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Landslide Remediation in Save Skarica Street, Sarajevo – A Case Study

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ABSTRACT
The Save Skarića landslide is located in an urban area of Sarajevo, on the northern slopes of Mount Trebević. During a period of heavy rainfall, slope movement occurred and caused damage to several residential buildings.
This paper presents the scope of engineering-geological and geotechnical investigations, the remediation design, and the monitoring plan. Activation of the landslide was manifested by cracks in residential buildings, retaining walls, and the access road. Engineering-geological and geotechnical investigations established that sliding occurs predominantly within the clayey eluvial-deluvial cover above a more competent Miocene geological substratum. Water was identified as the key destabilizing factor. Water from a local culvert, which had been obstructed by the construction of a retaining wall beside one of the buildings and by backfilling behind the wall, spread uncontrolled over the slope. This caused saturation and weakening of the cover material. The resulting reduction in shear strength led to deformations that appeared as cracks in nearby buildings and retaining walls.

Keywords: *landslide, groundwater, substratum, shear strength, slope stability, bored piles, retaining wall.*

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I. INTRODUCTION

Landslides involve the downslope movement of soil, rock, or debris, while the mechanism and rate of movement may vary considerably depending on geological structure, morphology, water conditions, and human activities [3,4]. In urban areas, the consequences of instability are not limited to the slope itself: deformations may affect buildings, retaining structures, utilities, and access roads. Therefore, risk assessment and the selection of remediation measures require an integrated consideration of engineering geology, soil mechanics, hydrogeology, and structural analysis [5–7].

The subject of this paper is the landslide at 22 Save Skarića Street in the Municipality of Stari Grad Sarajevo. According to the available design documentation, cracks were recorded in retaining walls and residential buildings, the access road was damaged, and continuous water flow was observed down the slope. Field observations and investigation works indicated that the long-term uncontrolled spreading of water over the slope was caused by blockage of the culvert.

The objectives of the paper are to: (1) present the engineering-geological and hydrogeological conditions of the site, (2) systematize the investigation results and relevant geotechnical parameters, (3) explain the landslide activation mechanism, (4) present the numerical stability analysis, and (5) analyze the selected remediation solution, which includes drainage and a retaining wall supported by bored piles.

II. LITERATURE REVIEW

2.1. Landslides and instability factors

Modern landslide classifications are based on the type of displaced material and the dominant mode of movement. Cruden and Varnes [3] provide a terminology widely used to describe slides, falls, topples, flows, and complex movements. For practical remediation, it is particularly important to distinguish between causes and triggers: slope geometry and weak soils may create a predisposition to instability, whereas intense rainfall, leakage from utilities, changes in drainage, or excavation may directly trigger movement [4,5]. Water affects stability by increasing pore-water pressure and reducing effective stress, changing the consistency of clayey materials, causing erosion, and softening shear zones. Therefore, surface and subsurface drainage are among the most common and effective remediation measures where hydrogeological conditions play a dominant role [5–7].

2.2. Slope stability analysis methods

Classical limit-equilibrium methods are based on the equilibrium of forces and/or moments along an assumed slip surface. Bishop's simplified method [8] and the Morgenstern–Price method [9] are fundamental approaches for the analysis of circular and general slip surfaces. Fredlund and Krahn [10] showed that the methods differ in their equilibrium conditions and assumptions regarding interslice forces. In modern practice, finite-element methods enable staged modelling of construction, deformation, and strength changes. In PLAXIS, safety analysis is performed by reducing the tan φ and c strength parameters until a failure mechanism develops, yielding a global safety multiplier [11].

2.3. Landslide remediation

The selection of remediation measures should be related to the instability mechanism. The literature distinguishes between modification of slope geometry, control of surface water and groundwater, retaining structures, piles, anchors, soil reinforcement, and combined solutions [5–7]. In urban conditions, space for unloading or reshaping the slope is often limited, so structural elements are combined with drainage and pile-supported retaining structures. Eurocode 7 requires geotechnical design to consider the relevant limit states and design situations and to be based on the results of ground investigations [12,13].

