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Slope stability back analysis and a proposition for rehabilitation of landslide on the road section Gornji Milanovac – Klatičevo

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Abstract: During the construction on the section of the designed road Gornji Milanovac - Klatičevo (Gornji Milanovac Bypass), in the period from November 2022 to April 2023, there was an occurrence of slope instability on the right side of road cut from km 0+910 to km 0+950 i.e., terrain sliding in the form of soil creep. A landslide occurred on the part of the constructed cut slope, which extends over a total length of approximately 125 m. The surface layer of soil affected by sliding (colluvium) is made of silty-sandy clay, soft to medium hard consistency and increased water content. This material was originally created by the decomposition of the basic rock mass (bedrock) and the deposition of material from the higher parts of the slope by planar erosion (diluvium). Bedrock under the diluvium layer consists of the Neogene (Miocene) complex of red sandstones. For the purposes of defining the natural conditions in the terrain under which the terrain sliding process was activated, a slope stability back analysis was performed for the Mohr–Coulomb Failure Criterion and the state of effective stresses. Defining the cause of the soil failure is imposed as the primary goal of paper, considering that during the engineering geological mapping of the terrain in the design phase, no phenomena were observed that would indicate soil instability. In addition, before the activation of the landslide, slope stability analysis with the influence of groundwater in design phase was performed in order to simulate extreme conditions during exploitation and a satisfactory safety factor was obtained. After defining the cause of landslide activation, the paper proposed the use of several remedial measures as well as their mutual combination to completely rehabilitate the landslide.

Keywords: landslide, slope stability back analysis, rehabilitation of landslide.

Introduction

On the section of road under construction Gornji Milanovac-Klatičevo, as a part of bypass around Gornji Milanovac, from km 0+910 to km 0+950 on the right side of the projected road, slope instability, i.e. terrain sliding, occurred. Landslides occurred on the part of the derived slope of the cut, which extends over a total length of about 125 m (from km 0+900 to km 1+025). The process of terrain sliding occurred in the period November 2022 - April 2023. The width of the landslide was about 40 m, and the length varied from 15 to 35 m (Figure 1). Taking into account the results of engineering geological mapping of the terrain and the results of previously performed research and tests, for the purposes of creating a project for a construction permit, an appropriate geotechnical model of the terrain with the position of the sliding plane was formed.

The surface layer of the soil affected by sliding - colluvium (Ko) is made of dusty-sandy clay, soft to medium hard consistency and increased humidity. This material was originally created by the decomposition of the bedrock mass and the deposition of material from the higher parts of the slope by planar erosion (deluvium). Within these deposits, local weak aquifer with slow drainage due to uneven drainability may occur.

Deluvial deposits (dl) are lithologically represented by dusty and dusty sandy clays, medium hard to hard consistency, low to high plasticity. Within the layer of deluvial clay, the presence of interlayers of sandy gravel was registered. Deluvial deposits are characterized by an intergranular type of porosity and low to medium water permeability. According to the GN-200 classification, these materials can be classified in II-III category.

The main rock mass under the deluvium layer is built by the Neogene (Miocene) complex of red sandstones. It is characterized by great facies diversity. The rock mass is represented by red sandstones and siltstones, with varying degrees of fracturing and alteration. Gradually changing of harder, less degraded zones with zones of a higher degree of alteration is characteristic (Figure 2).

