SUSTAINABLE DEVELOPMENT OF TERRITORIES WITH DEEP-SEATED LANDSLIDES

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ABSTRACT

The identification of the landslide mechanism of preparation and development is the key to the sustainable development of landslide and landslide-prone urban and mining territories. The understanding of the mechanism of preparation of a landslide is necessary for landslide hazard and risk assessments.

The mechanism and regularities of the formation of deep block landslides are considered.

The equation for the calculation of a landslide slip surface depth was obtained, using slope morphological and soil strength parameters. This equation can be implemented for deep landslides, occurring in different engineering geological conditions, from soils (weak loams) to rocks (calcareous clays, limestone).

A scientific explanation of effective reinforcement of territories with deep block-type landslides is provided.

The suggested protection strategy for sustainable development of slope territories bases on theoretical solutions of preparing of a destructive phase of landslide deformations, on taking into account mechanism peculiarities of deep block-type landslides, and also on investigation experience of such landslides in different engineering-geological conditions. New protection technologies for territories with deep-seated landslides of compression-extrusion type are considered in the article.

Keywords: *landslide mechanisms, compression-extrusion landslides, calculation of a slip surface depth, reinforcement measures*

INTRODUCTION

Landslides annually cause huge economic, social and environmental impacts to all countries, and also Russia. A significant part of urban areas is susceptible to landslides with the possibility of their destructive occurrence. Landslides often occur suddenly and unexpectedly. Deep block-type landslides are extremely widespread, especially on plain territories (on coastal slopes, river banks). Particularly big troubles concerning deep landslides appear on urban territories.

From one hand, the slow development of deformations on landslide areas makes the illusion of relative stability of the considered territory with the possibility of its economic use. Especially it takes place in conditions of high dense city building and willingness to place important sport and other objects on picturesque sites. From the other hand, periodic destructive landslide activizations, affecting significant territories, sometimes make impossible to protect economical objects on slopes and native landscape.

The reinforcement of slopes on territories with deep block-type landslides is not easy because of the complexity of the mechanism of formation and activization of a landslide, large sizes of landslide cirques, and big depth of the slip surface. The assessment of the stress-strain state of a landslide mass which consists of displaced landslide blocks, and its correlation with a native mass situated above it represents a challenging task [13].

Over 700 cities in Russia are liable to landslide hazards (including deep-seated landslides). Among them are Moscow, Nizhniy Novgorod, Kazan, Ulyanovsk, Volgograd, Cheboksary, Saratov, Saransk, Perm, Sochi, Rostov-on-Don, Tomsk, Barnaul and others. Significant losses from destructive deep landslides annually take place all over the world, e.g. in Russia (in Moscow in 2006, 2009, in Ulyanovsk in 2016, Cheboksary in 2012), in Ukraine (Odessa region in 2017-2018).

Large deep landslides also occur in mining areas on the slopes of quarries and dumps, for example, in Russia (Kuzbass, 2015), Spain (Las Cruces mine, 2019), Brazil (Brumadinho tailings dam landslide, 2019), etc.

Russian experience of urbanization of landslide-prone areas it is practically impossible to reach total stabilization of slopes with deep landslides. The most usual measurements used for this purpose, are: reinforcement of the coastal line, drainage, making terraces on a slope, building counter banquets (embankments) downslope and more rarely – pile works. However activization of deformations and catastrophic movements of deep landslides periodically occur also on the strengthened slopes, providing a considerable damage to existing infrastructure. For example, landslides with deformation of lower Cretaceous clays (depth of slip surface more than 100 m) periodically occurred in Saratov (Russia) on the reinforced slopes of Sokolova Mountain, with destructive deformations of the city territory and with lifting and bulging of the river Volga bottom. The volume of displacing masses is about 10 million $м^3$ [15].

