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Slope stability of fossil landslide in Flysch sediments

E. Angelova, B. Gjoshevski, L. Ivanovski & O. Petkovski
Geohydroconsulting, Skopje, RN Macedonia
elena@ghk.com.mk
0009-0008-2492-6162

Abstract

Following the construction of an electrical substation associated with a wind energy project, ground instabilities were observed in the surrounding area. These included surface settlements and the development of frontal and radial cracks in both the terrain and paved surfaces. Previous geological and geotechnical investigations, along with implemented remediation measures, yielded only limited improvement, and the instability progressed into an active landslide, posing a risk to infrastructure and equipment.

Stability analyses were conducted to evaluate potential stabilization solutions and assess slope safety under various conditions. Two geotechnical software tools were used with identical input parameters and methodologies in accordance with EN 1997 – Eurocode 7. Multiple scenarios were analyzed, incorporating different slope geometries and stabilization measures to simulate various stages of intervention.

The results obtained from both software tools were consistent, confirming the reliability of the applied methodology. Analyses demonstrated varying levels of slope stability depending on the configuration and type of stabilization measures applied. Certain scenarios showed improved safety factors, indicating that targeted interventions could effectively reduce the risk of further landslide development.

The study highlights the importance of comprehensive stability analyses in complex geotechnical conditions. The evaluated scenarios provide a basis for selecting appropriate stabilization measures and guiding future remediation efforts. Continued monitoring and implementation of optimized solutions are essential to ensure long-term slope stability and protection of critical infrastructure.

Keywords

Flysch sediments, Landslide, Slope stability, Geotechnical analysis.

1 Introduction

Ground instability following the construction of energy infrastructure represents a significant geotechnical challenge, particularly in complex geological environments. In the case considered in this study, the development of settlements and the formation of frontal and radial cracks in both natural terrain and paved surfaces indicated progressive degradation of slope stability. Despite prior geological and geotechnical investigations and the implementation of remediation measures, the effectiveness of these interventions proved limited, and the instability evolved into an active landslide, raising concerns regarding the safety and functionality of critical infrastructure.

In response to these conditions, comprehensive engineering-geological and geotechnical investigations were undertaken to better understand the subsurface characteristics and mechanisms driving slope failure. Fieldwork included detailed geological mapping and the execution of boreholes, which revealed the presence of flysch sediments of Upper Eocene age (Rakicevic et al., 1968). These deposits consist of interbedded claystones, siltstones, marls, marly clays, and sandstones, forming a heterogeneous and mechanically complex geological medium. Surface layers are predominantly composed of diluvial materials derived from the weathering and decomposition of the underlying flysch. Additionally, the construction of the substation platform involved fill using the local material from excavation. Representative samples from all identified lithological units were collected and subjected to laboratory testing to determine their physical and mechanical properties.

The investigation program was designed to establish a comprehensive understanding of the geological structure, hydrogeological conditions, and geotechnical properties of the affected area. This included in-situ testing such as standard penetration tests and inclinometer monitoring, alongside laboratory analyses and a review of existing technical documentation. The study focused on defining lithological composition, spatial relationships between geological units, active geomorphological processes, and key physico-mechanical parameters of the materials involved.

A thorough characterization of these factors provides the necessary foundation for identifying the causes of instability and supports the development of effective and rational remediation strategies for landslide stabilization.

2 Engineering-Geological Conditions and Landslide Development

A detailed assessment of recent engineering-geological processes was done to better understand the causes and spatial extent of the identified instability. Field observations revealed the presence of tension and radial cracks, surface weathering of sedimentary rocks, localized landslides, and linear erosion features (Fig.1). These phenomena indicate that the geological environment, composed predominantly of heterogeneous flysch sediments (including sandstones, marls, siltstones, claystones, and clays), is highly sensitive to external influences. Anthropogenic activities, particularly slope cutting and filling, have further accelerated these processes and contributed to the reactivation of a pre-existing fossil landslide.

Analysis of the terrain morphology shows that natural slopes developed in such materials are generally characterized by gentle inclinations, reflecting their relatively low strength and deformation properties. On the investigated profile, the natural slope inclination at the toe is approximately 1(v):3.5(h), suggesting a tendency of the material toward gradual deformation and long-term movement in order to achieve equilibrium. Surface manifestations such as cracking and erosion represent only initial indicators of deeper-seated instability, confirming both local and global instability conditions and a high likelihood of further landslide activity.