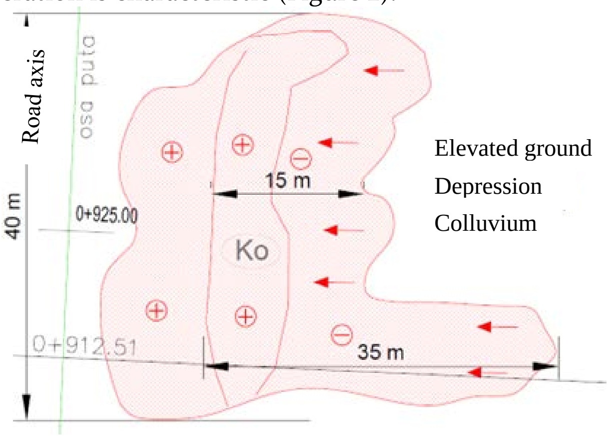


Figure 1. Situational plan of landslide from km 0+910 to km 0+950

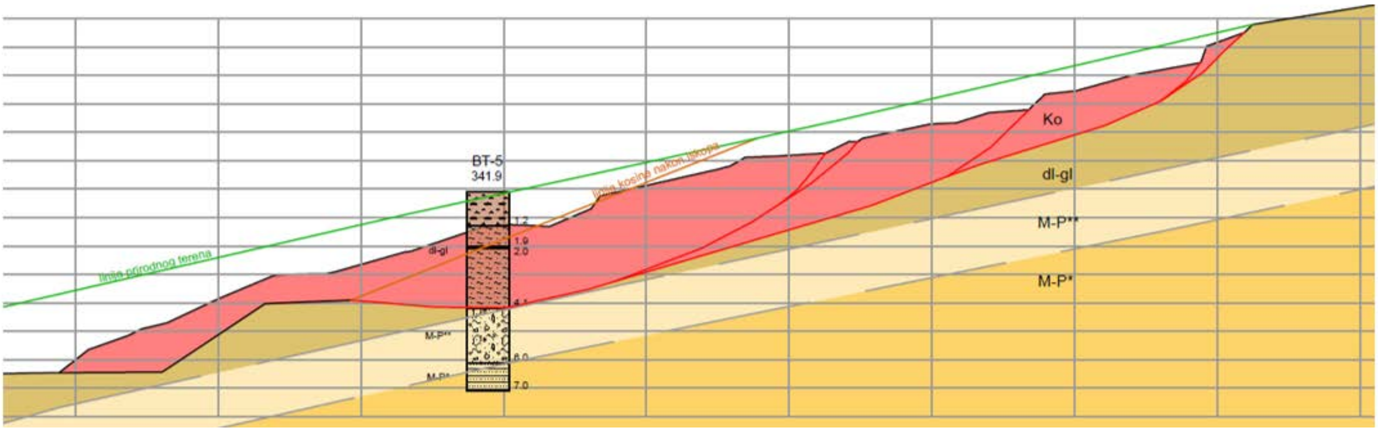


Figure 2. Engineering-geological cross section (km 0+912)

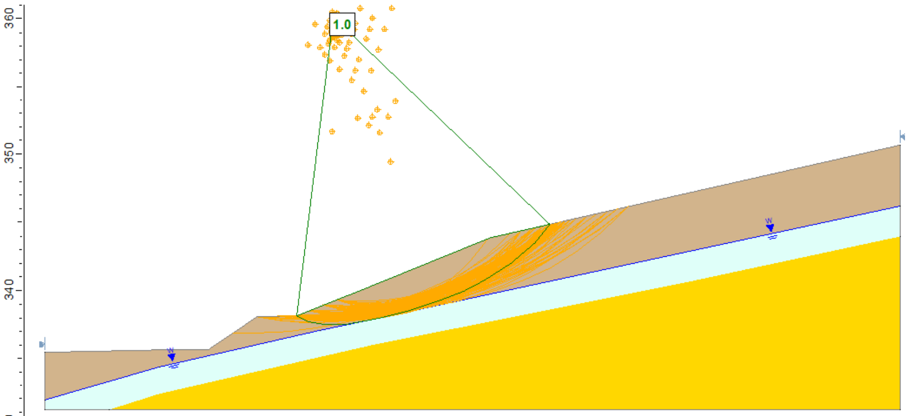
Slope stability back analysis

Slope stability back analysis was done for the Mohr–Coulomb failure criterion and the state of effective stresses, where the value of unit weight γ=19.0 kN/m³ was adopted. Stability calculations were done in the RocScience's Slide software (Figure 3).

Since at the moment of activation of the landslide, the terrain is in a state of limit equilibrium, the average values of the mobilized shear strength parameters along the critical sliding plane were obtained by slope stability back analysis:

- Friction angle (ϕ_m') = 17 °
- Cohesion (c_m') = 4 kPa

The mobilized strength represents the shear stress required to maintain the equilibrium of the sliding body. The parameters obtained by the back analysis are authoritative for the calculation of the effect of forces from the sliding body.