There are 15 major sites with the development of deep landslides in Moscow. An activization of landslides took place recently, in some cases directly connected with human engineering and economic activities. Protection measures that have been realized earlier as rule are not sufficiently effective. It is evidenced by the ongoing development of deformations on the slopes (in areas of Vorob'evy Hills, Phili-Kuntsevo, Kolomenskoye, Khoroshevo-2, Moskvorechye, etc.).

In 2006–2009 two catastrophic activizations of deep block landslides took place in Moscow on sites Khoroshevo and Moskvorechye. The destructive landslides occurred with the width of 220-330 m along the banks of the river Moscow. The cost of the designed protection at the site was more than 30 million $. There is a risk of activation of landslide process in other landslide areas.

Currently, a new large Ski Jump is being constructed of the on the slopes of Vorobevy Hills – in the largest landslide cirque in Moscow. The object is located on the landslide steps of a deep block type landslide, which is characterized by constant slow deep movements (up to 5 mm/year). It is absolutely obvious that the Ski jump would subsequently start to deform and its' protection would be needed.

Also at present time, a new escalator gallery is being designed, which is located on the same slope, connecting the metro station Vorobyovy Gory which is situated downslope with Kosygina street (situated upslope). And it is worth noting that the old escalator gallery served here less than 25 years (1959-1983) and was destroyed by slow landslide deformations on the slope. This shows that the risk of deformation and destruction of objects is being presented even without the formation and development of active landslide displacements on the slope.

Effective protective measurements and rational development of slope territories where the development of deep landslide movements is possible should be based on taking into account the peculiarities of the mechanism of block-type landslides forming and development. These aspects are considered in the given article.

LANDSLIDE MECHANISMS OF DEVELOPMENT

The number of different landslide classifications is great. As rule, they are based on certain characteristics, such as landsliding mechanism (i.e. the process); planar shape; the magnitude of an area or volume; landslide age; depth of a slip surface; occurrence within a certain geologic formation, the reason of activization, etc. Mechanism-based classifications are the most common [4], [6], [11]. For example, landslide classification based on a movement type of a landslide proposed by Cruden and Varnes [3] is quite popular. The mechanism of movement of a landslide mass is considered in this classification (sliding, rotation, translation, flow and etc.) depending on material type (rock, debris or earth). However, the mechanism of landslide formation (preparation, loss of stability of a soil mass and a separation of a landslide body) is being neglected in it. 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.

We consider 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 groundmass. Accordingly, when classifying landslides, it is considered reasonable to take into account driving and resisting forces and a mode of deformation of the groundmass during beginning (preparatory) stage of the landslide process, which would generally determine the mechanism of formation and development of a landslide. Therefore, based on the mechanism of formation, landslides may fall into three main categories [7]: 1) deep-seated compression-extrusion type; 2) shear–sliding type; 3) liquefaction–flow type.

Deep-seated block landslides of compression–extrusion type are considered in this research (Fig.1). This landslide type can be correlated in most cases with rotational slides, spreads and complex landslides from Varnes' classification [6].

The loss of a groundmass's stability and its progressive deformation takes place in accordance with the compression scheme. The horizon, characterized by soil strength σ_{str}, due to the compressive stress caused by the weight of overlying strata is being deformed. This leads to firstly subsidence in the overlying mass upslope, increase in tensile stresses in a zone of subsidence, and then to formation of a tension crack. Finally, a new landslide block separates in this upper part of the slope and displaces downwards along a 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 the displacement of the previously separated blocks located further downslope (which compose the landslide terrace).