III. SITE LOCATION AND ENGINEERING-GEOLOGICAL CONDITIONS

3.1. Location and morphology

The investigated site is located on the northern slopes of Mount Trebević, descending toward the Miljacka River valley. The morphology of the wider area is irregular, and the present-day relief has been influenced by erosion-denudation processes as well as by downslope movements of soil material [1]. At the site itself, the steep slope and existing development further limit the possibility of simple terrain reshaping.

Figure 1. Part of the slope and developed area at the site (from the design documentation).

3.2. ENGINEERING-GEOLOGICAL CHARACTERISTICS OF THE SITE

The engineering-geological classification of soil and rock at the site was carried out according to genetic-lithological and geochronological divisions. Quaternary deposits were considered according to their genetic-lithological origin, with particular attention to the eluvial-deluvial deposits present in the investigated area. Neogene formations were classified into the corresponding engineering-geological and geotechnical complexes according to their geochronological position.

3.3. Hydrogeological conditions and the role of water

The surface cover has relatively low permeability, but its loose structure and sandy fraction allow local accumulation of seepage water. During the investigation works, groundwater was recorded at a depth of approximately 4.0 m [1]. The design documentation also records water at the ground surface and continuous flow down the slope [2]. These observations indicate that hydrological conditions may vary locally and over time, particularly near the inadequately collected culvert discharge.

Figure 2. Water observed adjacent to an existing structure at the site (from the design documentation).

Figure 3. Local drainage/water system element at the site (from the design documentation).

III. MATERIALS AND METHODS

4.1. Investigation works

Five investigation boreholes were drilled, with Standard Penetration Tests (SPT) performed at 2.0 m depth intervals. Samples were taken from the cover and substratum, and a total of 10 samples were tested in the laboratory. After drilling was completed, piezometers were installed in two boreholes to monitor groundwater levels during and after remediation. Two inclinometers were also included in the monitoring system to measure ground movements.

4.2. Geotechnical parameters

For the purposes of the design, parameters reflecting the investigation results and the back-analysis of the landslide condition were adopted. The Mohr–Coulomb model was used in the numerical model for the cover, substratum, and stone backfill.

$$\tau_f = c' + \sigma'_n \cdot \tan\varphi'$$

gdje su: τ_f – smičuća čvrstoća tla, c' – efektivna kohezija, σ'_n– efektivni normalni napon i φ' – efektivni ugao unutrašnjeg trenja.

Material	γ [kN/m³]	Eref [kN/m²]	c' [kN/m²]	φ' [°]
Cover	19–20	3.000	5	32
Substratum	20	50.000	35	35
Stone backfill	23	40.000	0,5	40

Table 1. Soil parameters

4.3. Numerical model and design approach

The stability analysis before and after remediation was performed using PLAXIS 2D. The design first included a back-analysis for FS = 1.00, corresponding to a limiting equilibrium condition and allowing verification that the selected parameters produce a failure mechanism consistent with the observed slip surface [2]. The subsequent model stages included collection of the culvert discharge, excavation of the working platform, pile drilling, drainage installation, wall construction, backfilling, and the final service condition.

In PLAXIS safety analysis using the φ/c reduction method, the strength parameters are progressively reduced until a failure mechanism develops; the value of ΣMsf at failure represents the global factor of safety [11].

For design verification, the project documentation applies Eurocode 7: Design Approach 2 (DA2) for retaining structures and reinforced-concrete elements, and Design Approach 3 (DA3) for global stability and stabilization elements [2,12].

