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Assessment of the stability of some landslide bodies in Georgia using a numerical-analytical approach

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Abstract

Numerical-analytical methods of stability of consequential, block-flexure and creep-plastic landslide-prone slopes are being developed at the G.Tsulukidze Mining Institute. These methods have been used: to determine the degree of stability of the landslide-prone blocks remaining after the 2015 landslides in Tskneti-Samadlo, to calculate the stability of the landslide bodies of M. Machavariani and Sheshelidze Streets in Tbilisi, and then - to develop their strengthening projects together with the specialists of the German-Bavarian Bureau of Engineering Geology and the construction company CRP.

Keywords: numerical-analytical method; stability of consequential block-flexure and creep-plastic slopes.

Introduction

The history of calculating the stability of landslide-prone slopes dates back 250 years. To date, more than 5000 articles or monographs have been published. Most of them are simplified methods for calculating the stability of landslide bodies of assequental and consequental (fig.1, a) type, i.e. without stratification and sliding on stratification planes. In their calculation schemes, the landslide body is divided into vertical blocks, the stability coefficients of the individual block and then of the entire landslide body are determined by solving systems of equations with many unknowns under simplified assumptions. The weaknesses of this type of methods were noted by the authors themselves (Janbu, Bishop and others). Their critical analysis is also given, for example, in (Stability Modelling with SLOPE/W 2012). These shortcomings remain in a number of recently created computer programs (for example, "Rocscience" Slide 2, Slide 3, Slide 6 and others), which are specially designed for landslides and do not consider the stress-deformed state analysis of the landslide body.

In contrast to asequential and consequental, the first papers on the stability of block-flexure (Fig.1, b) landslides have appeared in recent years, and the first steps are still being taken to develop their stability calculation methods.

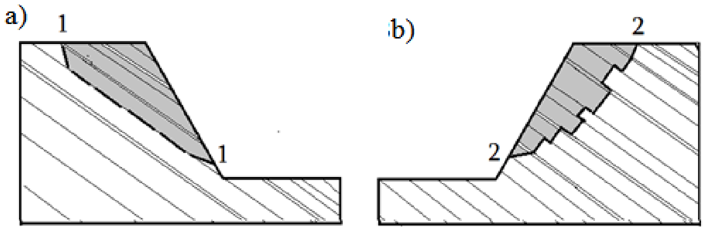

Figure 1. Schematic images of a) consequental and b) block-flexure landslides

Estimating the stability of block-flexure landslide bodies is much more difficult and calculation methods are less compared to consequential ones. As early as 1976, R. Goodman and J. Bray (Goodman & Bray1976) wrote that "our knowledge of this type of phenomena is still in its infancy". They compiled possible calculation schemes and identified the forms of collapse: flexural toppling, block toppling, block-flexural toppling (Goodman & Bray 1976), whose corresponding calculation methods are still in the study and development stage (Amini et. al., 2008).

In the vast majority of the methods developed for the study of landslide events, the stability of the slope is evaluated under the conditions of limit equilibrium, Coulomb-Moir and similar strength theories, and the influence of the time factor can only be reflected indirectly, according to the studies of recent years, through the limit values of the rock adhesion and the internal friction coefficient, i.e. the strength indicators, at the expense of degradation. This was called the "Shear Strength Reduction Factor" and its use in conjunction with the "Finite Element Technique method new era in the theory of landslide stability calculation (Rocscience, 2004).

Consideration of the "shear strength reduction factor" is very important when calculating the stability of block-type slide bodies that maintain a completely stable state for a long time and suddenly lose their stable equilibrium as a result of extreme meteorological challenge or other effects. Until then, long-term monitoring of such landslide-prone slopes may not show any significant rock movement.

In contrast, creep plastic deformation is more rheological in nature. Depending on the intensity of the active forces acting in a particular scheme and the mechanical parameters of the massif, creep deformation can occur very rapidly or very slowly, in periods ranging from a few hours to a hundred years. It is not only the strength (stress, angle of internal friction) but also the deformation characteristics (modulus of elasticity, creep parameters, etc.) of the rock that should be most characteristic. These can be determined by laboratory testing of samples of geological material and/or by processing images obtained from preliminary monitoring. "Natural analysis method (back analysis). The means for its full use will be created after the creation and improvement of the apparatus for the direct analysis of self-creeping plastic landslides. In all these directions, the development of methods for calculating the stability of landslide bodies and anchored constructions is a scientific and technical problem of international level.

