Received: 07.08.2023.
Accepted: 09.10.2023.

e-ZBORNIK Special Issue

Professional paper

Electronic collection of papers of the Faculty of Civil Engineering

https://doi.org/10.47960/2232-9080.2023.SI.13.90

ISSN 2232-9080

Influence of complex engineering geological and geotechnical conditions on the selection of combined measures for road landslide remediation

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Abstract: This paper presents the influence of complex engineering geological and geotechnical ground conditions on the selection of combined measures for the rehabilitation of landslide on the main road M5. Field and laboratory investigations were conducted to determine the engineering geological and geotechnical conditions of the site. The road is situated on a relatively high embankment within the landslide area, under which a culvert channels a natural stream. The geological substrate is found quite deep, 7 to 8 meters below the surface. Beneath the road, there is a mixture of fill materials of different qualities, indicating that a railway used to run along this route in the past. The slope below the road is relatively steep, approximately 10 meters in height, with a poorly maintained stone wall at its base. The fundamental concept of the proposed solution involves the construction of a support structure comprising piles, a head beam, and a reinforced concrete wall. The designed rehabilitation measures ensure the stability and functionality of the roadway.

Key words: engineering geological and geotechnical conditions, landslide, investigation works, remediation, drilled piles

Utjecaj složenih inženjersko-geoloških i geotehničkih uvjeta na izbor kombiniranih mjera sanacije klizanja trupa prometnice

Sažetak: U ovom radu prikazan je utjecaj složenih inženjersko-geoloških i geotehničkih uvjeta terena na odabir kombiniranih mjera sanacije klizanja trupa magistralne ceste M5. Za determinaciju inženjersko-geoloških i geotehničkih uvjeta predmetnog lokaliteta, izvedeni su terenski i laboratorijski istražni radovi. Cesta se u prostoru klizišta nalazi na relativno visokom nasipu ispod kojeg se nalazi propust, kojim se kanalizira prirodni potok. Geološki supstrat se nalazi relativno duboko, na dubini od 7 do 8 m, a ispod kolovozne konstrukcije je nasipni materijal raznolike kvalitete što je potvrdilo saznanje kako je ovom trasom nekada prolazila željeznička pruga. Kosina ispod ceste je relativno strma i visine cca 10 m. U dnu kosine se nalazi kameni zid u lošem stanju. U osnovi koncept rješenja se svodi na izradu potporne konstrukcije koju sačinjavaju šipovi, naglavna greda i AB platno. Projektirane sanacijske mjere osigurale su stabilnost i funkcionalnost prometnice.

Ključne riječi: inženjersko-geološki i geotehnički uvjeti, klizište, istražni radovi, sanacija, bušeni šipovi

1. INTRODUCTION

The investigation area of the landslide and the surrounding terrain covers an area of about 0.8 ha and administratively belongs to the municipality of Novo Sarajevo (Figure 1). Investigations and tests were carried out in accordance with the Terms of Reference, the Law on Geological Investigations, and depending on types and scope, they include: geodetic works, engineering geological mapping and profiling, drilling exploratory boreholes with field tests and sampling for laboratory testing of physical and mechanical characteristics of soil, and determining the groundwater level.

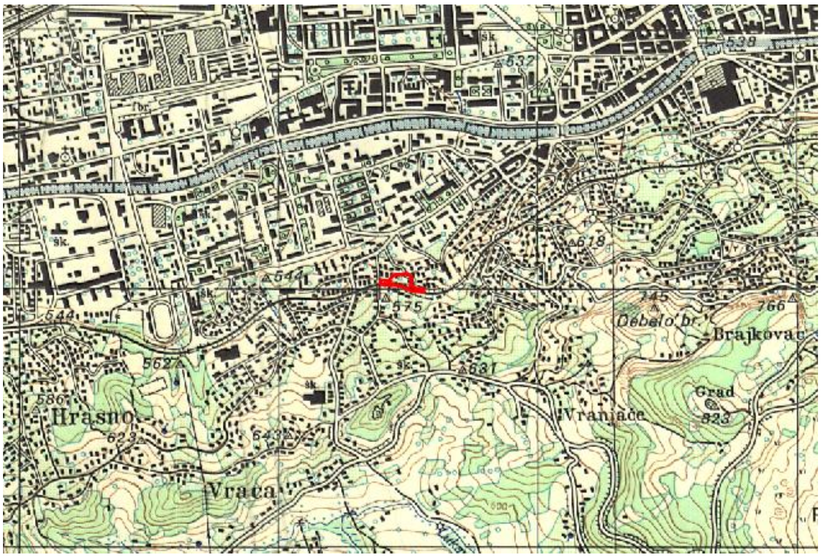

Figure 1. Geographical position of the site, Topographic map M 1:25 000, Sarajevo sheet