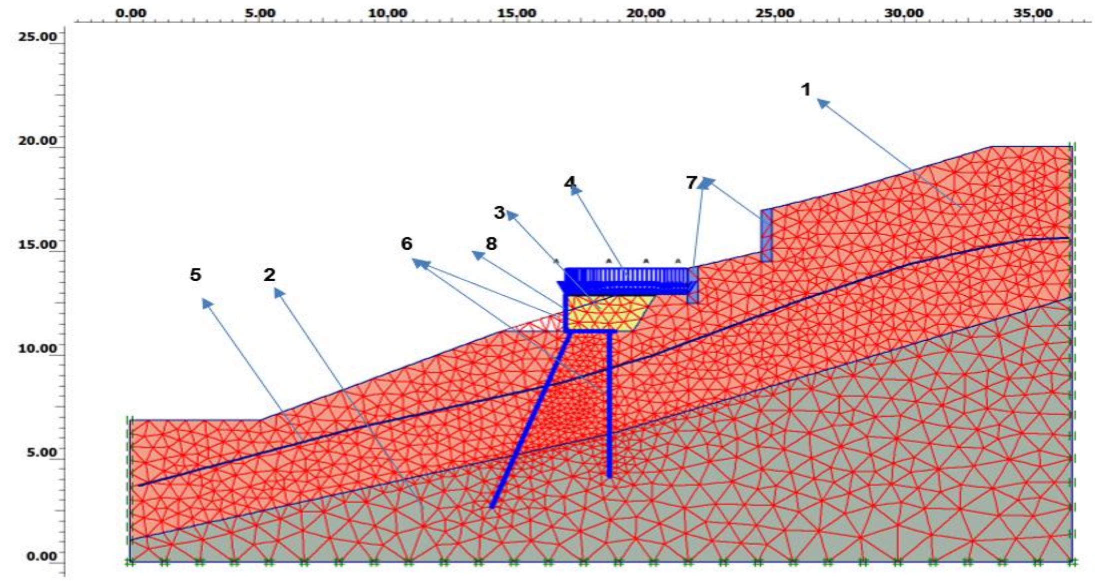

Figure 4. Numerical model of the slope with stabilization elements (from the design documentation).

LEGEND:
1. Cover – MC model
2. Substratum – MC model
3. Stone backfill – MC model
4. Traffic surcharge of 20 kN/m²
5. Groundwater level
6. Piles Φ300 mm/5.00 m – plate element
7. Existing concrete walls – linear elastic model
8. Wall d = 40 cm – plate element

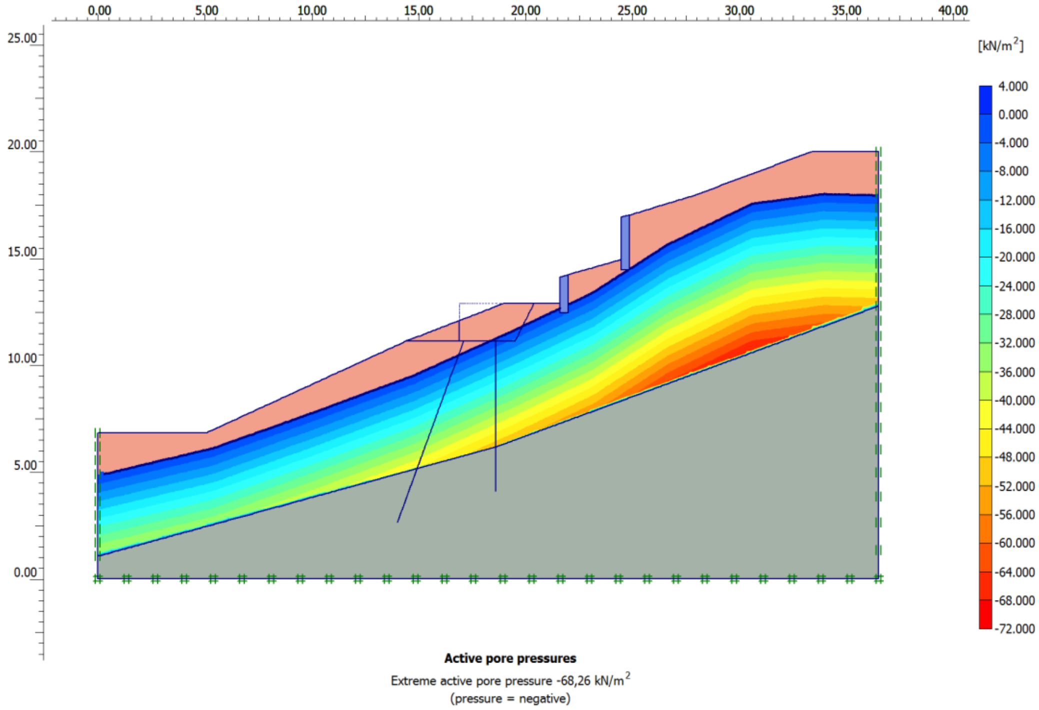

Figure 5. Numerical analysis result – zone of deformation/sliding mechanism development