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Water Surface	Hu Type	Hu	Ru
dl-gl		19	Mohr-Coulomb	4	17	None			0.2
M-P**		19.5	Mohr-Coulomb	5	25	Water Surface	Custom	1	
M-P*		21	Mohr-Coulomb	5	35	Water Surface	Custom	1	

Figure 3. Slope stability back analysis (cross section on km 0+912)

Scope and type of exploration before and after landslide activation

For the purposes of designing the subject slope, in the slope zone detailed geotechnical investigations of the terrain were carried out in august 2019, april and may 2021, which included:

- engineering geological mapping of the terrain,
- exploratory drilling in the slope zone and engineering geological mapping of the borehole core,
- observation of the occurrence and level of underground water in the borehole
- laboratory geomechanical testing of soil samples

The engineering geological mapping of the terrain at the subject location was carried out in august 2019. for the purposes of designing the preliminary project, as well as in the period april - may 2021. for the purposes of developing the project for the construction permit. During the mapping of the terrain, no phenomena were observed that would indicate instability of the soil under natural conditions.

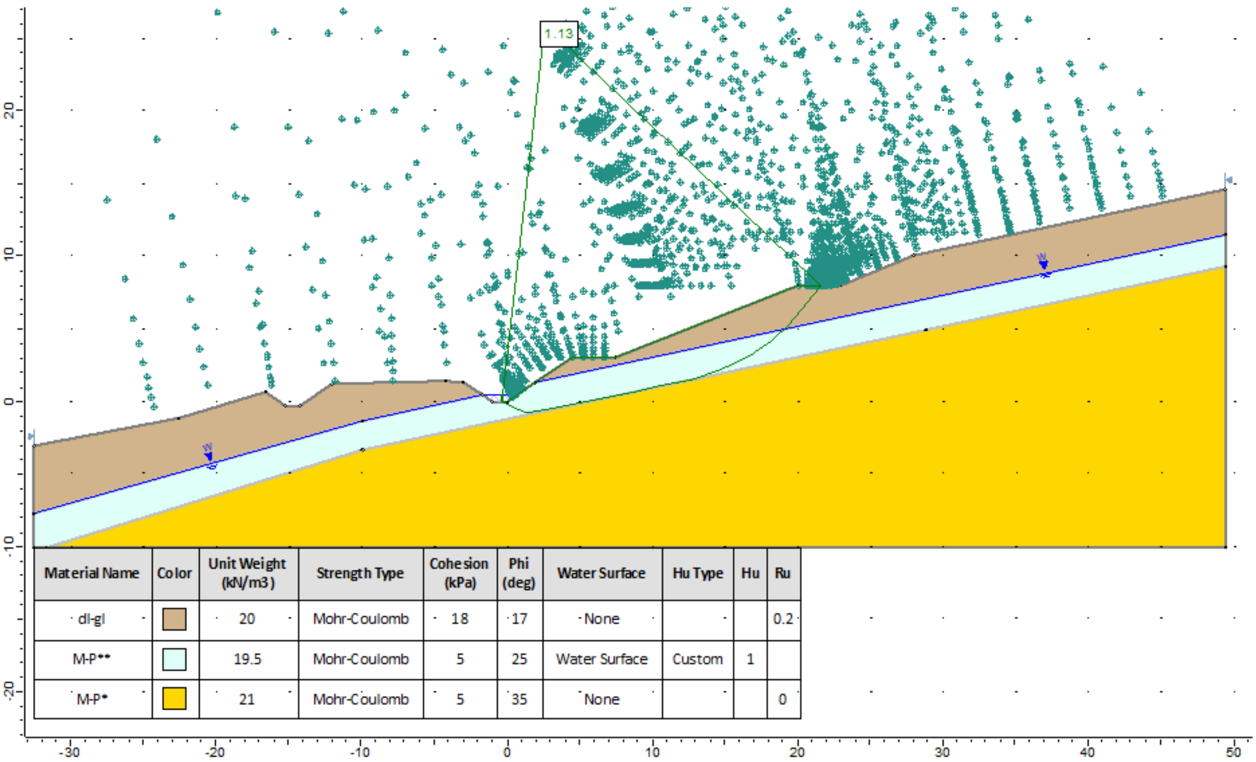
Exploratory drilling was carried out on the subject slope on chainage km 0+910, that is on the part of the constructed slope where the landslide occurred. The depth of the exploratory borehole was 7 m, and the drilling was completed in a layer of solid rock mass. During the execution of the exploratory borehole, engineering geological mapping of the core was carried out, i.e. identification and classification of lithological units.

