Geotechnical Conditions, Stability Analysis and Remedial Measures of Višnjička 74 Landslide in Belgrade

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Abstract This paper presents the results of geotechnical investigations, stability analysis and urgent remedial measures of the landslide at Višnjička 74 street in Belgrade. The area under study is located at the foot of an old fossil landslide. The landslide was activated due to excavation of the foundation pit in June 2023. Due to large displacements of the retaining structures and the surrounding objects, urgent remedial measures were proposed. Following these measures, further sliding was prevented. Additional geotechnical investigations were performed (geophysical investigations, inclinometer measurements, boreholes, soil sampling, laboratory tests, piezometers), to obtain more comprehensive insight into the processes responsible for sliding. Residual shear parameters were determined by laboratory tests, and back calculated using numerical analysis and inclinometer readings. Very complex geotechnical conditions were determined on-site and thus presented in the light of future construction works.

Keywords landslide, foundation pit, inclinometer, back analysis, stability analysis

Introduction

The site is located at the bottom of the residential area and the identically named natural slope Karaburma at Višnjička 74 street in Belgrade. It is bordered by the streets: Višnjička, Vojvode Micka Krstića, and Triglavska (Figure 1). The wider area is densely urbanized and represents a zone of combined activities (industrial, commercial, and residential). On the north side, the site is bordered by Višnjička Street, and on the south, there is a zone with objects for individual housing and the residential-business complex "Danube Terraces". To the east and the west, there are workshop halls and warehouse spaces.

The original design included the construction of two underground parking levels, and a piled retaining structure for excavation protection was already in place at the site.. The terrain at the site is not flat and is arranged for mechanization access.

The site is situated at the border between the Danube's highest river terrace and the Karaburma slope's bottom part. Within the site, the elevation of the terrain ranges from 70 to 80 m above sea level.

Excavations of the foundation pit were performed during June 2023, reaching a depth of approximately 6-7 meters. Due to the excavation procedure, combined with intensive rainfall during May and June 2023, significant displacements of the piled retaining structure occurred at the end of June 2023. According to the Expert Opinion of the Faculty of Civil Engineering in Belgrade, extensive displacements were caused by activating a part of the fossil landslide in the wider area of the location. These landslide movements threatened the neighbouring objects and the site itself. As a recommended measure for landslide remediation, - urgent, intensive, and therefore uncontrolled (in terms of compaction by standard procedures) filling of the foundation pit using predominantly earth material, and occasionally with construction debris, was done in the first half of July 2023. After the refilling of the pit, the landslide was stabilized.

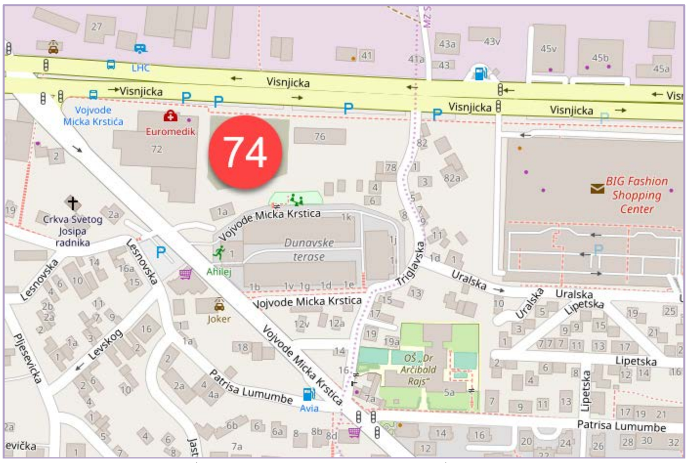

Figure 1. Site map (the site is marked by 74)

Previous geotechnical investigations

Last time, the site underwent geotechnical investigations in 2019 for a commercial-residential building design (manually drilled 4 boreholes, reaching up to 12 m in depth, each). Additionally, the area and its surroundings have been systematically investigated over the past 50 years. A major geotechnical study was conducted in 1975 for an industry hall construction, including 12 boreholes. In 1961, investigations were done to design a residential block (Dunavski Venac), uphill. Further studies occurred in 1989 for the "Stara Karaburma" urban plan. There were at least four archive boreholes close to the site. Detailed investigations were also conducted around Višnjička Street, with only one borehole near the site itself.

