The Impact of Construction Activities on the Stability of Highway Slopes

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ABSTRACT

This study concerns the case of a landslide that occurred at kilometer point PK 208 of the East-West Highway in the northeastern part of Algeria, located in the eastern region of Constantine Province. The primary objective is to understand the behavior and mechanisms of this complex landslide phenomenon. The phenomenon's relationship to various factors that influence this activity, including permanent causes, such as challenging terrain, the geological nature, and the evolving characteristics of the soil under the influence of various climatic conditions or human activities, was investigated. The study examined the impact of the East-West Highway construction at PK 208 on the stability of slopes composed of clayey and marly soils. Field investigations were conducted, and various studies on landslides were analyzed. A monitoring system was employed to track subsurface and surface movements, as well as changes in the groundwater table level. Additionally, numerical modeling using PLAXIS software was performed to evaluate the impact of construction activities, particularly the rise in the groundwater table, on slope stability. The obtained results demonstrated that the position of the groundwater table plays a crucial role in the stability of these structures, underscoring the importance of considering local hydrogeological conditions in the planning and execution of such projects. It is concluded that the complexity of such phenomena in slopes with similar geological, geomorphological, hydrogeological, and geotechnical characteristics is a significant issue that requires particular attention during the planning and execution of such projects.

Keywords-landslide; slope stability; construction activities; groundwater level; embankments

I. INTRODUCTION

Landslides, defined as the downslope movement of rock or soil masses under the influence of gravity [1, 2], pose a significant threat to infrastructure, causing damage and loss of life [3, 4]. In Algeria, the mountainous regions in the north, particularly near Constantine, are vulnerable due to clay and marl soils susceptible to moisture variations [5-7]. The East-West highway, traversing these areas, exemplifies these challenges, notably at PK 208, where a complex landslide was exacerbated by a rising groundwater table, reducing soil cohesion [8]. Contributing factors include geological conditions, precipitation, earthquakes, and anthropogenic activities, such as construction works [9-12]. Rising groundwater tables, often caused by water infiltration and drainage disruption, decrease soil shear strength [13, 14]. Monitoring through inclinometers and piezometers [15-17] and numerical modeling [18] are crucial for anticipating and mitigating these phenomena. The study of the landslide at PK 208 underscores the importance of considering local hydrogeological conditions in infrastructure planning and suggests tailored stabilization solutions [19, 20]. This analysis highlights the complex interaction between natural and anthropogenic factors and the urgency of an integrated approach to ensure infrastructure safety in risk-prone areas.

II. METHODOLOGY

The methodology followed in this study aims to elucidate the mechanisms underlying the discussed landslide that occurred at kilometer marker 208 of the East-West highway in Algeria through a multidisciplinary approach. This approach integrates field investigations, geotechnical analyses (the database is the Algerian National Highway Agency - ANAS – and the climatological data source is the Hamma Bouziane Constantine station), and numerical modeling. The location, situated in a steep mountainous area, exhibits a complex geology characterized by folded and thrusted sedimentary formations, with clayey and marly soils [8]. Figure 1 provides an overview of the study area, depicting the topography and the significant slope gradient of the region, which are crucial for understanding the landslide risks.

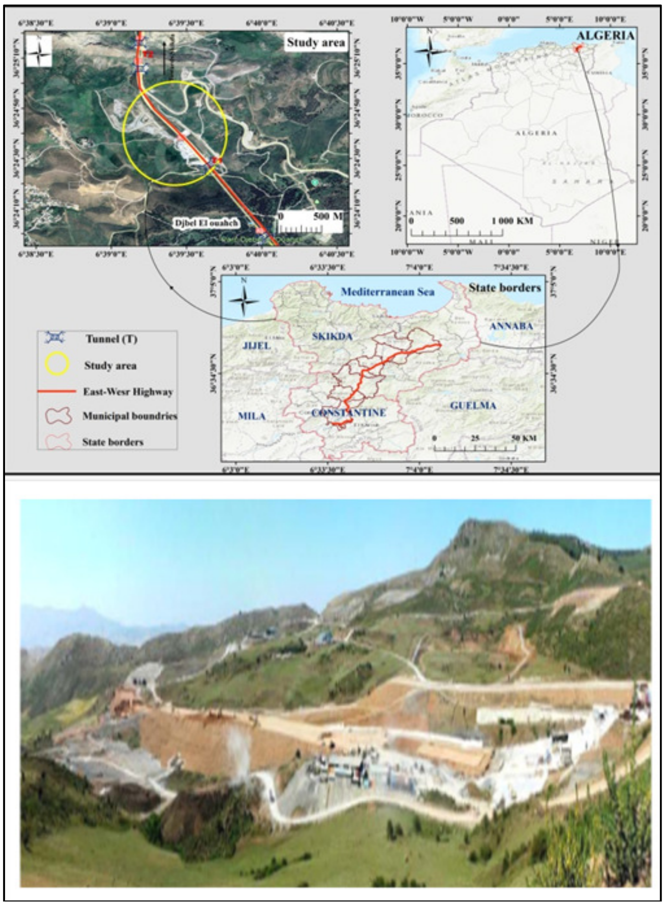


Fig. 1. The study area.

Soil and rock samples were analyzed for their geotechnical properties to be determined and to the slope stability to be assessed, as seen in Table I. Figure 2 depicts the extracted soil cores, illustrating the geological conditions of the samples. The climatic data obtained from local stations exhibit a semi-arid Mediterranean climate with concentrated precipitation in winter, promoting water infiltration and the rise of the groundwater table. This hydrological recharge influences the stability of clay and marly soils. Field investigations, including geological mapping and sample collection, allowed for the characterization of the slope geometry. Topographic surveys were conducted to measure the dimensions of the slope failure, such as the length, width, and depth of the affected zone. These investigations were crucial for feeding numerical simulation models.