Observation of the occurrence and level of underground water in the borehole: during the exploratory drilling in borehole in the slope zone was no occurrence of underground water.

Laboratory geomechanical testing of soil samples: One soil sample from the deluvial clay layer (dl-gl), also the layer in which the landslide occurred, was tested from the exploratory borehole drilled at the site in question. The examined sample was taken from a depth of 3.1-3.4 m. A total of 28 soil samples were examined from the layer of deluvial clay in the narrower and wider research area. All these results were used in the analysis and adoption of relevant soil strength parameters. The samples were tested according to valid standards.

Checking of the limit equilibrium of the cut slope was made according to SRPS EN 1997-1, using partial safety factors. Approach 3 was used, according to which partial factors were adopted for soil strength parameters: for the friction angle γ_ϕ=1.25 and for cohesion γ_c=1.25.

The incline of the slope is designed so that in the lower part of the slope the initial incline is 1:1.5 (33°) up to a height of 3 m, and the incline at a height of over 3 m is 1:2.5 (22°). The slope stability analysis was done with the influence of groundwater in order to simulate extreme conditions during exploitation. The influence of water was introduced into the calculation through the level of underground water in the layer of sandy clay debris (M-P**) and the coefficient Ru=0.2 in the layer of deluvial clay (dl-gl). The stability analysis was performed for the section at the chainage km 0+950, where the height of the slope was the highest (10.7 m) and a satisfactory safety factor was obtained (Fs=1.13) (Figure 4). The required value of the minimum global safety factor in calculating according to the Eurocode is Fs>1.



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Water Surface	Hu Type	Hu	Ru
dl-gl		20	Mohr-Coulomb	18	17	None			0.2
M-P**		19.5	Mohr-Coulomb	5	25	Water Surface	Custom	1	
M-P*		21	Mohr-Coulomb	5	35	None			0

Figure 4. Cut stability analysis on km 0+650 (Geotechnical Report, CIP, 2022.)

In order to define in more detail the construction of the terrain and the geotechnical conditions for the rehabilitation of the unstable slope, in august 2023, additional geotechnical investigations and tests were carried out, which included the following investigations:

- Exploratory drilling and engineering geological mapping of the borehole core,
- Installation of piezometer construction
- Observation of occurrences and levels of underground water in boreholes,
- Laboratory geomechanical testing of soil samples.

Exploratory drilling was carried out on the subject slope from chainage km 0+850 to km 1+035. A total of 6 exploratory boreholes were drilled, 7.0 - 10.0 m deep, total drilling length 57.0 m (Figure 5). During the execution of the exploratory boreholes, engineering geological mapping of the core was carried out, i.e. identification and classification of lithological members (Figure 5).

Installation of a piezometer construction: in order to be able to monitor changes in the groundwater level in the area of the slope in question, a piezometer construction was installed in the exploratory borehol.

Observation of the occurrence and level of underground water in the borehole: during the exploratory drilling in the exploratory boreholes, there was no occurrence of underground water.

Laboratory geomechanical testing of soil samples: 8 soil samples were tested from the exploratory boreholes carried out at the site in question. Of these, 2 samples from the layer of deluvial clay (dl-gl) - the layer in which the landslide occurred and 6 samples from the sandstone decay zone (M-P**). Identification and classification tests, peak and residual direct shear tests and oedometer compressibility tests were performed on the samples.