Additional investigations were necessary due to several factors. First, the previous studies were conducted decades ago, and geological conditions may have changed over time due to natural processes and human activities. Second, the reactivation of the fossil landslide that has occurred on the site required additional investigation to safeguard the site and the surroundings, since the results of the ground investigation campaign from 2019 were not adequate for this task.

Geological and geomorphological setting

The study area, situated on the right bank of the Danube, has previously undergone extensive earthworks, including levelling, excavation, filling, and material rearrangement. It features complex geomorphological and geological structures, primarily composed of Quaternary sediments from abrasion-erosion terraces. These terraces were covered by layers of loess deposited during the Quaternary period. Marly clays and Marls represent the oldest sediments identified via borehole core logging.

Variations in climatic conditions during the Quaternary era resulted in diverse sediment deposition, leading to challenges in delineating precise lithological boundaries. From the lithological point of view, these sediments range from gravel to sand, silt, and clay, with varying percentages of each component and predominantly fine to occasionally medium-grained texture. Sedimentological analyses indicate angular or weakly rounded grains, suggesting minimal transportation during the deposition time.

Engineering geological & Geotechnical investigations

Field investigations were conducted by the University of Belgrade - Faculty of Civil Engineering during the period from July to August 2024.

The following engineering-geological and geotechnical investigations and tests were carried out in the research area (Figure 2):

- Engineering-geological and geotechnical reconnaissance of the terrain;
- Borehole drilling with the installation of piezometer and inclinometer constructions;
- Engineering-geological mapping of the borehole core with soil/rock sampling;
- Geodetic and geotechnical monitoring of retaining structure and terrain;
- Geophysical investigations.

Engineering-geological reconnaissance

The reconnaissance included inspections of all structures on adjacent parcels as well as on the slope near the residential-business complex "Danube Terraces". During this process, the degree of damage to the constructed retaining structure, surrounding infrastructure and buildings was visually assessed. Locations for new investigation works (borehole drilling and geophysical surveys) were also identified. Given that the terrain is significantly urbanized, and that substantial backfilling of the previously excavated foundation pit has been carried out on the site itself, it was not possible to conduct geological surface analysis.

Geotechnical borehole core drilling

The borehole drilling was conducted using continuous coring to investigate subsurface geology, sediment properties, and hydrogeological characteristics. Six new boreholes, reaching depths of up to 36 meters (totalling 186.9 meters), supplemented previous investigations. Special attention was given to obtaining undisturbed core samples to identify potential landslide slip surface zones by reducing the drilling pressure and without using additional fluids. Detailed engineering-geological core logging aided in defining geological layers, while core samples were tested in geotechnical labs to determine soil physical and mechanical properties. Piezometers were drilled and installed close to the borehole positions to monitor groundwater levels and assess their influence on terrain deformation and nearby structures. Besides the piezometers, existing depression wells were also used for this purpose (Figure 2).

Geodetic and geotechnical monitoring

A geodetic monitoring network was set up to track deformations in the retaining structure, neighbouring objects, and terrain surface. It included 55 stabilized points, using bolts or reflective markers. Typically, points were monitored once per day, but in cases of heavy rainfall or controlled excavation, monitoring was conducted twice daily, before and after the excavation completion.

Geophysical investigations

Geophysical investigations were undertaken at the site by seismic refraction profiling along six profiles (Figure 2). Their positions and lengths were customized based on site conditions. The aim was to identify geological layers with varying primary seismic wave velocities, that could indicate diverse lithological environments, and to ascertain the presence of a solid rock mass. Across 5 of 6 profiles, four different layers were identified, with three boundaries that delineate them. Despite the efforts, the presence of a solid rock mass within the investigation area could not be confirmed. The south-eastern border zone with a piled retaining structure including the RC pile cap disabled its confirmation. Contour maps of identified geological unit borders were generated to determine spatial positioning and quantify angle variations, crucial for assessing potential instability or slip surface zone.