The geodetic survey of an area of about 0.8 ha was carried out. The geodetic survey was performed in the Gauss-Krüger system, in the national coordinate system. The plan made in this way represents an essential basis for work in the field and also a basis for the development of the road rehabilitation design. On the geodetic plan, a detailed engineering geological mapping of the terrain was conducted and an engineering geological map and characteristic profiles were made. Six exploratory boreholes with depths from 5 m to 9 m (46 m in total) were drilled with 40 SPT tests, while taking 12 samples for laboratory geomechanical tests and registering the presence and level of groundwater (Table 1).

Table 1. Coordinates, elevations and depths of the drilled exploratory boreholes

Borehole	X	Y	Z	Depth (m)	SPT (test)	Samples (pcs.)
B-1	6532463.39	4856007.47	559.85	7	3	2
B-2	6532482.93	4856013.51	559.75	9	9	2
B-3	6532473.76	4856016.62	559.50	9	8	2
B-4	6532482.39	4855997.75	560.40	7	6	2
B-5	6532463.66	4856018.33	560.00	9	9	2
B-6	6532489.60	4856041.04	547.30	5	5	2
		Total:		46	40	12

SPT tests were performed according to the adopted international standard ASTM D1586-20 and according to BAS ISO 22476-3. A two-part cylinder ("split barrel") was used in clays, and a "cone" was used in gravel (debris) and substrate rock masses. Geomechanical tests were carried out according to ASTM, BS and BAS ISO standards. The water content, bulk density, grain size distribution and parameters of shear strength and soil deformability were tested on the taken cover and substrate samples.

2. INVESTIGATION AND TEST RESULTS

The investigated landslide terrain at the site of the main road M5 morphologically belongs to the hilly-mountainous type of relief, with elevations of 550.00 m a.s.l. in the north at the toe of the landslide, up to 560.00 m a.s.l. at the level of the main road M5 in the southern part at the head of the landslide. Due to the heterogeneous geological structure, anthropogenic influences, neotectonic activity and different behavior of rock masses in the surface weathering zone under the influence of exogenous geological factors, the geomorphological structure of the terrain is complex. According to the geological structure, in morphogenetic terms, the subject terrain and its immediate surroundings belong to the hilly-mountainous and gravity-accumulation types of relief.

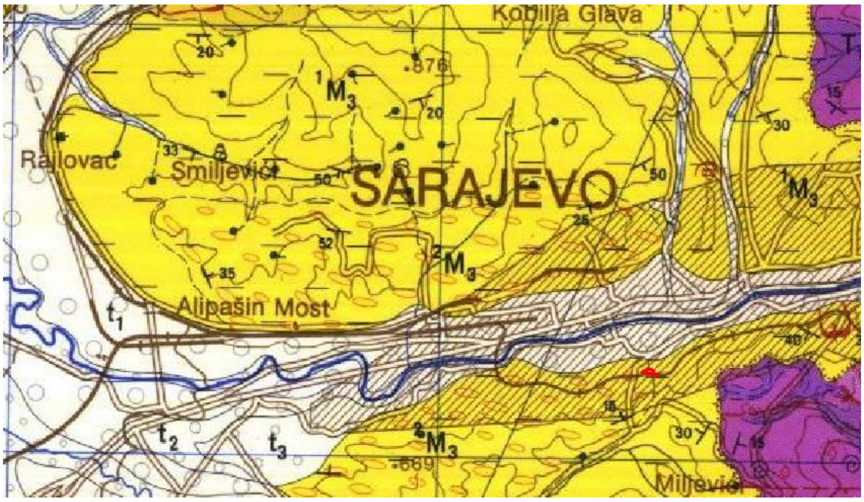

Figure 2. Geological structure of the studied terrain, [1]