Weathering and degradation processes significantly affect the near-surface layers of the terrain. Under the influence of environmental factors, stronger lithological units progressively weaken: sandstones may degrade into loosely bound or unbound sands, claystones into soft clays, and siltstones into materials with reduced mechanical strength such as marly clays and silts. Laboratory testing of borehole samples confirmed these transformations, and the reduced strength parameters were incorporated into the geotechnical analyses for surface layers, while deeper zones were assumed to retain their original properties due to limited degradation.

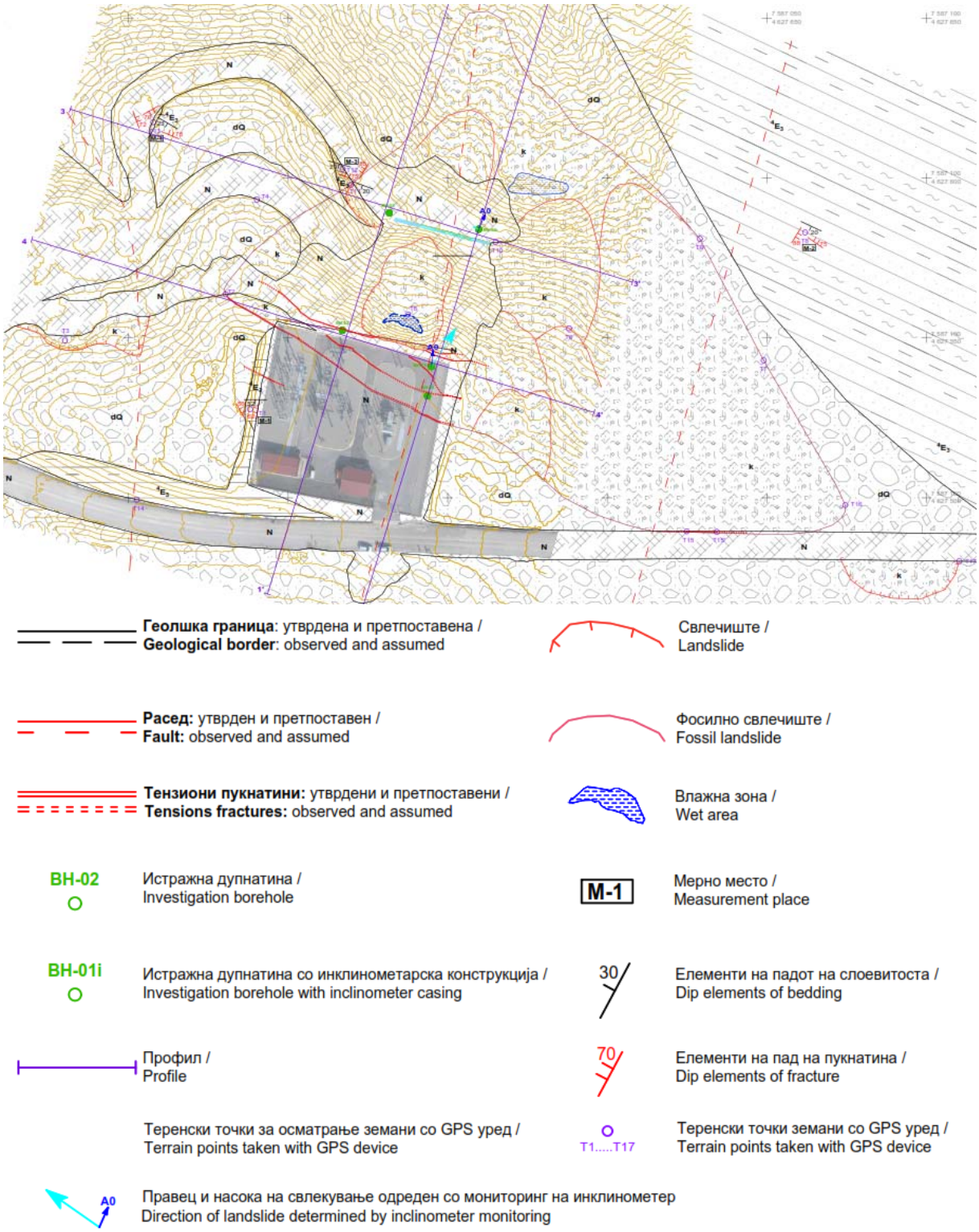


Fig. 1 Overview of fossil landslide of large scale.