Geotechnical laboratory testing

Laboratory tests of the physical-mechanical properties of soil were conducted at the accredited Laboratory for Soil Mechanics at the University of Belgrade, Faculty of Civil Engineering, as well as at the accredited Laboratory for Roads and Geotechnics at the Institute for Testing of Materials Serbia (IMS), Belgrade. Tests were conducted on 43 representative samples. Additionally, 65 additional samples were taken from the boreholes for testing the soil moisture content.

The results of these laboratory tests provided valuable data to define representative soil profiles for slope stability analysis and to assess and mitigate landslide hazards.

Results of the geological & geotechnical investigations

The wider area surrounding the site is characterized by the terrain surface that has varying surface slopes, composed of colluvial loess, diluvial clays, and other Quaternary sediments overlaying Neogene marly clays, clayey marls, and marls interbedded with layers of limestone (Figure 4). The marly clays in the subsurface zone are weathered and prone to volumetric changes (swelling). Such terrains are characterized by slow movements of soil masses, affecting degraded diluvial clays in the slope.

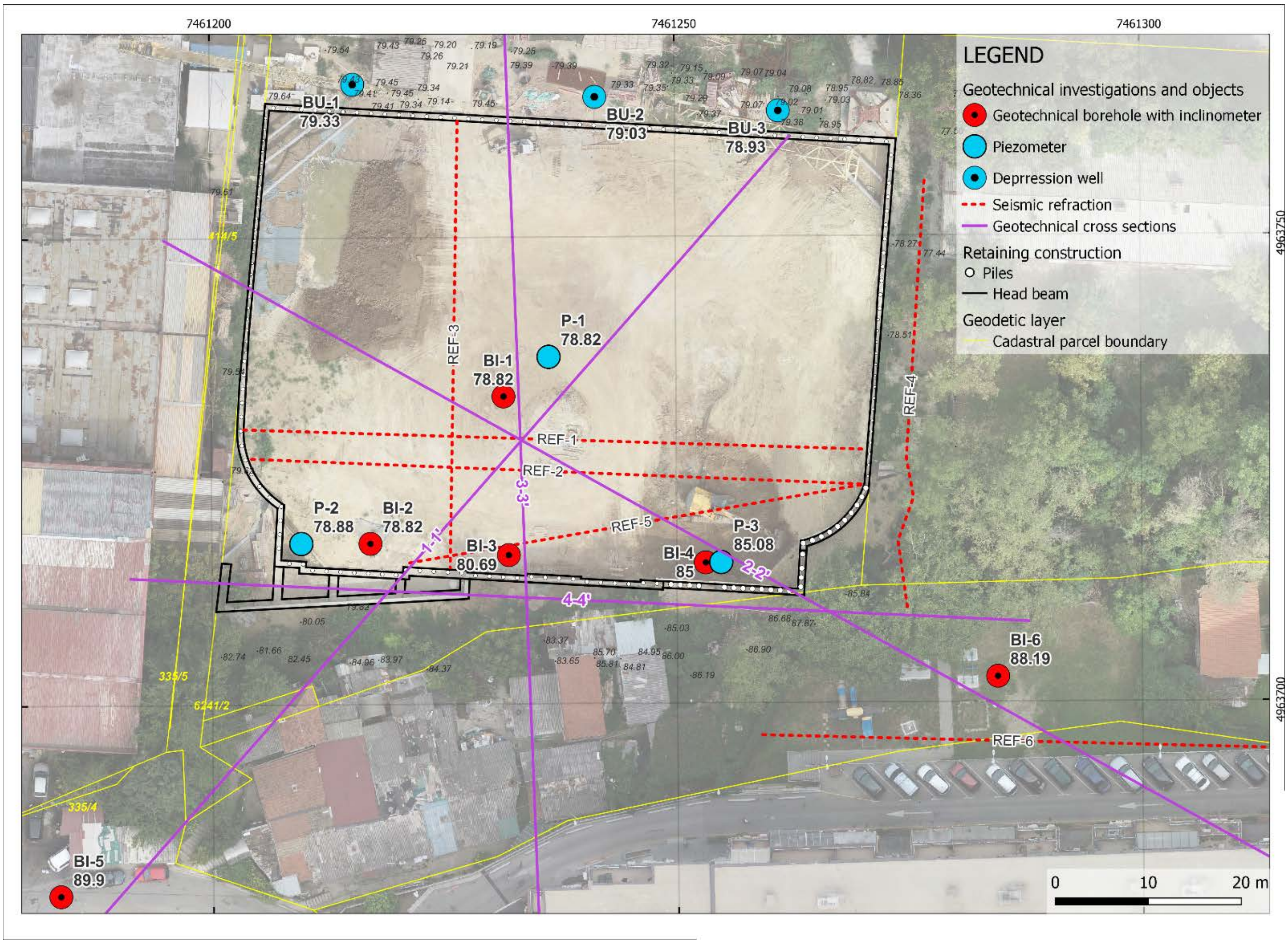

Figure 2. Situation of newly conducted geotechnical investigations

The engineering-geological conditions in such environments, which need to be thoroughly and comprehensively investigated beforehand, require complex geotechnical measures to enable rational space utilization for construction purposes. In such terrains, measures such as proper drainage system and slope stabilization are