Methods and Materials

The numerical-analytical version of the method for assessing and calculating the stability of landslide bodies, both unstratified and consequential, was developed at the G. Tsulukidze Mining Institute. This was done by combining a stress analysis apparatus and computer programs, in particular Phase2, developed by Rocscience not for landslide problems. Unlike existing methods, this version makes it possible to simulate design schemes of various forms of possible collapse of landslide bodies, based on an analysis of the stress-strain state of both an unstratified and a consequent structure; the necessary measures to ensure its stability under normal and extreme conditions under the influence of gravitational and seismic forces must be calculated.

Figure 2. The topographic plan, top view and a section of remained rock block - "Southern Cliff".

The computerised numerical-analytical method for determining the stability of landslide-prone blocks was used to ensure the safety of the remaining blocks after the 2015 landslide events in Tskneti-Samadlo and is described in (Japaridze et. al. 2020). Situation images of one example of them are shown in Fig. 2. Using the calculation diagram and the Rocscience Phase2 computer program, horizontal (XX), vertical (YY) and shear (XY) stresses caused by gravitational and seismic forces were determined. The corresponding polychromes of vertical and shear stresses are shown in Fig. 3.

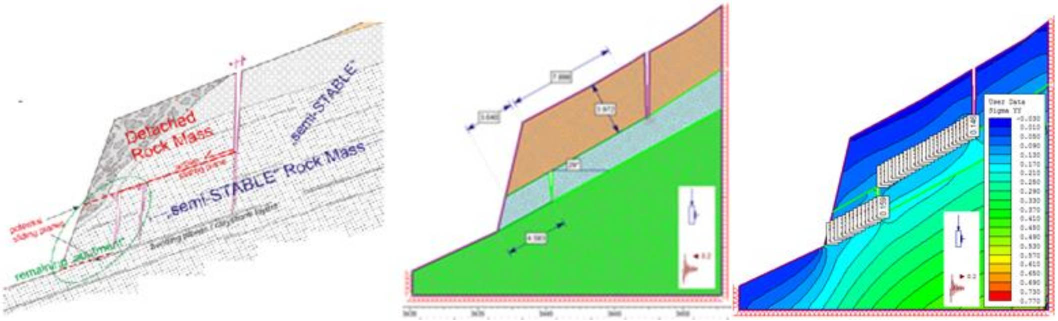

Figure 3. Finite element model of the "upper cliff" of the 2015 large landslide of Tskneti-Samadlo

The values of engineering geological elements, cohesion (c) and angle of internal friction (φ) for the sliding surfaces of the blocks were determined by preliminary exploration studies (Table 1).

Table 1. The values of engineering geological elements for the sliding surfaces

Type of discontinuity Sliding plane	Filling	Cohesion c' [MN/m^2]	Friction φ [o]
Slickenside (normal fault)	Locally fault gouge	0	15-20
Join (rough, medium transection)	Locally clay/silt	(0.005)	28
Bedding plane in claystone	-	0.05	22.5
Bedding plane in strongly weathered claystone/clay	-	0.01	20

Using Rocscience Phase2, the values of horizontal (XX), vertical (YY) and tangential (XY) stresses at 30 points of the potential slip planes were determined and entered into Excel Table 2. At the same points on the slip planes with an angle of θ, the normal N and shear T stresses are calculated according to the following relationships:

$$N = 0.5(XX + YY) + 0.5(XX - YY)cos2\theta + XYsin2\theta \qquad (1)$$

$$T = 0.5(YY - XX)\, sin2\theta + XY\, cos\, 2\theta \qquad (2)$$

where θ is the angle from the positive direction of the x axis to the plane on which the stresses (1), (2) are determined.

By inserting them and the rock cohesion C and the coefficient of internal friction φ on the sliding surface into the Coulomb-Maure limit equilibrium formula (3), stability is estimated at each (30) point and then over the entire area of the slope under normal and extreme conditions.

$$[T] = C + Ntg\varphi \geq T \qquad (3)$$

The values of the holding stresses [T] are entered into the Excel 2 table and the safety factors are calculated at the points of the potential slip surface (Fig. 3). For the given natural conditions C = 50 kPa, φ = 22.50, θ = 190, the total safety factor is SF = 6,07 and stability is maintained by a large margin.

