslide body is also used as a basis of design decisions regarding construction sequence on the slope, such as excavations for various engineering structures.

In Russia, investigations of the stress–strain state of slope soil mass and the slope stability assessments are typically performed using finite element methods, limit-equilibrium numerical modeling, as well as old-fashioned pencil-and-paper engineering calculations methods. Both Russian software and international programs (such as Plaxis, Geostab, Slide, SlopeW.) are utilized.

10 Conclusions

Numerous research and industrial organizations conducted landslide investigations on the vast territory of the former Soviet Union (one-sixth of the world). Thousands of publications presented summaries of findings and/or focused on the certain important issues concerning the landslide distribution and development in different geological settings across the country. Russian scientists and investigators engaged in the landslide hazard evaluations made a great contribution to the development of state of knowledge regarding the landslide processes accumulated by the scientific community worldwide.

The landslide hazard assessment and effective prediction of possible landslide activation, coupled with the implementation of mitigative and protective measures, are impossible without characterization of a possible landslide based on the mechanism of its formation, as well as conditions and mechanics of the stress–strain state changes in the landslide mass prior to reaching their threshold limit values. Neither they are possible without taking into account the dynamics of the landslide processes and the criteria that mark transition of the landslide development into a catastrophic phase.

For the past several decades and into the present, the Russian scientists carried out a high-level research of landslides that included landslide classifications, specific issues in the landslide assessment and the development of the necessary protective measures, often achieving distinctive results, some of which are presented in this article.

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