necessary, involving the design and construction of massive protective or retaining structures using piles (or diaphragm walls) and landslide remediation based on detailed geotechnical terrain investigations and intensive and continuous geotechnical monitoring.

The stability of the slope extending from the site foundation pit across the “Danube terraces” is influenced by the specific natural terrain configuration. The most significant geological-morphological-hydrogeological factors stem from the interaction and disposition of Quaternary and Tertiary sediments, represented by weathered diluvial and marly clays, terrain inclination, and the geological history of Tertiary substrates (paleo-shorelines and adverse hydrogeological conditions).

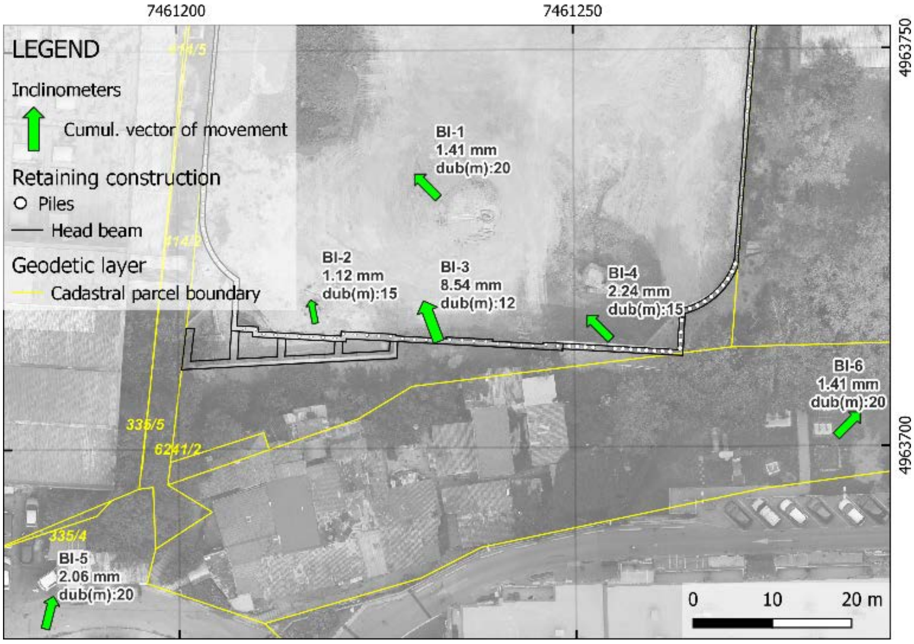

Figure 3. Vectors of maximum (cumulative) inclinometer displacements

A crucial factor in assessing the stability of the subject slope, as well as the broader surroundings, is the urbanization of the area - the impact of human activities, primarily unplanned or unprofessional earthworks, which often lead to the reactivation of certain parts of landslides or the formation of new local terrain instabilities. It is worth noting that during the construction of facilities in the immediate vicinity, relatively significant ground movements have occurred in the wider area, indicating potential fossil landslide (re)activations. These circumstances required redesign of the mentioned facilities, as well as the implementation of additional, non-planned measures for remediation and stabilization compared to the initial design solutions, which all led to significant construction delays.

