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Geomechanics

A Case Study of the Slope Stability after Large Landslide in the 2015 Flood in Tbilisi

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In the paper, case histories from Tbilisi multi-hazard event and largest landslide of June 13, 2015 are presented. The main focus was on the assessment stability of blocks remained in this slide area. In order to safely operate the road after its restoration, it was necessary to remove loose rock blocks or fix them with required safety factor. From the whole unstable area, 7 main critical sites were identified, the slopes of which could be in active motion. The stress-strained states of the unstable sections of the slopes and the safety factors (SF) of the problematic blocks are presented here. The following was considered: the expected gravity and seismic loads of earthquakes, the effect of reduction of the strength characteristics of rocks over time. The possibility of removing a potentially unstable exemplary block without an explosion is considered and the loads required for this are calculated. An example of the calculation of the number of anchors required for fixing of an unstable block is shown. *© 2020 Bull. Georg. Natl. Acad. Sci.*

Geological mapping, geomorphology, debris flow, safety factor

Tbilisi Flood of June 13, 2015 took 19 lives, destroyed housing and flooded the zoo, killing many of the animals. It was a multi-hazard event. According to the National Environmental Agency of Georgia approximately 100 mm of rainfall in 3-4 hours fell on already saturated soil conditions. The largest landslide near the town of Akhaldaba was approximately 32 hectares in size, traveled 1.3 km to the junction with the mainstream of the Vere River, and produced approximately 1 million cubic meters of sediment. Among the vast infrastructure was destroyed significant parts of Tskneti-Betania highway (Fig.1). After this event, a significant amount of debris and unstable blocks remained in this slide area.

Due to the strategic importance of the road it was decided to rehabilitate it. An integrated group of engineering geologist and geotechnics was involved in solving this problem. Restoration of the demolished sections was chosen from several alternatives. This was implemented (Fig. 1) by the "Caucasus Road Project" company in collaboration of Georgian and foreign firms. Geological and engineering-geotechnical characteristics of the site were provided by Ltd "Geoengineering" [1], "Geological Service", the Bavarian Engineering-

Fig. 1. Views of destroyed and restored parts of Tskneti-Betania highway.

Geologic Bureau (Baugeologishes Buro Bauer – BBB) [3,4], G. Tsulukidze Mining Institute.

In order to safely operate the road after its restoration, it was necessary to remove loose rock blocks from the destroyed slope above and to the sides. The slide zone was scraped of loose debris of weak material. More difficulties were connected with the rock blocks. There was decided to fixing or removing them without using of blasting due to the possibility of more destroying of the rock massif. Therefore, it was necessary to conduct: a quantitative assessment of their slip resistance, the calculation of the required number of mounting supports or efforts for the controlled removal of potential unstable blocks from landslide territory.

As of today, based on the consideration of the completeness, accuracy and practical easiness of estimating of these factors, there are many methods (W. Fellenius, A. Bishop, N. Janbu, T. Matsui, E.Spencer and others) developed for the stability of slopes. Inter alia, the recent method, which the experts [5] deem as a "New Era in reporting on the stability of slope", and it represents the combination of Limit Equilibrium (LE), Shear Stress Reduction (SSR) and Finite Elements Methods (FEM). The following estimation is made by means of this approach using the programs "Phase 2" and "Slide.v6.020" of the "Rockscience" firm, analytical relations and with approach of the so-called removable contact stresses.

The whole above mentioned unstable area was mapped by BBB and 7 main critical sites were identified, the slopes of which are in active motion and first deserve attention in terms of stability [4]. Below two of the seven characteristic examples of slopes are considered.

Vertical section for first of them on the western coast of the considered area and scheme of "Phase 2.7" program for calculated stress-deformed state and stability of the remaining parts are shown in Fig. 2.