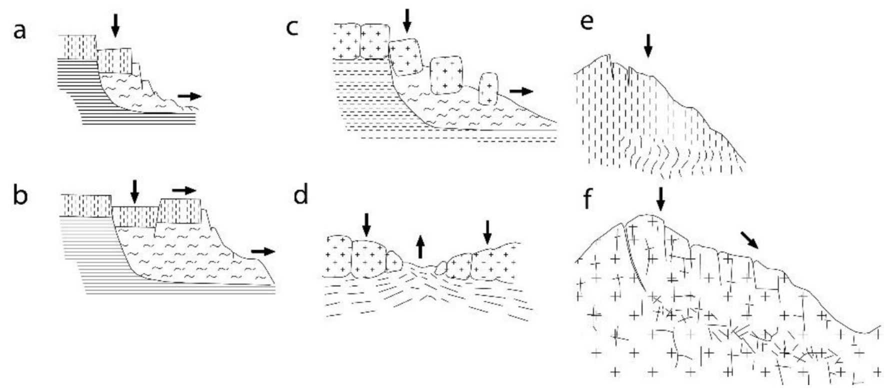

Fig. 1. Schemes of a landslide deformation with compression–extrusion mechanism: a, b – the compression landslide in cohesive soils; c – the subsidence and the spread of landslide blocks in rocks; d – bulging of the valley bottom; e – gravitational folds: deep creep with the S-shaped deformation of layers;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

The slip surfaces are formed typically in clayey soils. The landslides of considered type usually occur on coastal territories, river banks, and lake cliffs and may develop in slopes of excavations, embankments, and in quarry sides. Landslides in fractured, and/or weathered rocks 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 hundreds of years.

However, very often this stage of the new block formation (with deformation of the groundmass in accordance with the compression scheme) is not analysed 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.

The formation of a long front of landslide blocks and, moreover, the frontal character of landslide cirques is an important feature in recognition of considered landslide type. As rule, the relief is stepped, reflecting the blocky structure of a landslide mass. This stepped geomorphology is difficult to recognize at the end of the landslide cycle, when the landslide blocks reach the lowest position on the slope and form nearly horizontal landslide terrace.

The appearance of long continuous cracks is the feature of an active displacement of landslide blocks. Crown cracks usually occur at the top of the slope on the contact of the landslide with undisturbed native groundmass, and also on the boundaries between landslide blocks. Cracks are also usually formed along the compression 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 is being formed during the separation of a landslide block from the native groundmass. It is steep, curved, and has nearly circular profile. The slip surface 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 groundmass:

$$\sigma_{str} < \gamma h, \qquad (1)$$

where σ_{str} – material (soil or rock) strength of a layer in consideration; γ – unit weight of overburden material; h – depth of potentially deformable layer.

The displacement of a landslide body is caused by the pressure of the upslope blocks, therefore, a compressional bulge or ridge is usually formed in front of the youngest block. This geomorphic feature is especially visible 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. This characteristical bulge often occurs in front of each landslide block that composes the landslide body.

THE LIMIT-STATE OF A GROUNDMASS DURING THE FORMATION OF A NEW LANDSLIDE BLOCK

The reliable determination of a limit-state of slope groundmass and landslide hazard assessment are essential during site planning and designing of protection measures.

The landslide processes includes: 1) the preparatory stage, 2) the phase of catastrophic activization, when a new landslide block becomes separated from stable ground and joins with previously formed landslide body and 3) general continuous downslope displacement of the landslide body. The landslide displacement during the stage 2 is progressive and mostly destructive [8, 15].

The criteria for the limit-state of the soil mass assessment was developed [13], including the methodology of the limit-state calculations.

As it was mentioned above, the development of landsliding processes stops once a flat landslide terrace is formed on the slope, which represents the end of a landslide cycle. The height of a scarp wall reaches its critical value H_{cr} near the axis of a landslide cirque, (Fig. 2). At this moment there are temporarily no deformations on the landslide slope. The landslide body is motionless, but the native mass reaches the limit-state. The transition from this temporary quasi-equilibrium to a catastrophic activation of a landslide process (with formation of new landslide block and destructive deformations in 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.