From the perspective of slope stability, based on the results of engineering-geological and geotechnical investigation results (such as geotechnical monitoring, analysis of available technical documentation, and adopted engineering-geological and geotechnical terrain models), it has been determined that there is a direct correlation between the slope and the hillside sliding above the site, even during shallow excavations or the incision of the slope and hillside toe that is situated in the foundation pit of the site.

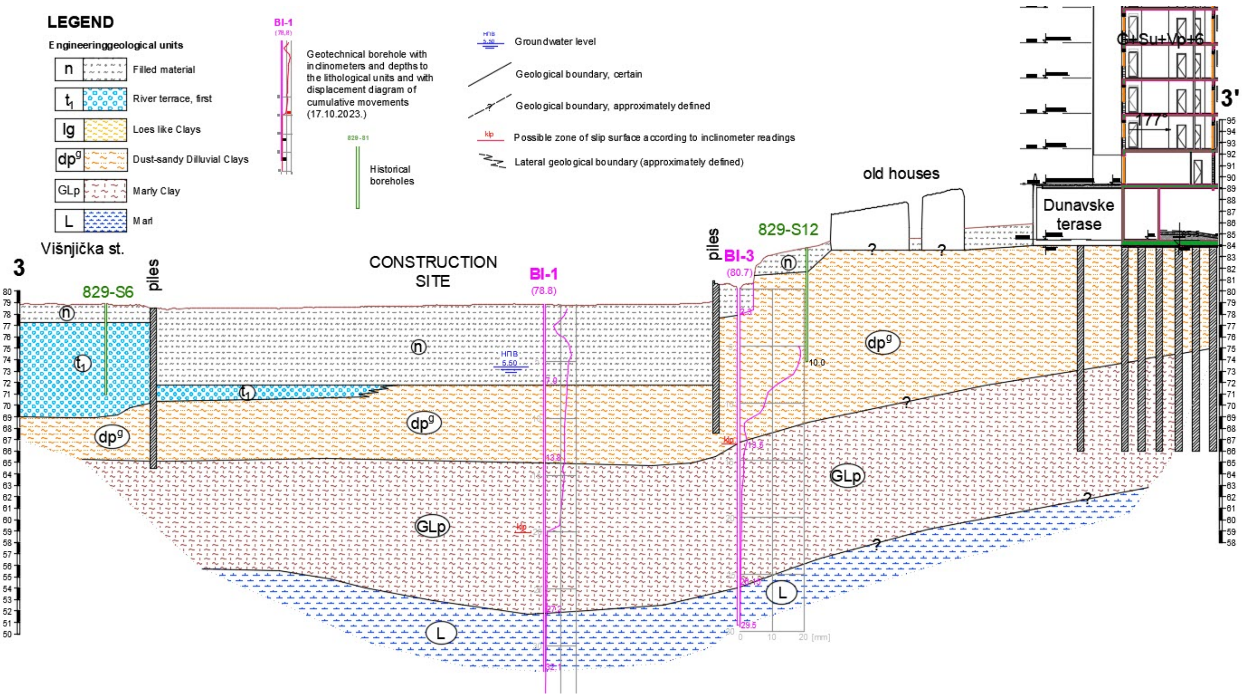

Figure 4. Geotechnical cross-section 3-3’

The ground investigations revealed a relatively high groundwater level (2 to 5 m below surface level, as shown in Figure 4), compared to the original excavation plan (up to 72 m above sea level), accompanied by occurrences of seepage and pressurized groundwater in soil fissures. A wet period from May to June 2023 coincided with excavation, leading to a rise in groundwater levels and unfavourable hydrological conditions. The hydrological state resulted in high pore pressures within the soil mass, contributing to the formation of deep sliding surfaces in the marly clays. These high pore pressures represent a significant geotechnical constraint for slope stability at the site location.