Tectonic influences, including identified fault systems, have further contributed to rock mass fracturing, facilitating water infiltration and enhancing erosion and slope deformation processes. These conditions historically enabled the formation of a large fossil landslide, which is now prone to reactivation under altered stress conditions.

Within this largely affected zone, a smaller, active landslide has developed directly downslope of the structure, characterized by a circular-rotational failure mechanism. Monitoring data obtained from inclinometer measurements confirm ongoing, albeit slow, displacement within the upper part of the land mass (Fig.2). While existing retaining structures provide partial stabilization of superficial materials, analyses indicate that the critical failure surface extends beneath these structures, limiting their overall effectiveness.

These findings highlight the necessity for continuous monitoring and the implementation of appropriate stabilization measures, as any acceleration in displacement could pose significant risks to the safety and integrity of the infrastructure.

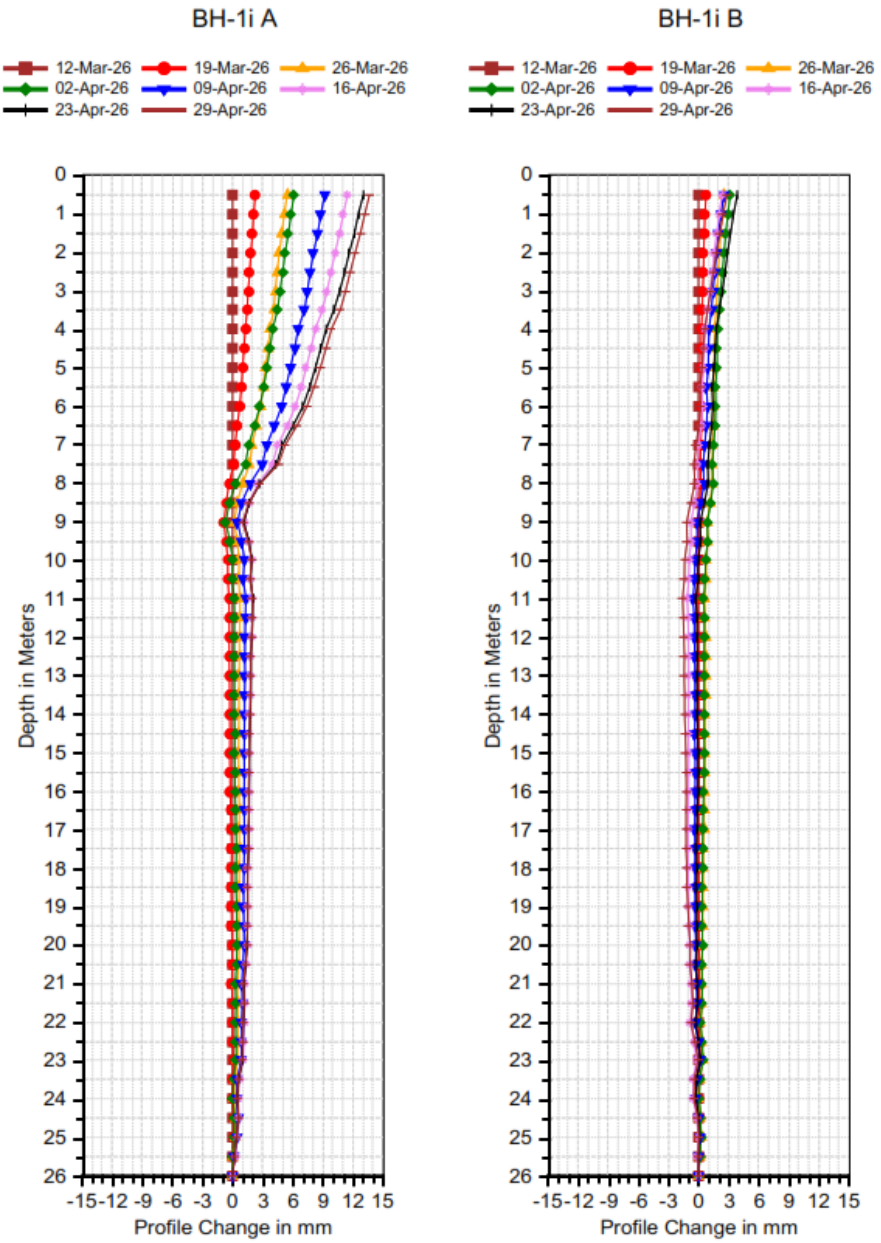


Fig. 2 Inclinometer measurements at the top of the landslide.