For the 2D case, considering landslide-prone slope mass with landslide deformation on i-th horizon at depth Z_a, implementing the Mohr-Coulomb theory (for localized zone in a groundmass), the equation for limit-state assessment of a native groundmass (Fig. 2) was developed as:

$$Z_a - \frac{\sigma_{str}}{\gamma} = \frac{\pi}{2}(Z_a - H_{cr}) \tag{2}$$

where γ – average unit weight of soils above the deformable horizon in a native groundmass (Fig. 4); Z_a – the depth of the slip surface; σ_{str} – the soil structural strength of the deformable horizon, $\sigma_{str} = 2c \cdot tg(45 + \frac{\varphi}{2})$; H_{cr} – critical height of the above-landslide slope (the excess of the circus ledge over the middle part of the landslide terrace) in central part of the cirque.

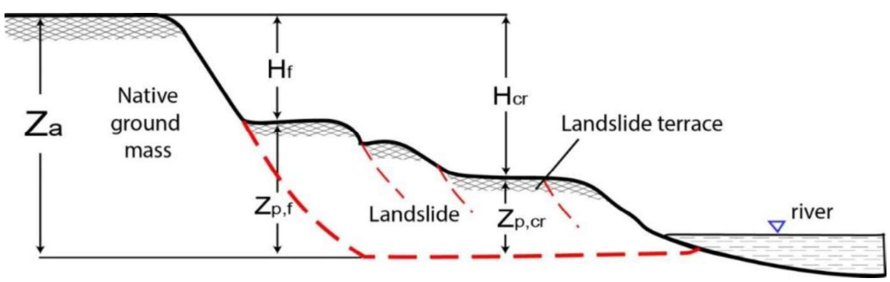

Fig. 2. The scheme for calculation of a slip surface depth (Z_a) in a central part of a landslide cirque [7]: H_{cr} – the height of a slope above landslide terrace; $Z_{p,cr}$ – thickness of a landslide under terrace; H_f – height of the above-landslide slope (above latest blocks); $Z_{p,f}$ – thickness of the youngest landslide block.

Thus, the developed method [12] allows to calculate and identify the depth of a slip surface, with the usage of the data from typical engineering geological surveys on landslide areas. This invention allows to calculate and define the slip surface depth in a landslide mass even on stage of absence of landslide displacements along slip surfaces (when the usage of e.g. inclinometers is not effective).

The block-type landslides of compression-extrusion mechanism are the most widespread and can be found in different engineering geological conditions. For example, typical deep landslides can be found in Russia (Moscow (Fig. 3), Nizhny Novgorod, Kazan, Ulyanovsk, Volgograd, Cheboksary, Saratov, Saransk, Sochi et.al.), Great Britain (Folkestone Warren) [1], [2], [14] (Fig. 4), Ukraine (Odessa (Fig. 5), Mariupol), etc.

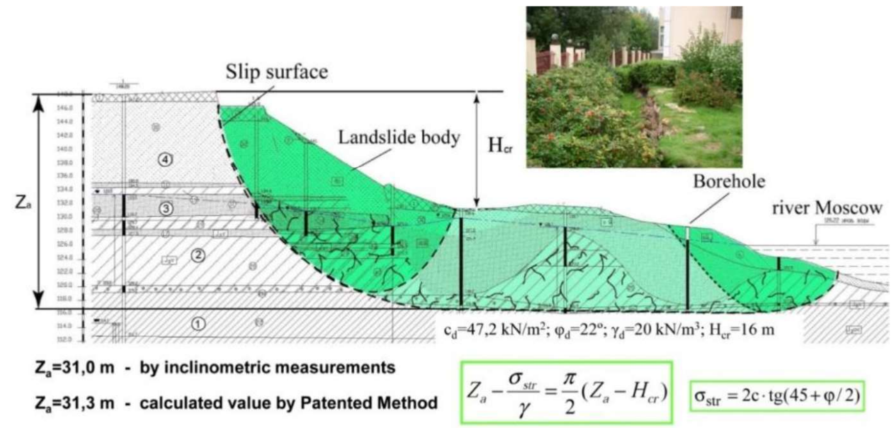

Fig. 3. A schematic cross-section of central part of a landslide cirque in Khoshevo, Moscow (Russia): 1 – clays J_3ox; 2 - clays J_3v; 3 – sands K_1; 4 – sands and loams Q_{IV}.