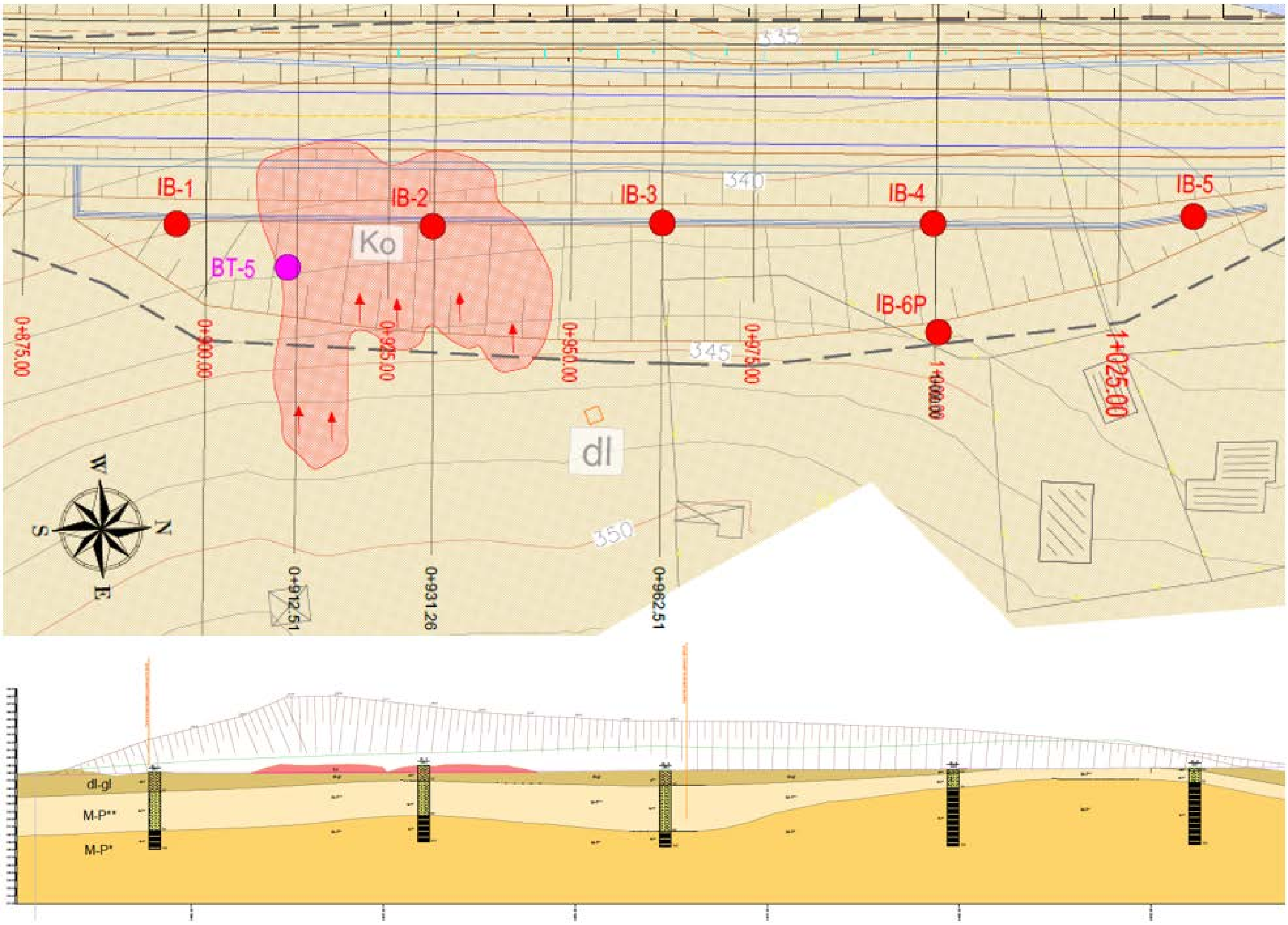


Figure 5. Engineering geological map with position of additional investigation works and an engineering geological section of terrain

Causes of slope instability

The instability of part of the slope occurred in the period november 2022 - april 2023. First, fissures and fractures appeared in the ground, and over time, a landslide occurred that gradually spread. The surface layer of deluvial clay (dl-gl) was affected by sliding to a depth of 1-3 m. The width of the landslide is about 40 m, and the length varies from 15 to 35 m.

After heavy rains in the winter period, there was an increased inflow of water into the soil and the formation of a local aquifer, which is fed by the infiltration of surface and seepage waters from the higher parts of the slope. The influence of this water is one of the causes that led to the instability of the constructed slope. The water affected the soil on the slope in different ways and led to a decrease in its shear strength. Also, a factor that significantly influenced the occurrence of landslides is the heterogeneity of the material affected by the slide, that is, the presence of sandy-gravelly interlayers in the clayey soil. These interlayers enabled seepage of underground water from the higher parts of the slope and the formation of compact aquifers in the clay layer, local wetting of the soil and reduction of soil strength parameters.

A set of immediate causes that appeared as a consequence of the action of water, and which, through combined action, led to the instability of the slope are:

- Increase in pore pressure of groundwater: Due to the saturation of the soil with groundwater, there is an increase in pore pressure, a decrease in normal effective stresses and a decrease in the shear strength of the soil. The influence of pore pressure was analyzed during the design process and was included in the slope stability calculation via the groundwater level and the Ru factor (Ru=0.2).