Two potential landsliding surfaces are indicated on this section. No. 1 is a dividing surface between the rough debris of the previously slided rocks and on the other hand, sandstones, argillites and residual masses of highly eroded conglomerates, geomechanical parameters of which are given in the Table provided on calculations scheme. The values of horizontal XX, vertical YY and tangent XY components of stresses during K=a/g=0.17 peak relative acceleration, characterizing the region at joint action of forces developed in the negative phase of the seismic wave in the massive, are calculated using "Phase 2" finite element modeling (FEM) program, and for short only XY stress components are shown in Fig. 2.

According to stress theory, having XX, YY, XY, one can determine normal – N and shear – T stresses in the points of the possible sliding plane, inclined on angle θ as:

$$N = 0.5\left(XX + YY\right) + 0.5\left(XX - YY\right)\cos 2\theta + +XY\sin 2\theta; \quad (1)$$

$$T = 0.5\left(YY - XX\right)\sin 2\theta + XY\cos\cos 2\theta \quad (2)$$

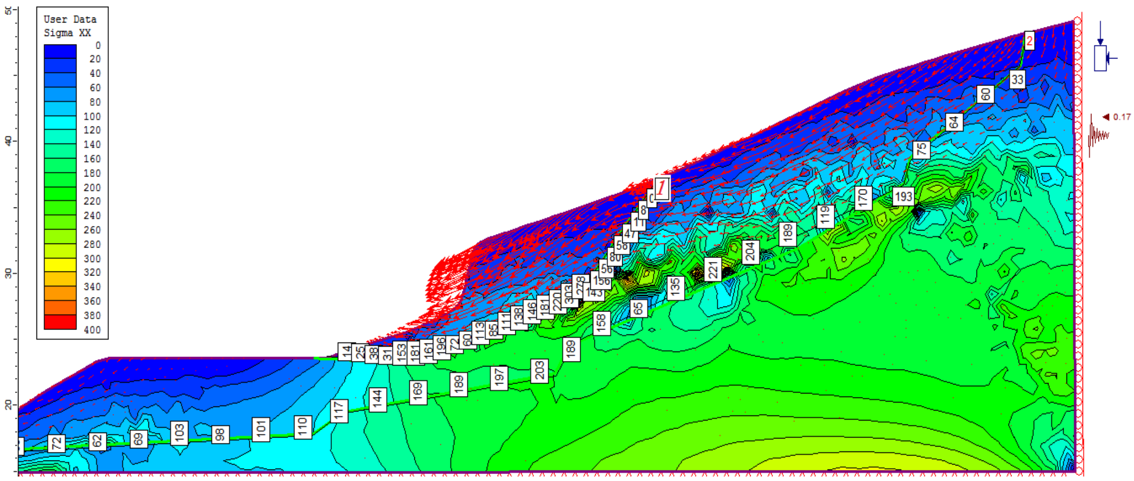

Fig. 2. Picture of stress-deformed state for the first site section taken with the "Phase 2.7".

and the assessment of slope stability in normal and extreme conditions can be made in accordance to Coulomb-Mohr Limit Equilibrium state in the form:

$$[T] = N \tan\varphi + C \geq T. \qquad (3)$$

The values thus determined are set out in the compressed form in Table 1, from which the overall safety factor of the first surface, SF=Σ[T]/ΣT=**1.6**.

To assess the overall stability of the N1 site, in addition to surfaces No. 1 and No. 2, it was necessary to find areas of minimal stability in previously displaced soils. This was more convenient to do using the "Rockscience Slide 6" computer program. So it was found that in the zone of coarse waste from previously displaced soils, the minimum safety factor, SF=0.98, i.e., even with peak strength indicators for these soils

Table 1. The values of stress components and safety factors in the terms of 28 points of the first surface (K=0.17, C =5kPa, φ =28°)