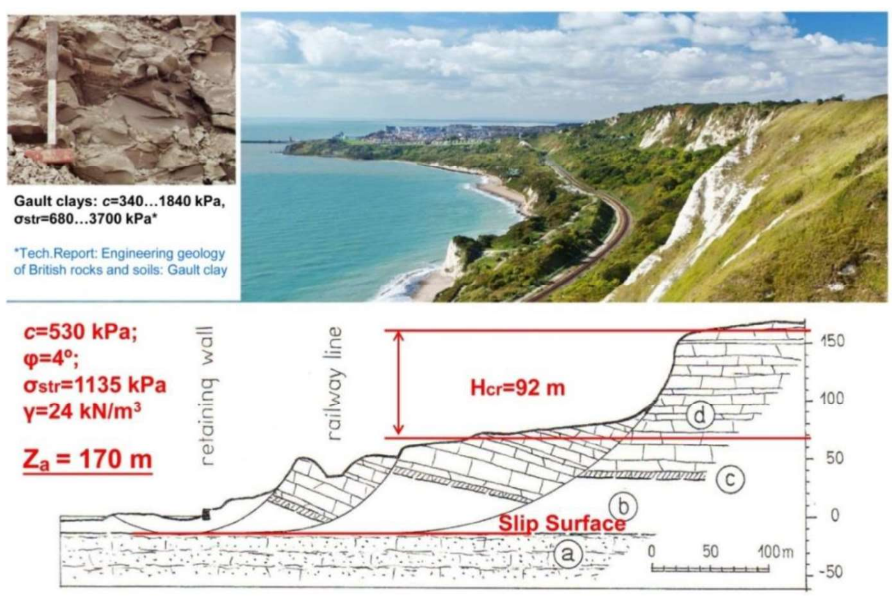

Fig. 4. The view of the landslide on the seashore near Folkstone (England), Gault clays (zone of a slip surface) and a schematic cross-section: a – glauconitic sandstones, b – Gault clays, c – glauconitic marls, d – sandy marlstone. [5, 16].

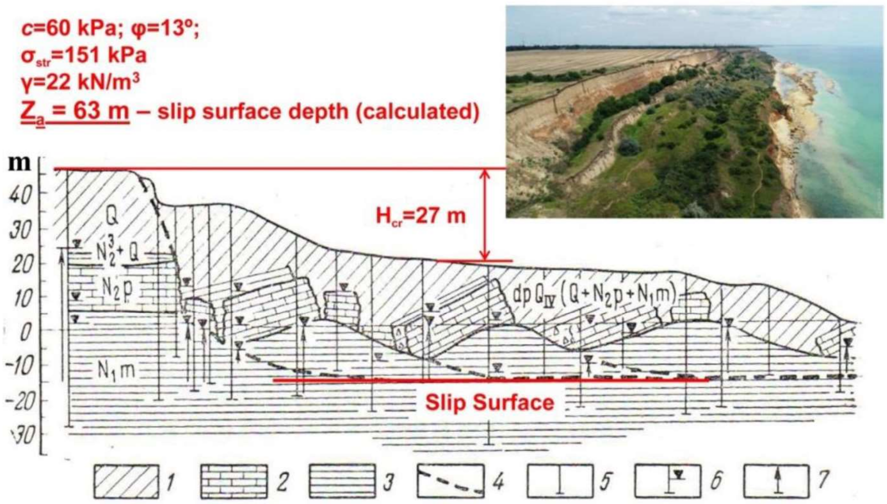

Fig. 5. A geological cross-section of a landslide in Odessa (Ukraine) [9]: 1 - loess-like loams, 2 - limestone, 3 – clays, 4 – slip surface (by inclinometers); 5 – boreholes, 6 – groundwater level, 7 - hydrostatic pressure.