- Sufosis: internal erosion that occurs when water moves through the soil. Water causes fine particles of material to be carried out, which leads to the destruction of the natural structure of the soil and the gradual reduction of its shear strength.

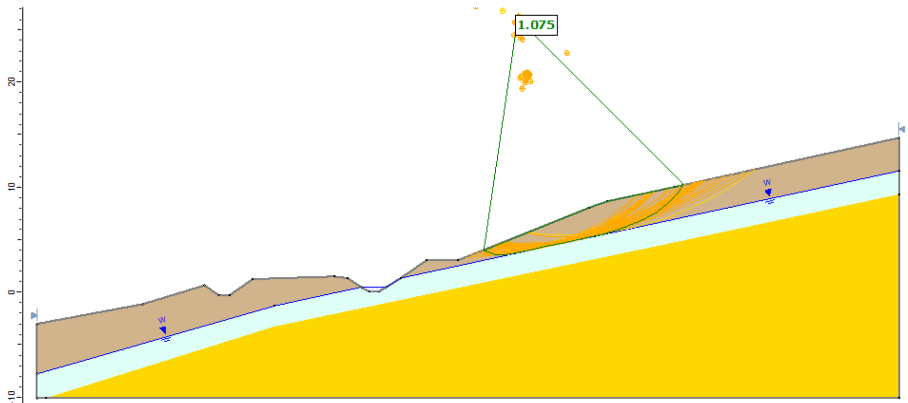
- Influence of surface and atmospheric water: During excavation, there is a reduction of horizontal stresses in the soil. When the terrain is built of hard highly plastic clays, reduced horizontal stresses can cause fissures to appear on the surface of the terrain. If the slope is open for a long time and there is a possibility of infiltration of surface and atmospheric water into the resulting fissures, there is a softening of the soil, a decrease in strength over time and a gradual shear deformation that leads to the progressive collapse of the slope. Touring the field in april 2023 it was observed that surface water was constantly flow in the body of the landslide on the part of the slope that is most affected by the slide around the chainage km 0+912.

- The impact of wastewater discharge: By visiting the field in april 2023, it was determined that the households located in the upper part of the slope, in the immediate vicinity of the landslide, do not have a connection to the city's sewerage network, and that they discharge waste water into septic tanks. Underground discharge of wastewater can contribute to additional wetting of the surrounding soil and decrease its shear strength.

Extreme conditions during stability analysis

During the analysis of the stability of the subject slope in the design process, critical (extreme) conditions that may occur during exploitation were assumed. Although there was no water in the soil during the research, underground water in the soil was assumed during the analyses. The influence of water was introduced into the calculation through the level of underground water in the layer of sandy clayey debris (M-P**) and the coefficient Ru=0.2 in the layer of deluvial clay (dl-gl). The adopted soil strength parameters are close to the minimum parameters obtained by laboratory tests. The samples tested in laboratory conditions were previously completely saturated with water during the shear strength test, according to current standards, so the negative influence of water on soil strength parameters is already included.

In order to demonstrate that the occurrence of a landslide (unstable slope) could not be predicted during the design process, we reduced the soil strength parameter to values lower than the minimum obtained by laboratory tests. We also included in the calculation the maximum hydrostatic influence of groundwater in the clay layer. By lowering the strength parameters of the deluvial clay layer (dl-gl) with cohesion values c=10 kPa and the friction angle ϕ=17°, as well as adopting the coefficient Ru=0.5, a satisfactory safety factor (Fs>1) is obtained (Figure 6).



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Water Surface	Hu Type	Hu	Ru
dl-gl		20	Mohr-Coulomb	10	15	None			0.5
M-P**		19.5	Mohr-Coulomb	10	25	Water Surface	Custom	1	
M-P*		21	Mohr-Coulomb	5	35	None			0

Figure 6. Cut slope analysis of the stability at km 0+950 with reduced soil strength parameters and complete saturation of the deluvial clay layer Ru=0.5

The stability analysis with reduced strength parameters shows that the occurrence of landslides could not be predicted because even with the adoption of significantly lower strength parameters than those obtained from laboratory tests (including parameters obtained from additional research), as well as the maximum hydrostatic influence in the deluvial clay layer, satisfactory factor of safety is obtained.