Table 2. Excel table for determining safety factors at potential sliding surface points

№	XX kPa	YY kPa	XY kPa	N kPa	T kPa	[T] kPa	SF
1	1.3	95.4	12.1	19	4.9	15	2.97
2	0.9	92.5	10.8	17	5.0	15	2.90
3	0.6	86.9	9.3	15	4.9	14	2.93
4	1.0	76.9	9.6	15	4.0	14	3.56
5	5.8	66.9	20.7	25	0.6	15	23.93
-	-	-	-	-	-	-	-
26	1.3	95.4	12.1	19	4.9	15	2.97
27	0.9	92.5	10.8	17	5.0	15	2.90
28	0.6	86.9	9.3	15	4.9	14	2.93
29	1.0	76.9	9.6	15	4.0	14	3.56
30	5.8	66.9	20.7	25	0.6	15	23.93

Due to the possible reduction of the rock strength characteristics in extreme conditions, the results of the calculation for the reduced rock shear strength indicators obtained as a result of additional investigations by the specialists of the Bavarian State Office for Engineering Geology are given in Table 3, from which it can be seen that with zero cohesion (c=0) and the coefficient of internal friction φ=150. In this case, the safety factor is less than one (SF=0.88), i.e. the slope will not be stable. Appropriate geotechnical measures were therefore recommended.

Table 3. Safety factors due to a possible reduction in the strength characteristics of rocks

Cohesion C, kPa	Internal friction φ, (0)	Safety Factor SF
50	22.5	6.07
10	20	2.13
0	15	0.88

The proposed numerical-analytical approach for calculating the stability of a block-flexure landslide-prone slope, whose finite element model is shown in Fig. 4, reflects the block-flexural toppling mechanism much more accurately than the current kinematic schemes of Goodman and Bray (Goodman & Bray 1976). Analytical and numerical methods have been developed. It differs substantially from the special computer program "RocTopple 1.0" recently developed by the company "Rockscience", which literally repeats the idealised calculation scheme of Goodman and Bray with very important simplifications and assumptions about the stiffness of the blocks, the equal thickness of the layers and their stability shapes. As an example of non-sequential landslides, we considered the landslide-prone areas on the slopes of the orographically left bank of the Vere River on the Chabua Amirejibi road. The stability coefficient of one of the slopes against gravitational and seismic loads was determined (SF=16.5).

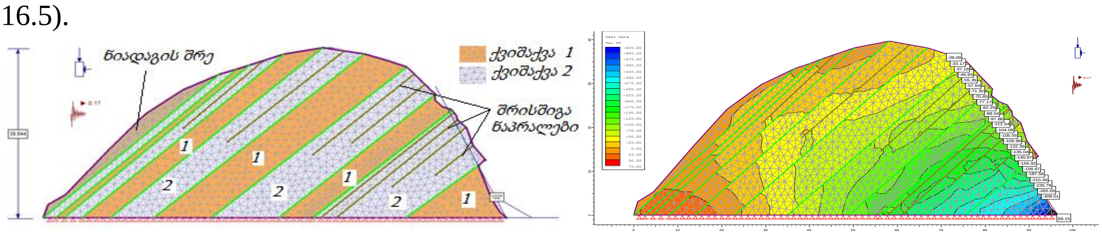

Figure 4. Finite element model of block-flexure slope on Chabua Amirejibi Street

In a large number of mechanical models describing landslide phenomena, rock masses are considered from the point of view of solid body mechanics. The stability of slopes is assessed under the conditions of limit equilibrium, the Coulomb-Moire theory and similar strength theories. Research in recent years has shown that the influence of the time factor can only be reflected indirectly in these methods by reducing the limit values for rock adhesion and the coefficient of internal friction, i.e. strength indicators. This has been termed the "shear strength reduction factor" and its use in combination with the finite element method has been described as "a new era in landslide stability analysis" (Stability Modelling with SLOPE/W, 2012).

Consideration of the 'sliding strength reduction factor' is very important when calculating the stability of block-type consequential and non-stratified landslide bodies, which maintain a stable state for a long time and then suddenly lose equilibrium as a result of extreme meteorological or other effects. Until then, long-term mini-tours of this type of landslide-prone slope may show no significant rock movement.