During the active mechanical excavation, the maximum daily value of displacements ranged from approximately 5 to 10 mm.These observations characterize the slope as a slow-moving landslide, with the slope currently considered to be in the intermediate stage of failure according to literature recommendations (Maksimović, 2008).

A total of 6 inclinometers were installed at the site. Based on the inclinometer readings, the sliding surface is detected at various depths, ranging from 13 to 20 m. Initially, all inclinometers showed zero movements, and therefore the controlled excavation in the southern part of the foundation pit was done, to "trigger" reactivation of the previously stabilized landslide. After the controlled excavation, all installed inclinometers showed movements. Final inclinometer readings are given in Figure 3. In this figure, only the cumulative vector of movements is depicted at depths corresponding to the highest movement rates identified in the analyzed incremental graphs.

Displacement values (> 2 mm) and landslide activity directions were recorded in inclinometers BI-3 (Figure 5) and BI-4 at depths of 12-15 m. Although the displacements near the precision limit (<2 mm) were detected in inclinometers BI-1, BI-2, and BI-6, they cannot be disregarded, as their activity coincided temporally and occurred at similar depths as those in inclinometers BI-3 and BI-4. Clear determination of the depth and shape of the landslide surface was not feasible without additional inclinometer movements and prolonged monitoring, risking the stability of adjacent structures, particularly the residential business complex "Danube Terraces".

Figure 5. Photograph of Bi-3 borehole core log in the zone of the slip surface (yellow arrow)

Conservative values were adopted for the shape and depth of the landslide slip surface, resulting in an irregular shape and block-like movement mechanism, categorizing the landslide as deep. The surface affected by sliding remains uncertain due to the inability to systematically monitor the wider area.

Numerical Analysis

Based on the results of the field and laboratory geotechnical investigations and inclinometer monitoring, it was concluded that the construction of a residential and commercial building in the considered location has an impact on neighbouring buildings and the global stability of the slope. Therefore, computational profiles of the terrain were formed and a numerical analysis of stability with back-analysis was performed. Analysis was performed on 2D models, using the limit equilibrium method in Rocscience Slide 6. Morgenstern-Price slice method was used, which simultaneously satisfies all equilibrium conditions. The global safety factor was adopted as a stability criterion. The piled retaining structure is modeled as a very high-strength material. Analysis was done on 2 representative 2D cross-sections.

First, the back analysis based on the inclinometer observations was done. According to these measurements, it was concluded that the sliding mechanism is block-like and the sliding zones are mainly in the layer of marly clay (in contact with laminar clays, in the contact zone with deluvial clay and in the contact zone with limestones). Therefore, two sliding surfaces (shallow and deeper) of the block type (slip zone) with residual shear strength parameters were assumed. The calculation was made assuming residual shear strength parameters for the entire layer of marly clay. Results of the numerical back analysis are in line with laboratory values of residual angle of internal friction, and the same values are obtained for both analyzed cross sections.

After the back analysis, the following situations (scenarios) were simulated:

- Backfilled foundation pit (after large displacements in the end of June 2023);
- Complete foundation pit excavation (with berms), according to the original design (Figure 6);
- Controlled excavation to "trigger" reactivation of the previously stabilized landslide, September and October 2023 (Figure 7);
- Excavation of 1-1.2 m - alternative design with shallow mat foundations.

Obtained results show that complete foundation pit excavation, as well as controlled excavation, leads to a factor of safety lower than 1, which is in line with the field observations and inclinometer readings. Also, surrounding objects are in the zone of critical sliding surfaces. With an unexcavated foundation pit, factors of safety range between 1.2-1.5, which is considered acceptable. Therefore, an alternative design solution with a shallow mat foundation is checked, and this scenario leads to the factors of safety 1.18-1.4, which is considered acceptable.