3 Slope stability analyses

3.1 Methodology of Stability Analyses

The stability analyses were performed using the GEO5 – Slope Stability software (Fine Ltd, 2026) in accordance with the requirements of Eurocode 7 (EN 1997-1), applying Design Approach 3 (DA3). Slope stability was evaluated using the Bishop Simplified Method, which was employed to assess both global and local stability conditions of the studied slope configurations.

Geotechnical parameters were defined based on the results of field investigations and laboratory testing. For soil materials, the Mohr–Coulomb model was adopted, incorporating unit weight, angle of shearing resistance, and cohesion. For rock masses, the Hoek–Brown model was used, with input parameters including the Geological Strength Index (GSI), material constant (mi), uniaxial compressive strength (σ_{ci}), and disturbance factor (D). These models enabled a representative characterization of both soil-like and rock-like behavior within the complex geological environment.

The analyses considered multiple loading scenarios to capture a range of possible conditions affecting slope stability. These included permanent (static) conditions, seismic loading defined through horizontal and vertical seismic coefficients, conditions incorporating pore pressure effects through the Ru coefficient (adopting conservative values derived from investigations), and the influence of loads imposed by existing structures.

In defining the strength and deformation parameters, all available data and the natural in-situ conditions of the materials were taken into account. Rather than adopting minimum laboratory-derived values, the analyses utilized representative parameters that reflect relatively favorable ground conditions. This approach acknowledges the susceptibility of weak rock masses to degradation while still considering realistic in-field behavior. Despite the use of such optimistic assumptions, the results of the analyses indicate that slope stability remains critical and that the landslide is active.

These findings demonstrate that even under favorable parameter selection, conventional stabilization measures may be insufficient, emphasizing the need for more robust and carefully designed remediation solutions.

3.2 Results

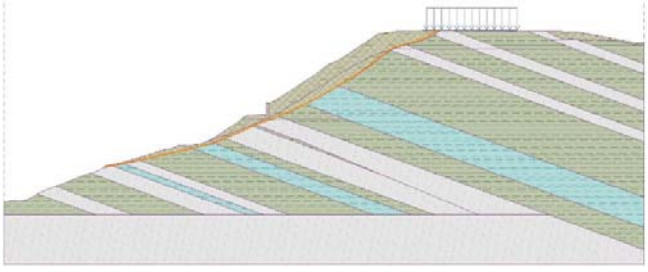
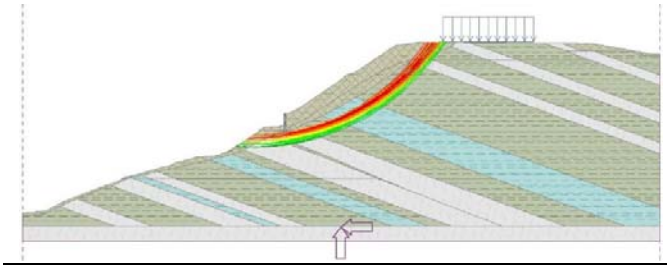
An initial back-analysis was performed to estimate the mobilized shear strength parameters along the active slip surface. The laboratory-derived residual strength parameters were found to be low, reflecting unfavorable conditions at already sheared zones. For deeper residence rock masses, a disturbance factor of D = 0.50 was adopted within the Hoek–Brown model, accounting for the influence of existingfaults and tectonic disturbances.