Creep-plastic deformations occur practically everywhere in rock massifs, and depending on the intensity of the active shear stresses acting in a particular scheme and the mechanical parameters of the massif, creep deformations can develop very rapidly or extremely slowly, in periods ranging from a few hours to hundreds of years. Active compressive stresses are mainly those caused by the gravitational forces acting in the rock mass. As far as the mechanical parameters of the massif are concerned, the most characteristic are not only the strength (density, angle of internal friction), but also the deformation characteristics of the rocks: modulus of elasticity, creep parameters. These can be determined by laboratory analysis of samples of geological material taken from the likely landslide-prone slope and/or by processing the image obtained by preliminary monitoring. using the "natural-analytical", i.e. reverse analysis (back analyse) method (Japaridze,1987). It should be noted that the means for the full use of the latter will be created in the wake of the creation and improvement of the direct analysis apparatus for creep-plastic landslides, which is still a current problem.

It is difficult to assess the stability of creep-plastic landslide bodies in terms of completeness, accuracy and practical possibility of taking into account the factors, and there are practically no calculation methods. Therefore, the modern stage of development of mining massif rheology can be considered only the beginning, when the primary stock of information, ideas, methods and results has been accumulated, but the main researches and practical application of their results are still ahead.

In this case, a study on the stability assessment of creep-plastic landslide slopes was considered in order to develop a calculation method which, unlike the method for calculating the stability of a block-type landslide body, should take into account the elastic-plastic and rheological deformations occurring continuously in the massif containing metamorphic clay rocks and the time factor. This problem is important and relevant both theoretically and practically in general, and also because there are geological formations in many places in Georgia where we have "creep-plastic" landslide-prone places. Local or large-scale landslides of this type are to be expected in areas with hilly terrain (Ministry of Environmental Protection and Agriculture of Georgia 2019) if, under the conditions of intensification of infrastructure construction, special attention is not paid to their prevention even at the early stage of design.

At present it is possible to determine the functions representing the displacement of the points of the array, to assess the stress-strain state of geotechnical objects taking into account creep, if the analytical solution of the task within the theory of elasticity is known. Such tasks include underground structures, namely tunnels, which can be mathematically modelled, for example, using the methods of complex potentials of N. Muskhelishvili. However, it is very difficult to do the same when assessing the stability of slopes prone to landslides.

The use of finite element methods in a limit equilibrium framework to analyse the stability of geotechnical structures is a significant step forward and has many advantages:

- It is no longer necessary to make assumptions about internal stresses (between prisms);
- The stability factor is determined after the stresses have been calculated, so there are no iterative convergence problems;
- The problem of mobility compatibility is solved;
- Calculated stresses are closer to reality;
- Stress concentrations are considered indirectly in the stability analysis;
- Dynamic stresses resulting from an earthquake can be considered directly under stability conditions.

Thus, the finite element approach overcomes many of the limitations inherent in limit equilibrium methods. The tools needed to perform stability analysis of geotechnical structures based on stresses calculated by the finite element method are available today, but they also have some weaknesses, and unforeseen problems may arise in the future. Such problems are currently the subject of research and will be solved over time as the method is increasingly used in geotechnical practice (Stability Modelling with SLOPE/W, 2012).

Due to the great practical importance of the task and the theoretical difficulties of a strict solution, the modelling of the creep-plastic landslide body can also be considered as a so-called "variable module" (Nicholson et. al. 1990; Technical Manual for Design and Construction of Road Tunnels, 2009)

The results of the research were used in the creep-plastic landslide reinforcement project of Tbilisi's Vashlijvari district, prepared by Caucasus Road Project LLC and the Bavarian Office of Engineering Geology, whose plan and section C-C as of the beginning of March 2021 is shown in Fig. 5.

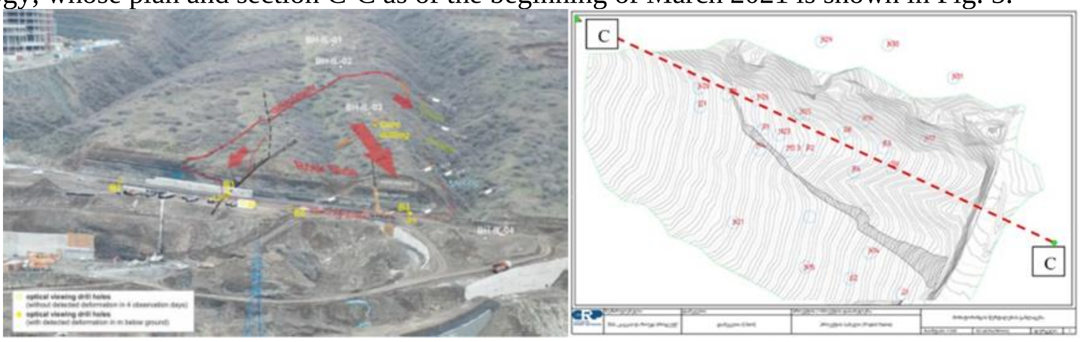

Figure 5. Top view and plan of "Vashlijvari Landslide" with observation points

To detect morphological changes in the landslide area, scientists from the University of Vienna carried out observations and satellite measurements using the Sentinel satellite's Interferometric Synthetic

Aperture Radar (InSAR). Observation points were placed on the landslide body and beyond (Fig. 5). The displacements of the geodetic markers in the direction of the landslide were recorded for 100 days.