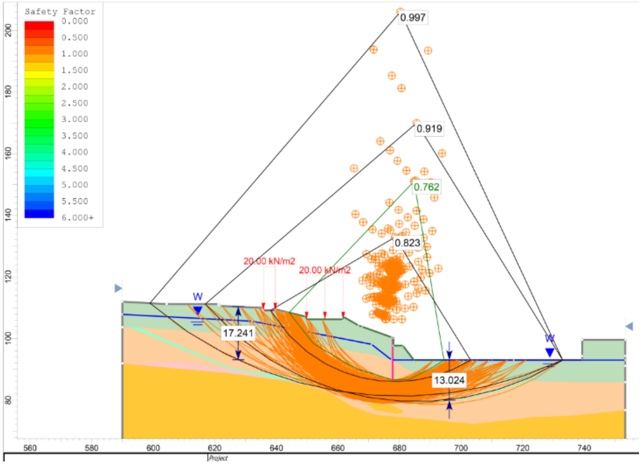

Figure 6. The factor of safety for complete foundation pit excavation (with berms), according to the original design (section 1-1). Both assumed sliding surfaces are critical

For the numerical back analysis profiles shown in Figures 6 and 7, we did not consider the load from the "Danube terraces" because the observed domain does not extend to the retaining structure on the construction site. On the other hand, the "Danube terraces" are founded on piles resting on a layer of marl that is considered as geotechnical bedrock.

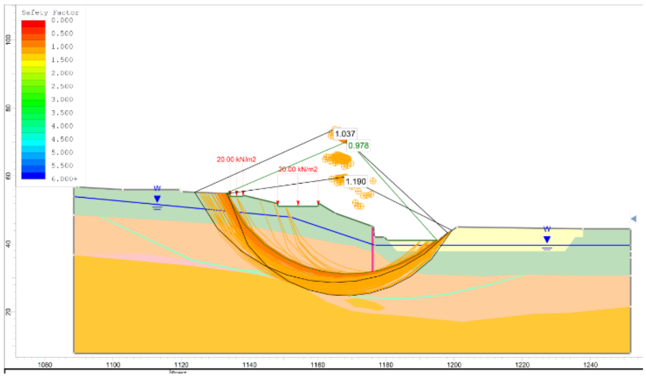

Figure 7. Factor of safety for controlled excavation to "trigger" reactivation of the previously stabilized landslide (section 1-1). Factor of safety ~1.0

Remediation Measures

As previously shown, foundation pit excavation would lead to a large movement of a landslide. Therefore, to proceed with an excavation, the very expensive retaining structure must be constructed first. Due to high costs, an alternative solution without underground floors is adopted. First, the shallow mat foundation is considered. However, due to the urgent and uncontrolled filling of the foundation pit, a very soft and thick (6-8 m) fill was formed, which made the shallow foundations impossible to construct. Estimated settlements of the shallow foundations on fill are in the range of 30-40 cm, which is considered unacceptable.

Due to the very high compressibility of the fill, ground improvement methods using jet-grouting or vibro-compactions were proposed. As an alternative, deep-piled foundations could also be a possible solution. In this case, the pile base should remain above the slip surface, to increase the normal pressure on the slip surface.

Before any further work on the foundation design and execution, an additional geotechnical study including CPT or DPHS testing of the fill is recommended. Due to the high heterogeneity of the backfill, there's a possibility that the coarse-grained components may restrict the effectiveness of such testing, necessitating caution in interpretation. Geotechnical and geodetic monitoring should be continued during all of the further works.

Conclusions

The landslide on the Višnjička 74 street was activated due to an excessive excavation of the foundation pit in June 2023. Urgent remedial measures and additional geotechnical investigations were executed. Ground investigations have shown very complex geotechnical conditions. Numerical analysis shows that the excavations of the foundation pit are impossible without placing a very expensive retaining structure. Therefore, alternative foundation solutions were proposed.

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