The geological structure of the studied terrain is complex because individual geological formations have a complex facial composition and a complex structure that significantly affects the qualitative and quantitative properties of the rock masses and their stability on the sloping parts of the terrain. The structure of the terrain includes Neogene sediments of the upper Miocene ($^1M_3$), "the Koševo series" as well as modern Quaternary deposits (Q) in the form of surface covers of different genesis and material composition. The Upper Miocene lacustrine sediments ($^1M_3$) of the Sarajevo-Zenica Neogene basin, better known as the "Koševo series", transgressively and discordantly overlie the Anisian limestones and polyfacial Werfenian complex. The composition of this complex includes marly clays, marls, sands, sandstones and aleurolites. All the aforementioned lithological members were identified by drilling, either in the previous or these conducted investigations. According to the Basic Geological Map (OGK), sheet Sarajevo M 1: 100,000 (Figure 2), the thickness of the "Koševo series" in the wider area is estimated to be approximately 400 m, [1]. Quaternary formations (Q) are represented by anthropogenic artificial materials, clastic and cohesionless formations, eluvial-diluvial products of decomposition of the geological substrate and colluvial materials of landslides. Surface covers occupy the entire area of the investigated terrain. The surface covers are of heterogeneous, predominantly clayey-sandy-detrital composition. The thickness of these materials varies in the range of values from 4.2 m (B-1; B-6) to 7.0 m (B-3; B-5).

The tectonic structure of the investigated and surrounding terrains, according to OGK, sheet Sarajevo (Figure 2), belongs to the structural-facial units "Crepoljsko - Trebević - Treskavica - Prača" and "Sarajevo - Zenica Neogene Basin". The structural setting of the Sarajevo-Zenica Basin unit is relatively complex due to pronounced folding into folds whose axes are approximately perpendicular to the Dinaric structures. Tectonic movements in this part of the terrain had a significant effect on the disintegration of rock masses, increased fracturing, weathering and permeability, which is why the weathering crust of the geological substrate has a significant thickness and very variable and uneven physical and mechanical properties. Smaller folds with a higher folding index occur in the lower clastite horizons containing sandstones and marls.

In terms of the engineering geological composition, condition and properties of soil and rocks, two basic environments that reflect the geological structure of the terrain within the landslide and in the immediate environment have been identified: Quaternary surface covers and geological substrate.

Quaternary covers occupy the entire surface of the considered area. These are materials formed by the geological substrate decomposition processes or by anthropogenic activity during construction of roads and structures. Depending on the genesis, the following types or horizons of surface covers are identified: anthropogenic (technogenic) cover, colluvial material and eluvial-diluvial cover.

Anthropogenic materials - embankment was established in the road structure and around residential buildings. They are composed of asphalt, concrete, limestone debris, clay, sand, sandy clay. The embankment materials were identified in exploratory boreholes B-1 to B-5. Their thickness is up to 5.0 m. Colluvium is a very heterogeneous material environment, and its formation is related to the processes of physical decomposition of the geological substrate and anthropogenic artificial formations. Gravitational movements resulted in the mixing of limestone debris material and weathering crust material of Neogene sediments. Considering the aforementioned, the colluvial cover contains mixed clayey and debris materials. Namely, the colluvial cover is composed of red and brown sandy clays, red fine-grained sands. From the above, it can be concluded that the grain size distribution of artificial, anthropogenic formations (Vt) and colluvial materials (kl) is very heterogeneous. It should be emphasized that sometimes it is very difficult to draw a clear boundary between colluvial and eluvial-diluvial cover. In the vertical profile and laterally, individual lithological members often alternate so that the geomechanical properties of this cover are very variable and uneven. The thickness of anthropogenic formations of artificial materials of the colluvial type varies in values from 2.5 to 5.0 m (Table 2).

Table 2. Thickness of Vt, kl, cover [3]

Borehole mark	Borehole depth (m)	Thickness of Vt,kl, cover (m)	Average thickness (m)
B-1	7	2.5	3.3
B-2	9	5.0	
B-3	9	5.0	
B-4	7	1.5	
B-5	9	2.5	
B-6	-	-	