№	XX	YY	XY	θ°	θ, r	N	T	C	φ°	[T]	SF
1	14.3	13.8	1.9	-2.0	-0.03	14.5	2.0	5.0	28.0	12.7	6.5
2	25.1	22.5	2.5	-2.0	-0.03	25.3	2.5	5.0	28.0	18.5	7.3
-	-	-	-	-	-	-	-	-	-	-	-
27	8.2	11.3	-0.1	45.0	0.79	9.9	1.5	5.0	28.0	10.3	6.7
28	0.1	0.1	0.0	50.0	0.87	0.1	1.1	5.0	28.0	5.1	4.6
						ΣT	32.2		**Σ[T]**	51.4	
										SFavar	**1.6**

Potential landsliding surface No. 2 is placed in the sandstones, argillites and residual masses of highly eroded conglomerates, geomechanical parameters for the normal conditions are cohesion C=1900 kPa and the angle of the internal friction φ=28°. For such a case, stability is also well preserved in all points of surface 2 and the total safety factor for, determined by same method, SF=42.6.

(C=5 kPa, φ=28°), the slope is still at the threshold of stability. Also found is the surface with SF=1.426, which can be taken for an optimal profile surface with good safety for the soils of the first section.

The second section, so-called "Southern cliff", was remaining 85 m above the level of the road. Top view and topographic plan of the "Southern cliff" are shown in Fig. 3.

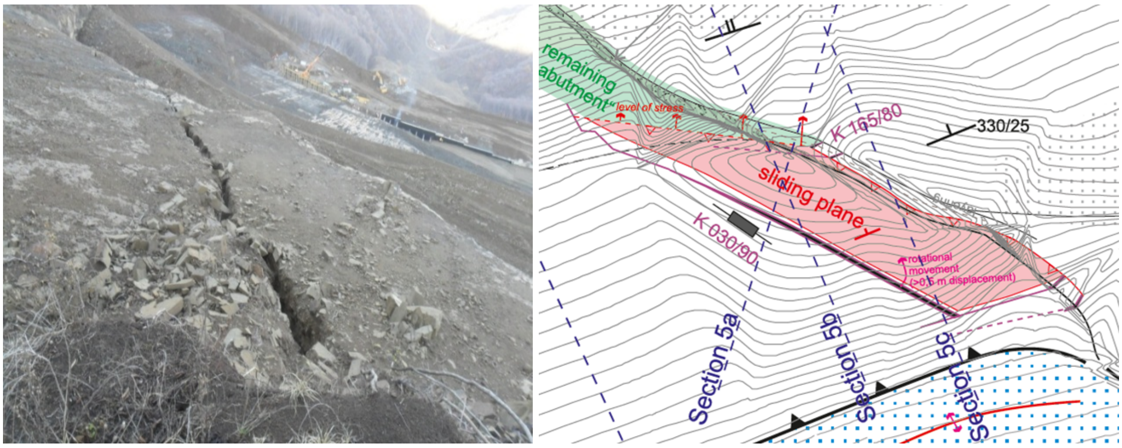

Fig. 3. The top view and a topographic plan of remained rock block – "Southern Cliff".