V. RESULTS

5.1. Landslide activation mechanism

The results of field observations and investigations indicate a combined hydrogeological-geotechnical mechanism. Sliding occurs within the clayey cover of poorer geotechnical properties above the more competent Miocene substratum. The inadequately managed culvert caused water to spread over the slope and locally saturate the cover. Increased moisture content and pore-water pressure reduced the effective stress and available shear resistance, while the steep slope inclination represented an additional adverse factor. The resulting effects were deformations and cracks in walls, buildings, and the access road [1,2].

$$\sigma' = \sigma - u$$

where σ' is the effective stress, σ is the total normal stress, and u is the pore-water pressure. An increase in pore-water pressure reduces the effective stress and consequently the available shear resistance of the soil.

Figure 6. Cracks and damage to the existing retaining wall (from the design documentation).

5.2. Selected remediation solution

The design adopts a combined solution addressing both the cause and the consequences of instability. The first group of measures concerns water management: the existing culvert discharge is collected in an inspection chamber and conveyed through collector pipes to the receiving outlet; the RO2–RO3 drainage line and drainage behind the retaining wall are also provided. The second group comprises structural measures: a reinforced-concrete L-shaped wall, 24.90 m long and 2.0 m high, with a 2.0 m wide footing and a footing and stem thickness of 0.40 m, is constructed. The wall is supported by Φ300 mm piles at 5.0 m spacing. Each pile pair consists of one vertical pile and one inclined pile at 20° from the vertical, with lengths of 8.0 m and 10.0 m [2].

Stone backfill and drainage are installed behind the wall, while PEHD Ø100 mm weep holes are provided in the wall at 1.0 m spacing. This concept combines drainage, which reduces hydraulic loading, with piles that transfer stabilizing forces into the deeper, more competent substratum. Construction is planned in stages and under continuous geotechnical supervision [2].

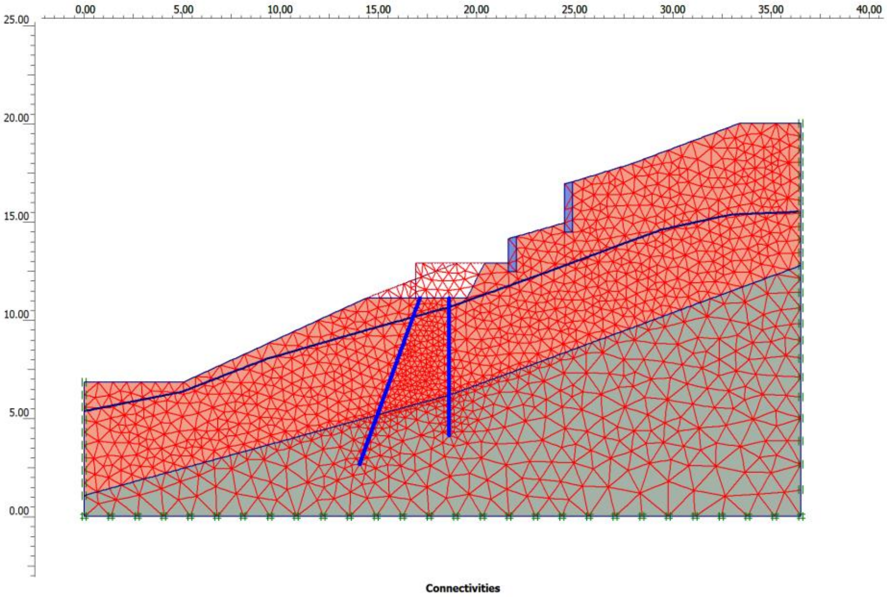

Figure 7. Model stage with installed piles and retaining structure (from the design documentation).