THE PECULIARITIES OF DEEP-SEATED LANDSLIDES AND THE PROTECTION STRATEGY

The economic development of territories with deep-seated landslide of compression-extrusion type should take into account the peculiarities and characteristic features of development of landslides of the considered type.

1. The degree of activity and the velocity of displacements in a landslide cirque is correlated with a high position of landslide blocks adjacent to the scarp wall on a slope (Fig. 6, a). As it was shown above, the displacement of the whole landslide body in the cirque results from the pressure of the youngest block. The magnitude of displacement depends on the size of sliding blocks, soil parameters and other factors. On high slopes composed of strong rocks this process may continue for many centuries. This is an important characteristic of deep displacements that should be taken into account when planning the construction in areas of known (or suspected) landslide hazard, even when there is no visual deformations on the slope.

2. The lateral and rotational displacement of landslide blocks is a specific feature of compression-extrusion landslides. This peculiarity is explained by the mechanism of formation of landslide blocks as a result of compression within the zone of undergoing deformation, the soil squeeze towards the slope, with separation and rotation of the blocks (Fig. 6, b). Naumenko P.N. [9] has shown based on the results of landslide researches on the Odessa coastline of the Black Sea 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) was increasing with progressive translational movement of a landslide mass. Characteristical extrusional ridges form underneath the blocks, as soil mass continues to deform (Fig. 6, b). In some cases islands can be formed in the aquifer (Fig. 5).

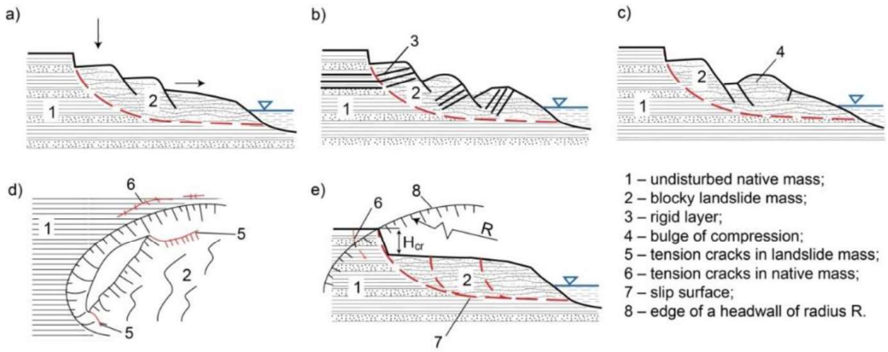

Fig. 6. Characteristic schemes of a landslide slope with deep-seated block-type landslide. A) high position of the upper sliding block, regulating the displacement; b) translation and rotary movements of blocks; c) formation of a bulge of compression in a landslide body; d) formation of a "cutting" failure 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.

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 landslides, the possibility of continuous deformations on slopes should be considered in design projects, as well as post-construction maintenance of buildings and infrastructure to provide sustainable existence and functionality of engineering objects that may be a difficult task.

3. The formation of compressional ridge (bulge). This element of relief can be found in landside cirques, where the landslide terrace is composed of a significant number of sliding blocks. In this case, a middle landslide compressional bulge may form in any part of a landslide slope resulted from the pressure of a new settling block (Fig. 6, c). Landslide deformations below this bulge are usually insignificant.

This peculiarity may influence the requirements for selecting the type and location of protective structures. The activity and the potential for landslide displacements is maximum in the upper part of the slope (in place of youngest landslide block).

4.4. The self-developing effect is a specific feature of deep-seated block-type landslides. Each new landslide block pushes the landslide masses away from the scar wall while displacing. This leads to the formation of a deep tensile crack along the side margins of a landslide body (Fig. 6, d). This cracks undercut adjacent landslide-prone groundmasses, forming "heading" tensile cracks on the plateau, which are the forerunners of the beginning of decrease of slope stability and the formation of new landslide blocks on adjacent sites. This is a common for instance in long landslide cirques along coastal lines. Instances of this phenomenon can be illustrated by catastrophic landslide activations in the same landslide amphitheater in Odessa in 1964 and 1965 [9].