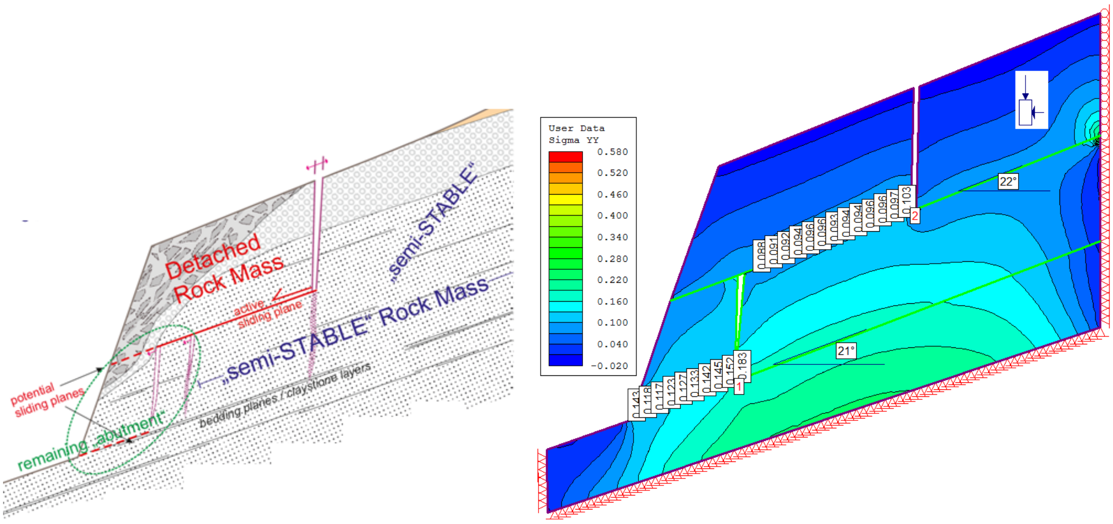

Fig. 4. Cross-section and picture of the stress-deformed state of "Southern Cliff".

There was provided the specified values for estimations of the basic engineering geological elements, the cohesion (c) and the angle of internal friction (φ) for cliffs' sliding planes (Table 2).

Table 2. The basic engineering geological elements for cliffs sliding planes

Tipe of discontinuity	filling	Cohesion C, kPa	Friction φ°
Slickenside (normal fault)	Locally fault gouge	0	15-20
Joint (rough, medium)	Locally clay/silt	5	28
Bedding plane in claystone	–	50	22.5
Bedding plane in strongly weadered claystone/clay	–	10	20

Since slip already took place, which could further reduce friction along the slip plane, it was recommended that in the calculations assume zero adhesion (C = 0).

The topographical plan of "Southern Cliff" is imported from the surface topographic map in accordance with coordinates and the scale, by AutoCad and provided in Fig. 3. Respective cross-section 5 a provided in Fig. 4.

The values thus determined are set out in compressed form in Table 3, from which the overall safety factor, **SF= Σ[T] / ΣT =4.42.**

If the rock strength parameters will be reduced due to the meteorological or seismic circumstances, the corresponding values of total safety factors for

Table 3. The values of stress components and safety factors in the terms of 23 points for the "Southern Cliff" (C =50 kPa, φ =22.5°)

№	XX	YY	XY	θ ⁰	N kPa	T kPa	C kPa	φ °	[T] kPa	SF
1	45	143	60	21	90	12	**50**	**22.5**	87	7.28
2	28	118	45	21	76	4	**50**	**22.5**	81	22.9
-	-	-	-	-	-	-	**-**	**-**	-	-
22	18	97	-4	22	89	30	**50**	**22.5**	87	2.87
23	22	103	-8	22	97	34	**50**	**22.5**	90	2.69
					ΣT=	460		Σ[T]=	1252	**4.42**

this scheme will be also reduced and if C=0 and φ=12°, safety factor becomes less than one.

This confirmed the dangerous situation and necessity [3] of temporary support or removal of this loose block.

In the first case, to determine the total resistance, for example, of anchors, it is necessary to calculate the holding force from the data in the above Tables at the minimum (reduced) total shear strength (C=0, φ=10°) of the rock, Σ[T]. The total retention force of all anchors required to compensate for the so-called removed stresses caused by a decrease in rock shear strength (SSRF) for a block with a length L=24 m. will be:

$$F_{ret} = \left(\Sigma T - \Sigma[T]_{min}\right) L = \left(460 - 378\right) * 24 = \\ = 1980\ kN \tag{6}$$

and with taking into account seismic loads F_{ret}=2800 kN.

Therefore, the number of anchors with a load capacity for example of 30 tons per 1 anchor needed to provide a total holding force at the minimum (reduced) total shear strength (C=0, φ=10°) of the rock could be 2800/(30*10)≈10, i.e. one anchor per 2.4 m of block length.