If during the design assumed that the influence of water that appears in the soil during a short period of time will lower the soil parameters to values close to the residual c_r=3 kPa and ϕ_r=12° (the values of the strength parameters c=4 kPa and ϕ =17°), most of the slopes that were designed on the route would have to be protected by supporting structures.

The instability occurred in the part of the slope from km 0+910 to km 0+950, with a total length of about 40 m, while the entire slope of the cut is about 125 m long (km 0+900 to km 1+025).

On the route of the Gornji Milanovac-Klatičevo road section, from km 0+000 to km 4+675, about 1200 m of road was designed/constructed in cuts in the same or similar clay materials (dusty clay, degraded marl, sandy marl) that occur on unstable part of the slope. The incline of the slopes are designed with the same inclines so that in the lower part of the slope the initial incline is 1:1.5 (33°) up to a height of 3 m, and the incline above 3 m is 1:2.5 (22°) with berms every 5 m height. The maximum slope height in the cuts is 4.8 - 11.5 m

Geotechnical recommendation for landslide rehabilitation

It is recommended to rehabilitate the unstable slope by creating a support structure in the lower part of the landslide or by replacing the clay material in the part of the unstable slope. It is also recommended to protect the part of the slope that is stable with geogrids in order to prevent the eventual occurrence of instability on that part of the slope as well. The recommended values of geotechnical parameters required for stress-deformation analyzes and stability calculations, when developing a landslide rehabilitation project, are shown in table 1.

Table 1. Recommended geotechnical parameters

Layer mark	Unit weight (kN/m^3)	Cohesion (kPa)	Friction angle (°)	Compressibility modulus (MPa)	Deformation modulus (MPa)
k_o	19.0	3	12	7 - 8	-
dl-gl	19.0	13	17	9 - 11	-
M-P**	19.0	18	25	10 - 14	-
M-P*	21.0	51-64	28-30	-	62 - 85

Conclusion

For the purposes of designing the subject slope, detailed geotechnical investigations of the terrain were carried out, which included: engineering geological mapping of the terrain, exploratory drilling in the slope zone and engineering geological mapping of the borehole core, observation of the occurrence of groundwater in the borehole and laboratory geomechanical testing of soil samples.

The slope stability analysis during design was done with soil strength parameters that are close to the minimum parameters obtained by laboratory tests and with the influence of groundwater, in order to simulate extreme conditions during exploitation. The stability analysis was performed for the section at the chainage km 0+950 (the highest part of the slope) and a satisfactory safety factor was obtained (Fs=1.13).

The water affected the soil on the slope in different ways and led to a decrease in its shear strength. Also, a factor that significantly influenced the occurrence of landslides is the heterogeneity of the material affected by the slide, that is, the presence of sandy-gravelly interlayers in the clayey soil. These interlayers enabled seepage of underground water from the higher parts of the slope and the formation of compact aquifer in the clay layer, local wetting of the soil and reduction of soil strength parameters.

In order to define in more detail the construction of the terrain and the geotechnical conditions for the rehabilitation of the unstable slope, additional geotechnical investigations were carried out in August 2023. Additional geotechnical investigations yielded very similar geotechnical parameters of the soil layers to those used in slope design. There was no underground water in the ground during the investigation.

The subsequent stability analysis with reduced strength parameters shows that the occurrence of landslides could not be predicted because even with the adoption of significantly lower strength parameters than those obtained from laboratory tests (including parameters obtained from additional research), as well as the maximum hydrostatic influence in the deluvial clay layer, satisfactory factor of safety is obtained.

The conditions that led to the instability of the slope are of a local nature and could not be foreseen during the design, which can be seen from the fact that the instability occurred in a part of the slope with a length of about 40 m, while the entire slope of the cut is about 125 m long. Also, on the route of the Gornji Milanovac-Klatičevo road section, about 1200 m of the road was designed / constructed in cuts in the same or similar clay materials that occur on the unstable part of the slope.

On the basis of everything previously stated, it can be concluded that the design of the subject slope is in accordance with all relevant standards and rules of the profession and that the occurrence of instability could not be predicted, i.e. that the occurrence of landslides occurred due to unforeseen underground conditions that occurred locally in the part of the designed slopes.

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