The eluvial-diluvial cover was found partially on the surface of the subject part of the terrain. Observed in a vertical section, the eluvial-diluvial materials underlie the anthropogenic and colluvial materials, and overlie the rock masses of geological substrate. The eluvial-diluvial cover is a lithological complex composed of multi-colored silty and sandy clays of red, gray, dark gray, brown, and yellow-brown colors, fine-grained sands of red, gray, yellow, and pale green colors, fine-grained debris of sandstones, claystones, and aleurolites, and marly clays. Multicolored sandy clays and sands, which in the vertical profile and laterally often alternate with other lithological members in the form of thin intercalations or isolated lenses, are dominant. This cover as a whole has a plastic to hard consistency and very variable and uneven geomechanical properties, which mainly depends on the percentage of water and rocky fraction. In a dry state, they have relatively favorable properties, and in a water-saturated state, they turn into an easily movable muddy-mashy mass. In a state of natural humidity, they are subject to swelling and increased settlement or, at low temperatures, to frost swelling. The eluvial-diluvial cover as a whole represents a favorable environment for the formation of landslides, and the contact with geological substrate represents the critical discontinuity for generation of sliding processes. According to the results of the conducted exploratory drilling, as well as the results of earlier investigations, the thickness of the eluvial-diluvial cover (el-dl) was found to be in the range of values from 1.5 to 4.5 m (Table 3).

Table 3. Thickness of eluvial-diluvial cover [3]

Borehole mark	Borehole depth (m)	Thickness of el-dl cover [3]	Average thickness (m)
B-1	7	1.5	2.43
B-2	9	1.5	
B-3	9	1.8	
B-4	7	2.5	
B-5	9	4.5	
B-6	5	2.8	

The geological substrate lies in the deeper parts of the terrain under the surface cover. Due to the exceptionally complex geological relationships in this investigated terrain, two substrate horizons have been identified: the geological substrate weathering crust and the geological substrate. The weathering crust of Upper Miocene sediments is identified under the cover material, and directly overlies fresh Upper Miocene sediments. The weathering crust is a product of *in situ* decomposition of bedrock under the effect of atmospheric agents and infiltration water.

In terms of material composition, it is also a heterogeneous environment composed of marly clay of light to dark gray color, and fractured, disintegrated and weathered clays, marls, aleurolites and sandstones. As a whole, the lithological members of this weathering crust are characterized by good natural compactness and relatively high penetration resistance values. Under the influence of water and climate changes, they are subject to disintegration into a loose mass. The thickness of the weathering crust zone of Upper Miocene sediments and substrate varies in a wide range, from a minimum of 2.1 to a maximum of 3.1 m (Table 4).

The geological substrate, or the geological basis of the terrain in the area of the landslide, is built up of the lithostratigraphic member - clastic sediments of the "Koševo series" of the Upper Miocene ($^1M_3$). The Miocene polyfacial complex underlies the deteriorated substrate material. The vertical and lateral alternation of individual lithological types such as aleurolites, claystones, marls, sands and sandstones is established by exploratory drilling within the lithological complex. The complex has a thinly stratified to stratified texture and a psammitic - aleuritic - pelitic structure. Aleurites and claystones predominate in the massif, while other lithological types occasionally alternate in the form of intercalations. The complex is generally characterized by a low degree of diagenesis (which is why marls turn into marly clays). The physical and mechanical properties of this complex are variable and uneven. Based on field investigations, it was determined that this marly complex *in situ* has very high penetration resistance values. Under the influence of water and climate changes, the lithological types of this complex are subject to processes of surface decomposition.

Table 4. The thickness of the weakened geological cover and extracted geological substrate, [3]

Borehole mark	Borehole depth (m)	Thickness of weathering crust and substrate of sediments 1M3 (m)	Average thickness (m)
B-1	7	3.1	2.46
B-2	9	2.3	
B-3	9	2.1	
B-4	7	3.1	
B-5	9	2.1	
B-6	5	2.1	

3. CAUSES OF LANDSLIDE FORMATION

The causes of landslides can basically be reduced to: predispositions due to the geological structure of the slope, which basically consists of erodible rocks subject to processes of decomposition and formation of clayey-sandy-detrital covers, artificial formations, covers, poor geomechanical characteristics, long-term creep of materials on the slope and changes in shear strength from peak to residual values, high groundwater levels due to intense precipitation or melting of snow cover.

4. HYDROGEOLOGICAL CHARACTERISTICS OF THE TERRAIN

The hydrogeological characteristics of the terrain in the landslide area at the site of the main road M5 are very complex primarily thanks to the geological structure of the terrain, the structure of porosity and the general permeability of the rock masses. According to permeability and the hydrogeological functions they have, two basic categories of rock masses can be identified in the terrain: permeable rocks with the function of reservoir rocks and impermeable rocks with the function of hydrogeological insulators.