There was considered the option of removing the held by contact strength forces (C=50 kPa, φ=22.5°) block without using an explosion. For this case required removal force per unit length of block, F_{rem} was determined by total shear stresses from Table 2:

$$F_{rem} = \Sigma[T] - \Sigma T = 1252 - 460 = 792\ kN.$$

In this case, preference was given to removing this block by artificially reducing the strength characteristics to C=0, φ=12°, after which SF<1. It was decided to do this by pouring water into a over crack on the slope. But this did not have time. Soon, as a result of heavy rain, the block early in the morning, at the traffic absence, moved, collapsed and caused some damage to the lower-standing road equipment.

Conclusions

Two of seven characteristic examples of slopes are considered in this work. Calculayions were made by approach which represents the combination of Limit Equilibrium (LE), Shear Stress Reduction (SSR), Finite Elements (FEM) and analytical methods, using the computer programs "Slide.v6.020" and "Phase 2.7" of the "Rockscience" firm. The following are evaluated: stress-strain states and safety factors (SF) of unstable sections of slopes, taking into account: gravitational and seismic loads, the possibility of reducing the strength characteristics of the rocks. The option of removing a potentially unstable block without explosion was considered and the necessary removal force was calculated for this case; An example of determining the amount of the anchors for fixing of unstable block according required factor of safety is shown.

გეომექანიკა

თბილისში 2015 წლის წყალდიდობისას წარმოშობილი დიდი მეწყრის შემდეგ ფერდობის მდგრადობის ანალიზი

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სტატიაში მოცემულია თბილისის 2015 წლის 13 ივნისის წყალდიდობის და წყნეთი-ბეთანიის დიდი მეწყრის შემდეგ დანგრეული გზის უსაფრთხო ექსპლუატაციის ზოგიერთი საკითხი. ყურადღება გამახვილებულია ამ მეწყრის არეალში დარჩენილი ბლოკების სტაბილურობის შეფასებაზე. გზის აღდგენის შემდეგ მისი უსაფრთხოდ გამოყენების მიზნით, აუცილებელი იყო ფერდობიდან დარჩენილი კლდოვანი ბლოკების საიმედოთ დამაგრება ან მათი მოხსნა. დასაცავი ფართობიდან გამოვლენილ იქნა 7 აქტიური ადგილი, რომელთა სტაბილურობა პირველ რიგში იმსახურებდა ყურადღებას. წარმოდგენილ სტატიაში განხილულია შვიდი ადგილიდან ორი ჭრილი. გაანგარიშებები გაკეთდა ორიგინალური მიდგომით, რაც წარმოადგენს ზღვრული წონასწორობის (LE), მხები ძაბვების შემცირების (SSR), სასრული ელემენტების (FEM) და ანალიზური მეთოდების ერთობლიობას, ფირმა „Rockscience“-ის კომპიუტერული პროგრამების, „Slide.v6.020“ და „Phase 2“ გამოყენებით. ასეთი მიდგომით შეფასებულია: ფერდობების არასტაბილური მონაკვეთების დაძაბულ-დეფორმირებული მდგომარეობები და იქ არსებული პრობლემური ბლოკების მდგრადობის კოეფიციენტები (SF). მხედველობაში მიიღება: გრავიტაციული და მიწისძვრის მოსალოდნელი სეისმური დატვირთვები, ქანების სიმტკიცის მახასიათებლების დროში შემცირების შესაძლებლობა. განხილულია პოტენციურად არასტაბილური ბლოკის მოხსნის შესაძლებლობა აფეთქების გამოყენების გარეშე და გამოთვლილია ამისათვის საჭირო ძალა; ნაჩვენებია დაცურებისადმი საშიში ბლოკის დამაგრებისთვის საჭირო ანკერული სამაგრის რაოდენობის გაანგარიშების მაგალითი.

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