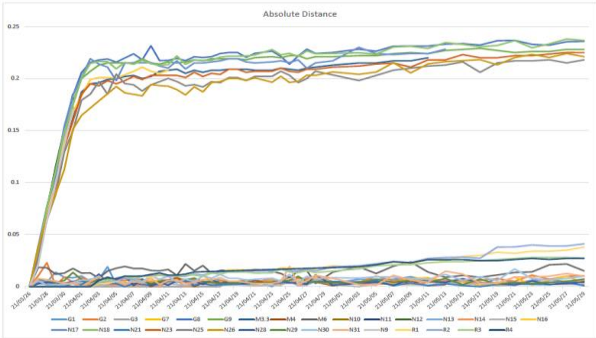

Figure 6. Movements of observational geodetic markers in the direction of the landslide

The displacements caused by the gravitational forces of the observational geodetic markers shown in Fig. 6 make it possible to determine the creep parameters of the entire landslide body massif using the proposed natural-analytical method, the so-called use of time-varying modules.

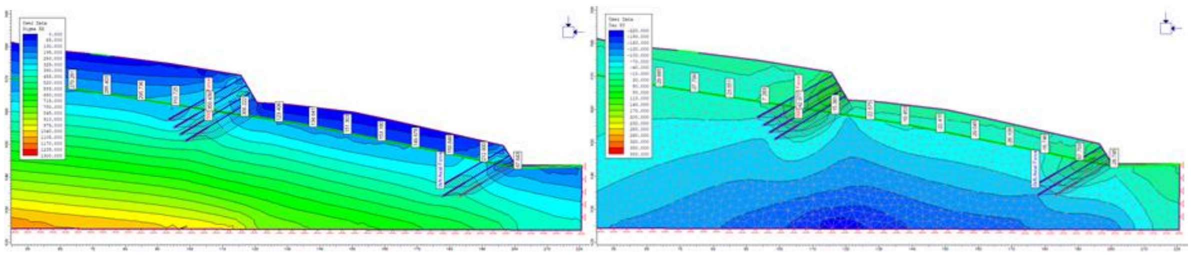

Figure 7. Polychromy of stresses XX and XY acting in the CC plane when anchors are placed at two levels

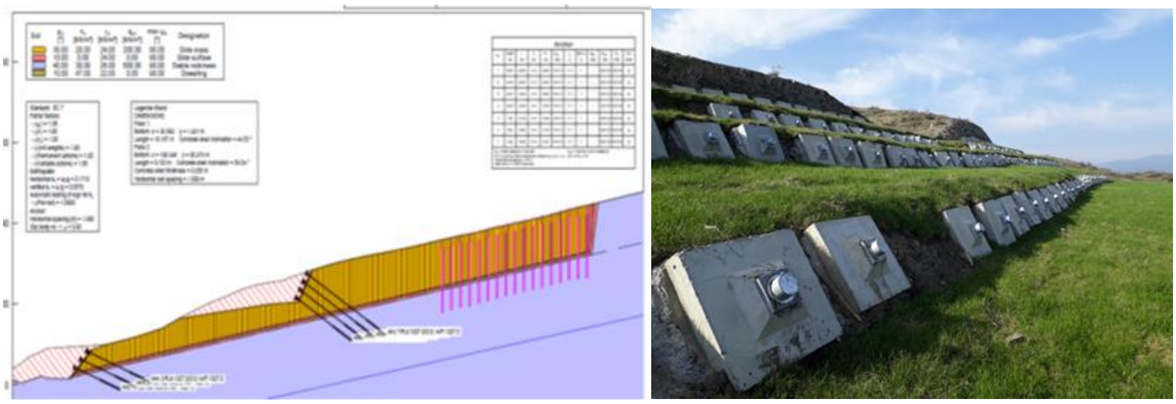

Figure 8. Project of anchor reinforcement of the Vashlijvari landslide slope and its fragment

These data, obtained by the natural analytical method carried out on the landslide body of M. Machavariani Street, were used for the calculation of the stability of the landslide body, for the preparation of the strengthening project (Fig. 7, Fig. 8) and its implementation.