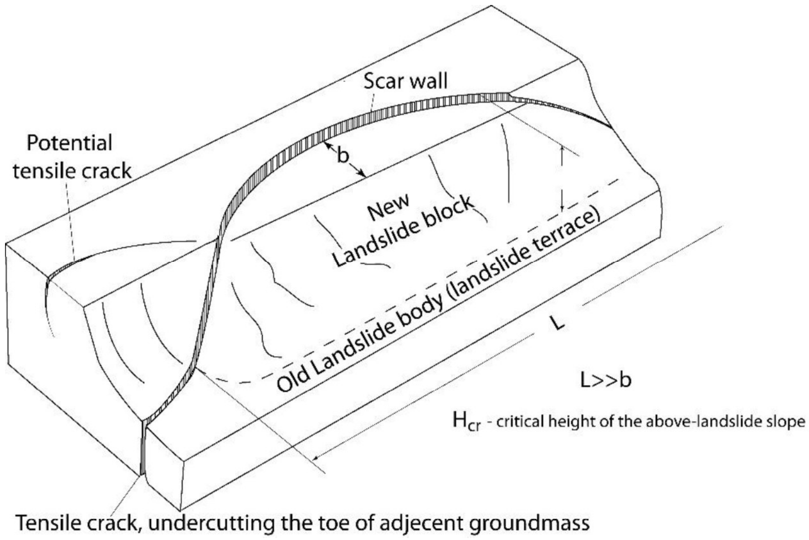

Fig. 7. The scheme of a "self-development" feature of deep-seated landslides.

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 landslide process has started, it may continue even without influence of external factors, such as undercutting or removal of the masses and the toe. Thus, the mechanism of self-development should be considered in designing of appropriate mitigation and protection measures.

5. The mechanism of catastrophic activations. As it was illustrated above, landslide displacements on the slope stops when a flat landslide terrace is formed in the middle part of the slope (Fig. 6, e), which represents the end of a landslide cycle. The height of a scarp wall reaches critical value H_{cr} in the axis of a landslide cirque. The landslide body is motionless, but the native groundmass reaches its limit-state. Thus, protective measures in areas with a potential for deep-seated block-type landsliding should include: 1) timely revealing of landslide-prone native groundmasses, which are close to limit-state condition; 2) the development of protection measures for slopes which are close to a limit-state, to prevent the formation of new landslide blocks and development of destructive deformations.

NEW PROTECTION MEASURES FOR TERRITORIES WITH DEAP-SEATED LANDSLIDES

Several new methods were elaborated to increase slope stability, based on the above-presented methodology for the limit-state analysis and taking into account the peculiarities of development of deep compression-extrusion landslides.

The first invention involves construction of artificial cuts similar to erosional downcuts (natural gully or ravine) that can be considered as a natural-like technology (patent for invention RF №2413056, authors: Postoev G.P., Kazeev A.I.). The main aim of these cuts is break long continuous front character of the slope or a scar wall that have high potential for landslide hazard (Fig. 8).