Permeable rocks of intergranular porosity are cohesionless or poorly cohesive colluvial and eluvial-diluvial deposits, and anthropogenic materials (Vt). Their composition mainly consists of clayey debris, sand, stone aggregate, smaller and larger blocks, and silty and sandy clays. Based on the values of hydrogeological parameters and abundance of water phenomena, colluvial materials can be separated into the class of moderately permeable rocks, while eluvial-diluvial and anthropogenic materials can be separated into the class of low-permeable rocks. As a whole, they represent hydrogeological complexes in which lithological members of different permeability often alternate laterally and vertically. Permeable rocks of intergranular permeability have the function of a near-surface aquifer of more or less continuous extent, but of small to medium yield, and occasionally rapid and sudden recharge. Depending on the hypsometric position of permeable and impermeable rocks, gravity and overflow type springs appear in the surrounding area. They more intensively soak parts of the slopes composed of plastic clayey Neogene formations and thus generate sliding processes on the slope. The zone of primary groundwater discharge is almost typically masked by limestone scree material, so that now they are discharged through a network of secondary streams scattered all over the slope. For this reason, some parts of the slopes are more heavily soaked throughout the year, and increased moisture content in environments with highly variable physical and mechanical properties is most often the cause of the uncontrolled development of landslides in this part of the investigated terrain.

The "Koševo series" rock complex of the Upper Miocene ($^1M_3$) is included in the category of impermeable rocks that function as hydrogeological barriers. The $^1M_3$ complex includes aleurolites, marls, sands and sandstones. They typically discordantly overlie Anisian limestone. Miocene deposits are mainly covered by Quaternary eluvial-diluvial and colluvial formations. Considering the position they occupy in the terrain, the rock masses of the Upper Miocene hydrogeological complex represent an overlying hydrogeological barrier to Anisian limestones and an underlying barrier to Quaternary formations. During the investigation works on the subject terrain, groundwater was found at different depths in the eluvial-diluvial and colluvial cover. In addition to boreholes with water, there were also dry boreholes. The occurrences and levels of groundwater in the exploratory boreholes that were drilled as part of these investigations are shown in the following table.

Table 5. Groundwater occurrences and levels in exploratory boreholes, [3]

Borehole mark	Groundwater occurrence (m)	Groundwater level (m)
B-1	4.5	6.1
B-2	6.2	-
B-3	-	-
B-4	-	-
B-5	7.0	-
B-6	1.5	-

4. RESULTS OF LABORATORY AND SPT TESTS

In the materials of artificial formations (horizon 1a), sampling for laboratory tests was not performed (Table 6), and the mean value of standard penetration test is 27.41 (Table 7). Six samples from the eluvial-diluvial and colluvial cover materials (horizon 1) were tested during the investigations conducted for landslide rehabilitation. The bulk density of the material of this horizon was determined to be 21.0 kN/m3. The performed direct shear test resulted in the values of cohesion c = 4-10 kPa and internal friction angle φ = 19-31°. The above indicates a very variable composition of these materials, where the basic component is predominantly the debris fraction, but with very different ingredients, from clay, to silty fraction, to sand. The conducted penetration tests resulted in an average value of N = 21.91 blows, which corresponds to a very stiff consistency, [2].

Three samples from the material of weathering crust (horizon 2) were tested for the needs of landslide rehabilitation. According to the USC classification, these materials are also classified as CI - low plasticity clay. On one sample of these materials, direct shear tests were performed, and gave the values of internal friction angle φ = 24.1° and cohesion c = 25 kPa. The bulk density was also determined and its value is γ = 21.8 kN/m3. Five SPT tests were performed in these materials, resulting in an average value of N = 44.2 blows, which indicates a very stiff and firm consistency, [2].

Table 6. Sample overview, [3]

Borehole	1a	1	2	3
B-1	-	1		1
B-2	-	1		1
B-3	-	1	1	
B-4	-	1		1
B-5		1	1	
B-6		1	1	
TOTAL:	-	6	3	3

Table 7. Results of SPT tests - uncorrected values, [3]

Horizon	Number of tests	Value (N30)		
		mean	minimum	maximum
1a	12	27.41	10	53
1	12	21.91	12	30
2	5	44.20	39	50/05
3	11	50/08	59	50/06

Three samples from horizon 3 (upper Miocene polyfacial complex) were taken and tested for the purposes of landslide rehabilitation. The conducted direct shear tests gave the values of cohesion of c = 8-9.8 kPa as well as internal friction angle φ = 25-27°. The bulk density of both samples was also determined and its value is γ = 21.0-22.0 kN/m^3. Eleven SPT tests were performed in these materials, resulting in a value of N = 50/08 blows, which indicates a firm consistency, [2].