Results

1. The original numerical-analytical version of the method for assessing and calculating the stability of landslide bodies, both unstratified and consequential, was developed. Unlike existing methods, this version makes it possible to simulate design schemes of various forms of possible collapse of landslide bodies, based on an analysis of the stress-strain state under the influence of gravitational and seismic forces;
2. Proposed numerical-analytical approach for calculating the stability of a block-flexure landslide-prone slope reflects the toppling mechanism much more accurately than the current kinematic schemes. As an example of non-sequential landslides, landslide-prone areas on the slopes of the orographically left bank of the Vere River were considered.

3. Morphological changes and displacements of geodetic marks in the direction of a creeping-plastic landslide body in the Vashlijvari region of Tbilisi were established together with scientists from the University of Vienna using the interferometric synthetic aperture radar (InSAR) of the Sentinel satellite. These data were used to calculate the stability of the landslide body using the natural-analytical method, to prepare a project for strengthening the slope and its implementation.

Conclusion

When checking the condition of stability of landslide-prone slopes and calculating their Safety Factor (SF), the rock mass should be characterised by its long-term shear strength and full deformation expected in all parts of the sliding plane. In cases where the laboratory study of the engineering-geological material of the object as a result of practically instantaneous tests gives indicators of the peak strength of the rocks, the stability condition cannot be lower than the ratio of the immediate and long-term strength;

It is well known that the rock mass passes through different stages of deformation before collapsing and undergoes significant plastic deformations, the magnitude of which depends on lithology, density, moisture, liquefaction during seismic impact and many other indicators. All the rocks that make up the stratified massif and that participate in the landslide event are characterised by different deformation properties. Therefore, even if they undergo almost the same deformation at each moment, the stresses acting on them are different. In the less plastic layer, the shear deformation stresses reach the limit, while in the more plastic layer they are still far from the limit. The magnitude of the resistance to slope displacement is not equal to the sum of the resistances of the individual layers at any stage of deformation;

The value of the creep-plastic landslide stability coefficient depends not only on the Coulomb-Mohr strength characteristics, but also on the deformation parameters of the rocks in general, including the creep characteristics;

The treatment of displacements caused by the gravitational forces of observational geodetic marks by the proposed "natural-analytical method" compared to the cylindrical dilatometric method indicated in the normative documents of the Eurocodes, provides a better opportunity to determine the equivalent creep parameters of the entire landslide body array.

Due to the great practical importance of the task and the theoretical difficulties of a strict solution, the possibility of modelling a creep-plastic landslide body should be studied by the so-called Using the idea of a "variable module". In this case, it is necessary to consider the proposal and development of the "Shear Modulus Reduction" factor similar to the already established "Shear Strength Reduction" factor;

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Due to the great practical importance of the task and the theoretical difficulties of a strict solution, the possibility of modelling a creep-plastic landslide body using the so-called "variable modulus" idea should be studied. In this case, it is necessary to consider the proposal and development of the "shear modulus reduction" factor, similar to the already established "shear strength reduction" factor; geological investigation of a specific landslide-prone site, together with other rock parameters, "natural-analytical" and/or laboratory methods should determine rock creep parameters, or in extreme cases - peak and residual deformation modulus. The quantities are as required, for example, in the "Material Properties" table of the Phase 2.7 program. It should also be noted that the magnitude of the "time-varying modulus" of deformation depends on the stress-strain state of a particular rock mass, i.e. on the overall calculation scheme of the geotechnical situation. Similarly, the creep characteristics will not be invariant to stress, since their curves reflect the evolution of both creep and creep-plastic deformation over time.

The proposed natural-analytical method has been used: to determine the degree of stability of the landslide-prone blocks remaining after the 2015 landslides in Tskneti-Samadlo; St. to calculate the stability of the landslide bodies of M. Machavariani and Sheshelidze Streets in Tbilisi, and then - to develop their strengthening projects together with the specialists of the German-Bavarian Bureau of Engineering Geology and the construction company CRP.

Competing interests

The authors declare that they have no competing interests.

Authors' contribution

L. J. conceived of the presented idea and performed the numerical-analytical calculations, N. C. conceived of the presented idea, T. A. provided critical analysis, T. G. provided critical analysis and performed the analytic calculations.

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