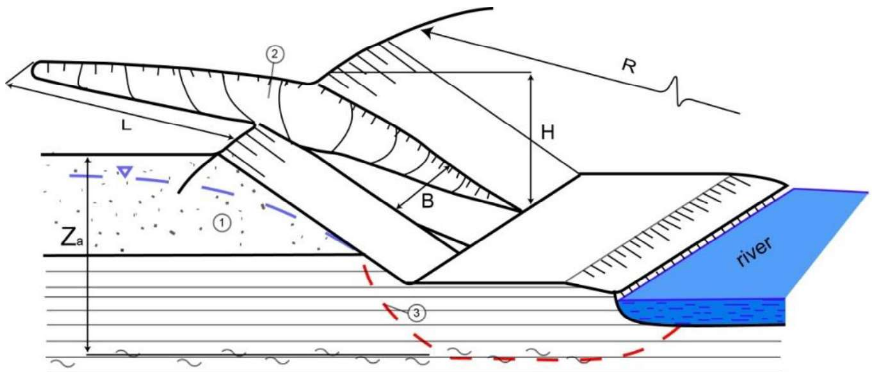

Fig. 8. Artificial "gully" cuts in a landslide-prone mass. 1 – landslide-prone groundmass; 2 – artificial local "gully" cut; 3 – slip surface; H – height of a scarp wall; L & B – length and width of a "gully" cut; R – radius of the scarp wall; Z_a – depth to potentially deformable horizon.

The proposed method would result in a decrease of active earth pressure and a reduction of driving force that defines the possibility of new landslide block formation. The drainage of the groundmass due to the cut becomes significantly improved, takes place the reduction of hydrostatic and hydrodynamic pressures. It should be noted that this leads to a general change of seepage paths in cut sidewalls from original downslope direction (before the cut, which results in increased hydrodynamic and static pressures in saturated landslide-prone zones) to the direction towards the thalweg of the artificial gully. Thus, stability of sidewalls, and the overall slope stability is increased.

This effect was 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 in **1.5 times**, as compared to the initial state of unmodified long slope that has a nearly linear crown-edge.

The method is very effective in preventing huge massive landslides of compression-extrusion type, because the division of the groundmass 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 (see Fig. 7).

Another possible way to stabilize a landslide-prone groundmass (1) effectively is to transform it into a useful stable object with a sub ground part (3), placed above the landslide (2) (Fig. 9.) [10]. It should be noticed, that a similar useful construction can be placed also in an artificial gully cut, shown on Fig. 8

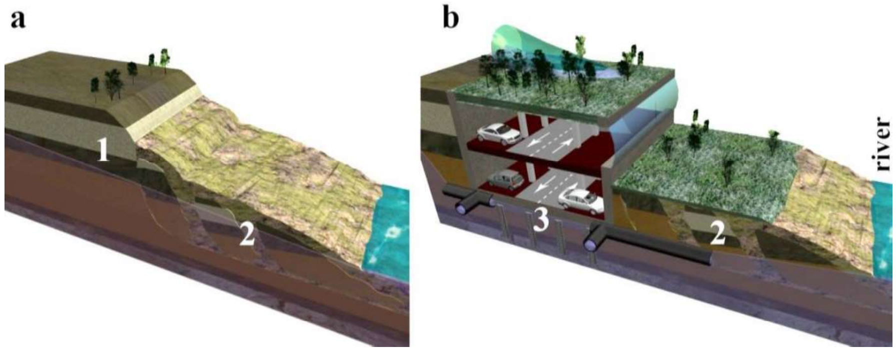

Fig. 9. The scheme the landslide slope with deep landslide (a) and reinforced slope (b).

CONCLUSIONS

Deep landslides of the compression-extrusion mechanism represent a major hazard to urban and mining infrastructure. They have a complex mechanism of development, huge weight, and cause a large problem in the implementation of protection measures.

The landslide hazard assessment and reliable prediction of possible landslide activations, as well as the implementation of effective protective measures are impossible without characterization of a possible landslide based on the mechanism of its formation, on conditions and mechanics of the stress-strain state changes in the landslide mass. Planning of construc6tion on such territories should account the specific dynamics of deep landslides and definition of limit states of groundmasses on slopes.

One of the most important things in stability analysis and designing of protection measures is to define the slip surface depth and the landslide sizes. A new method was elaborated which allows to calculate the slip surface depth with the usage of slope geometry and soil strength parameters. It is based on the results of our researches of peculiarities of development of deed block-type landslides.

New methods for landslide slope stabilization were elaborated on taking into account the main features of landslide development of the considered landslide type. In most cases, it is very difficult to totally stabilize a deep landslide. But the construction on landslide slopes should account the peculiarities of deep block type landslides for providing the sustainable development of slope territories.

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