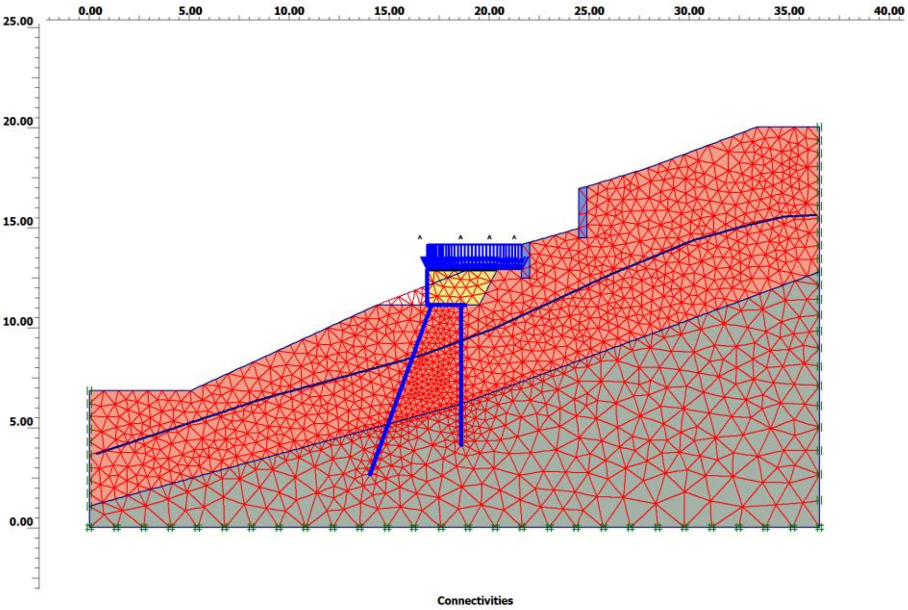

Figure 8. Final geometry of the stabilization system in the numerical model (from the design documentation).

5.3. Stability after remediation

The design calculation gives a factor of safety of FS = 1.08 > 1.00 for the temporary excavation of the working platform, while after implementation of the remediation measures the calculated factor of safety is FS = 1.34 > 1.25 [2]. In the service condition, the maximum horizontal wall displacement is approximately 43 mm and the maximum vertical displacement is approximately 26 mm. The governing bending moments and forces in the wall and piles were determined for design, followed by verification of resistance and the required reinforcement.

Condition / result	Value
Back-analysis – sliding condition	FS = 1,00
Temporary excavation of working platform	FS = 1,08
After remediation	FS = 1,34 > 1,25
Max. horizontal wall displacement	≈ 43 mm
Max. vertical wall displacement	≈ 26 mm