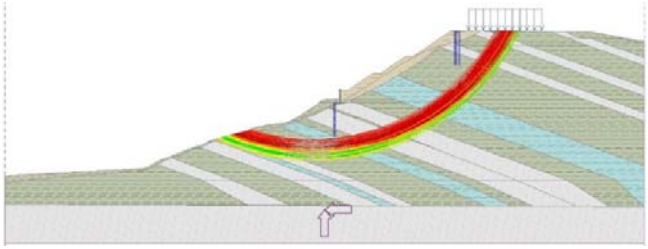
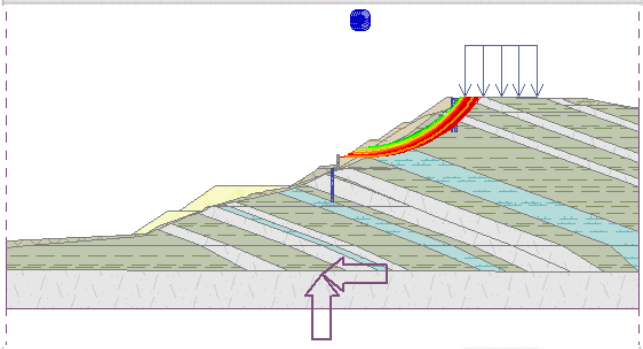
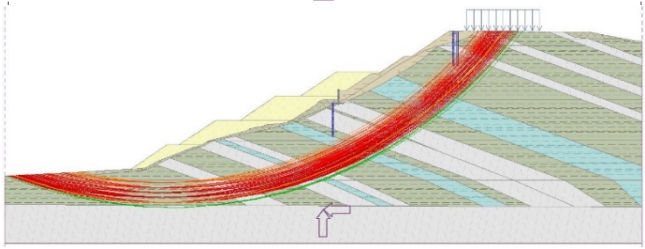
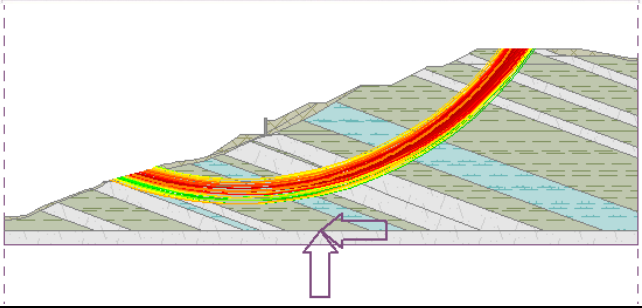
The stability assessment included multiple scenarios representing different phases of potential intervention. These considered the existing condition, as well as configurations incorporating stabilization measures such as reinforced concrete piles, counterweight loading, and modified slope inclinations (1:1.5 and 1:2). All analyses considered the influence of structural loads, groundwater conditions influenced by precipitation, and both static and seismic loading cases.

Results were evaluated through the ratio of driving and resisting forces, as well as sliding and resistance moments, expressed through utilization degree (%). Particular attention was given to conditions involving seismic action, which consistently produced the most critical stability scenarios.

The presented graphical outputs provide a clear comparison of the different scenarios and demonstrate the relative effectiveness of each stabilization measure. Overall, the findings highlight that while certain interventions improve stability, critical conditions persist, particularly under seismic loading and elevated pore pressure, indicating the need for comprehensive and robust design solutions.

Table 1. Cases for slope stability analyses –results, comments and visual presentation.

Analysed case	Description of analysis
	**Case 1: Back analysis** Iterative adjustment of strength parameters for fill and colluvial material until Fs ≈ 1 (U=100%), yielding representative values that reflect actual fieldconditions and observed deformations.
	**Case 2: Current state** Indicates local instability with critical slip surfaces developing in the fill and beneath the retaining wall. Under seismic (U=115%) and pore pressure (Ru) conditions (U=158%), stability is inadequate, confirming limited influence of the existing wall.

Analysed case	Description of analysis
	**Case 3: Piles + slope 1:1.5** Partial improvement in local stability (U=105%), but global stability remains critical, especially under seismic loading (U=94%). Piles alone are insufficient for long-term stabilization
	**Case 4: Piles + counterweight (2 levels)** Moderate improvement in global stability (U=90%), but significant local instability persists in the upper slope (U=105%). Additional counterweight is required.
	**Case 5: Piles + counterweight (4 levels)** Best performance among counterweight options, with notable improvement in both local (U=88%) and global stability (U=93%) under seismic conditions. However, stability remains borderline.
	**Case 6: Reduced slope (1:2)** Provides the most effective stabilization, significantly improving overall stability (U=81%). However, it requires substantial space and potential relocation of infrastructure.

4 Conclusion

The investigations and analyses confirm that the studied slope, composed of weak and sensitive flysch materials, is in a critically unstable condition due to both natural geological factors and construction activities. Field observations and analytical results show high utilization levels, indicating that the current condition does not satisfy stability requirements and that the landslide remains active. Conventional stabilization measures, such as reinforced concrete piles and counterweights, provide only limited improvement and are insufficient to ensure long-term global stability, especially under seismic loading and increased pore pressure conditions. Significant improvement is achieved only by reducing the slope inclination to gentler angles, consistent with natural terrain equilibrium. However, this approach requires substantial space and may involve relocation of existing facilities, making it technically and economically demanding. Therefore, long-term stability can only be ensured through either complete relocation of the facility or a complex, costly stabilization solution combining multiple measures, as conventional approaches alone are inadequate.

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