5. DESCRIPTION OF REMEDIAL MEASURES AND NUMERICAL CALCULATION

Spatial possibilities, slope inclination, municipal infrastructure and the impossibility to interrupt the traffic flow limit the use of heavy machinery for the rehabilitation of the landslide. Remedial measures include the construction of a support structure consisting of piles with a diameter of 600 mm, a head beam and a reinforced concrete wall. The piles are 10 m long and 600 mm in diameter. The upper 80 cm of the pile is not concreted, but only the reinforcement is left, which is tied to the reinforcement of the head beam. The piles are spaced 2.0 m from axis to axis and a total of 19 piles are constructed. The dimensions of the head beam are 80x80 cm and its length is 38.75 m. From the head beam, as a single unit, a 30 cm thick and 1.35 m high reinforced concrete wall is constructed. A favorable circumstance for accepting this type of support structure is relatively small excavations, which minimizes the risk to the stability of the terrain during the execution of works. In addition, the rehabilitation measures include the replacement of the subbase and asphalt in the unstable part of the road and sidewalk, and construction of a drainage system. The role of the drainage system is to collect and in a controlled manner remove the seepage water that reaches the landslide zone from the higher parts of the slope. The stability and functionality of the support structure consisting of piles with the head beam is proven by the 3D numerical model. The finite element method was used for the calculation. Soil materials were modeled by the Mohr-Coulomb constitutive behavior law. The strength and deformability parameters of the soil material are shown in Table 8. The calculation model with a finite element mesh is shown in Figure 3.

Table 8. Geotechnical characteristics of soil and rocks, [3]

Material / Soil parameters	Embankment of crushed stone with clay	Sandy clay	Marly clay/ Loose substrate	Marl/ Substrate
Bulk density [kN/m^3]	20	20	20	21
Internal friction angle [º]	33	22	30	30
Cohesion [kPa]	5	5	10	20
Dilatancy angle [º]	3	0	0	0
E reference [kPa]	20 000	10 000	15 000	35 000

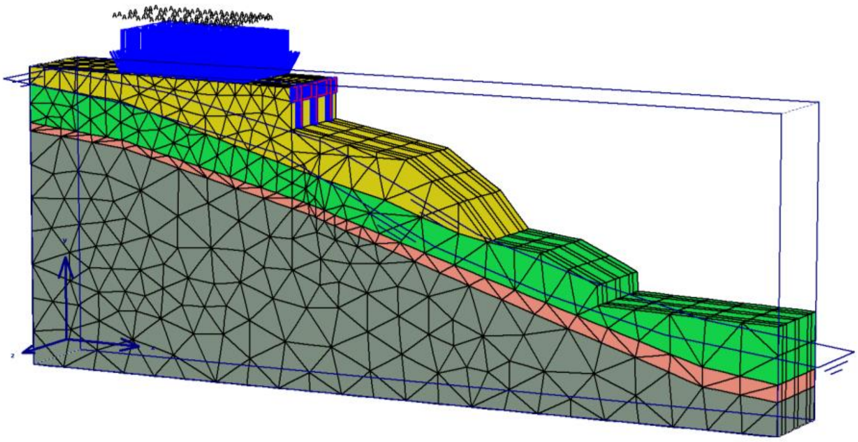

Figure 3. Analyzed model with finite element mesh

6. CONCLUSION

This paper presents the influence of complex engineering geological and geotechnical ground conditions on the selection of combined measures for the rehabilitation of landslide on the main road M5. To determine the engineering geological and geotechnical conditions of the site, a total of 5 exploratory boreholes were drilled, with a depth of 5.0 to 9.0 m, 40 standard penetration tests and groundwater level measurements were performed, and 12 samples were taken for laboratory geomechanical tests. The use of heavy machinery is limited by spatial possibilities, slope inclination, utility infrastructure and the impossibility to interrupt the traffic flow. Basically, the concept of the solution is reduced to the construction of a supporting structure consisting of piles with a diameter of 600 mm, a head beam and a reinforced concrete fabric. This includes replacement of the road base and asphalt in the unstable part of the road and sidewalk, and construction of drainage. The designed rehabilitation measures ensure the stability and functionality of the roadway.

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