Table 2. Summary of numerical analysis results

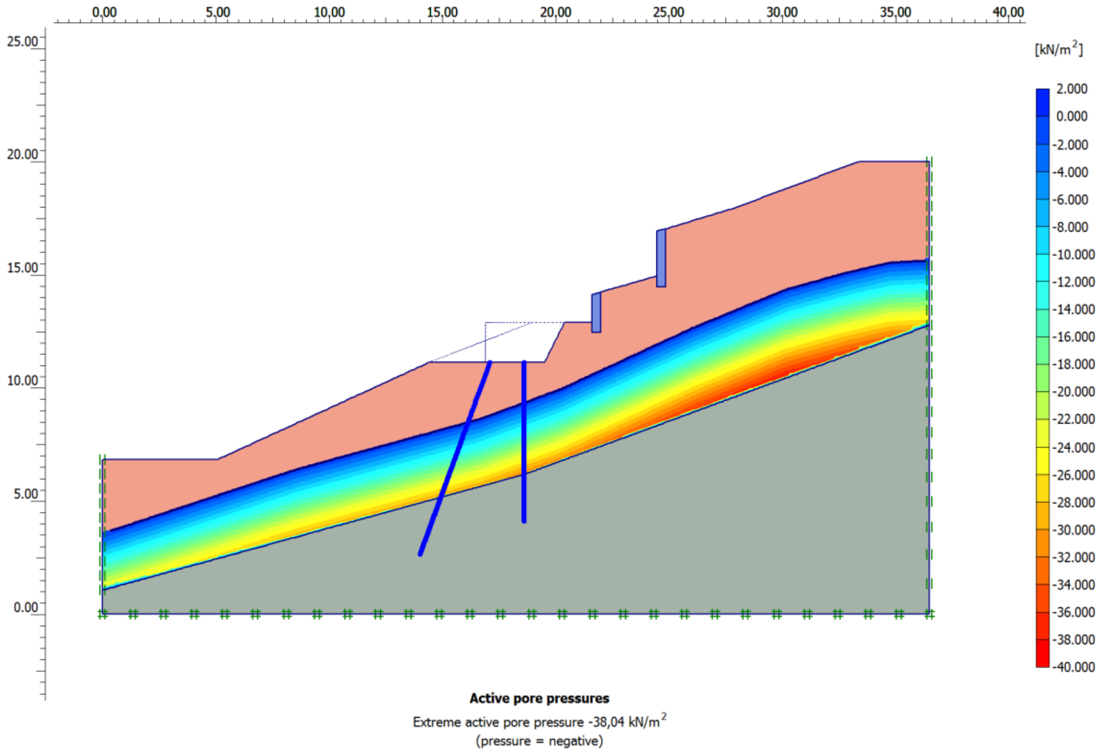

Figure 9. Numerical representation of the sliding mechanism in the analysed stage (from the design documentation).

VI. DISCUSSION

The case study clearly shows that landslide remediation should not be limited to increasing the mechanical resistance of the slope. When water is the principal trigger, a structural measure without reliable drainage may have a limited effect. The Save Skarića remediation design therefore combines controlled collection of the culvert discharge, drainage, and a pile-supported retaining system. This approach is consistent with general recommendations in the technical literature, according to which water control is one of the priority measures, while retaining structures are introduced where slope geometry, existing development, and the depth of the sliding zone do not permit simple unloading of the slope [5–7].

The back-analysis is particularly important. Instead of basing the model solely on nominal laboratory parameters, the parameters were checked at FS = 1.00 and against the observed position of the slip surface. This provides a better relationship between the numerical model and the actual behaviour of the ground. Nevertheless, every numerical model remains an idealization, and the result depends on geometry, groundwater level, the constitutive model, and the representativeness of the adopted parameters.

Therefore, construction control and monitoring of slope behaviour after remediation are important elements of geotechnical risk management. Eurocode 7 emphasizes that geotechnical design should be based on ground investigations and verification of the relevant limit states [12,13]. Different design approaches were used in this project for structural and global geotechnical verifications, allowing the resistance of individual elements and the stability of the overall system to be considered separately. For bored piles, construction control is as important as the calculation, particularly with regard to the actual depth of the substratum, borehole stability, centring of the reinforcement cage, and continuity of concrete placement [2,14].

VII. CONCLUSION

For reliable landslide remediation, proper planning and definition of the scope of investigation works are of particular importance. The number, location, and depth of investigation boreholes should allow reliable definition of the geological structure, the position of the substratum, and the hydrogeological conditions. This is followed by field investigations, sampling, and laboratory testing, on the basis of which the relevant geotechnical parameters are determined for stability analysis and preparation of the remediation design.

At the investigated site, sliding was found to occur predominantly within the clayey eluvial-deluvial cover above the Miocene substratum, with water playing a significant role in landslide activation. The designed remediation solution includes controlled water conveyance, drainage, and a reinforced-concrete retaining wall supported by bored piles. Numerical analysis in PLAXIS 2D gave a factor of safety of FS = 1.34 after remediation, which is greater than the design value of FS = 1.25.

In addition to proper design and execution of the remediation measures, monitoring is an important part of landslide remediation. Ground behaviour should be monitored during the works and after their completion in order to assess the condition of the remediated slope and the performance of the implemented measures.

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