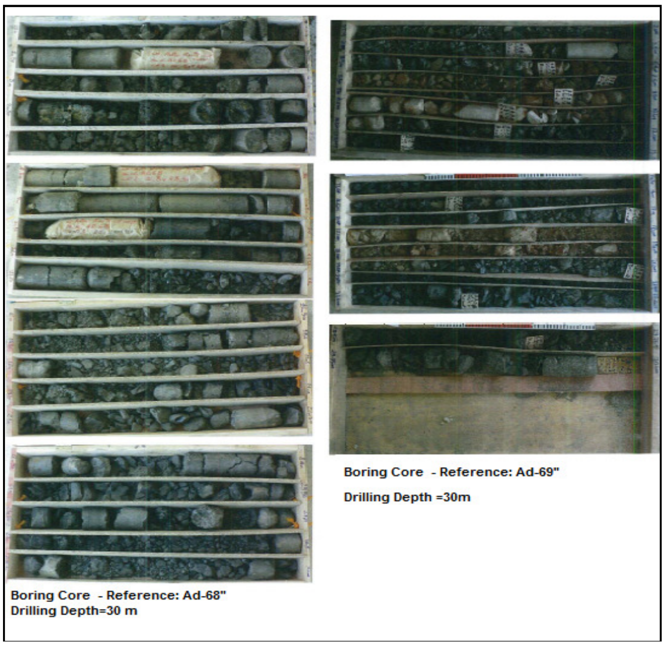


Fig. 2. Photos of the collected soil cores.

TABLE I. SUMMARY OF GEOTECHNICAL PROPERTIES

Nature of soil	Dry density (kN/m³)	Cohesion C' (kN/m²)	Friction angle φ' (°)
Embankment	21.0	5.0	30.0
Clay	20.9	14.5	18.5
Marl	21.8	17.6	21.0

A monitoring system consisting of inclinometers installed at various depths has been set up to track underground movements and detect horizontal displacements. Piezometers have been used to monitor fluctuations in groundwater level in response to rainfall, which is a critical factor in slope stability. Two numerical models were established to investigate slope stability deploying PLAXIS software. The first model, displayed in Figure 3, contains 1607 nodes and 187 elements, while the second model, shown in Figure 4, consists of 1609 nodes and 190 elements. The boundary conditions were carefully defined to mirror site conditions: lateral edges are fixed in horizontal displacement but free in vertical movement, and the model base is fully constrained. The loading comprises two types. The first is the staged construction, which calculates stresses and deformations using a plastic load in sequential steps, and the second constitutes the incremental additional loading for FOS analysis through a -Phi/C- reduction. The model encompassed several scenarios, namely the measured groundwater level on the ground, the groundwater rising to the surface, for example, after intense rainfall, and the absence of groundwater to simulate dry conditions. Figures 3 and 4, respectively, portray the numerical models of the natural slope before and after the works, and the construction phases of the road. These simulations allowed for the evaluation of the influence of groundwater position on slope stability and the identification of critical conditions that could trigger a landslide.

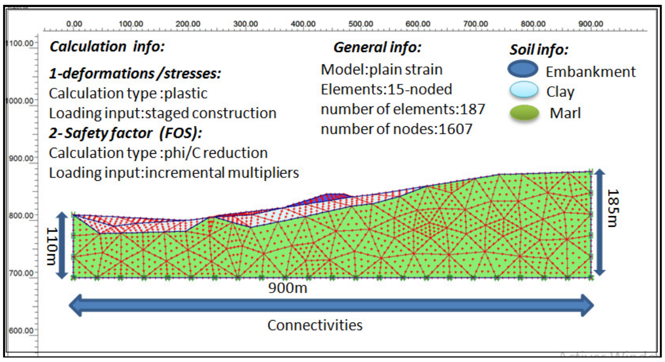


Fig. 3. Numerical model of the natural slope.

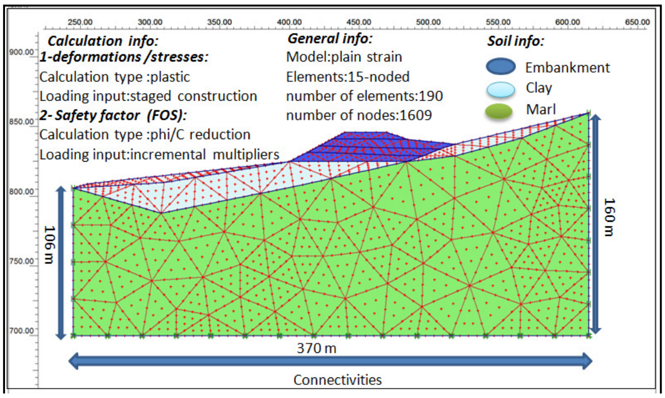


Fig. 4. Numerical model of the road construction phases.

The analysis of the data includes the interpretation of geotechnical measurements and displacements obtained from the monitoring systems, as well as the correlation of piezometric fluctuations with landslide events. The results of the numerical simulations highlight that the rise of the water table plays a crucial role in the destabilization of the slopes. The study limitations include the variability of geotechnical properties, the necessary simplifications in the numerical models, and the uncertainties related to the prediction of climatic conditions. Nevertheless, this methodology provides a comprehensive understanding of the complex mechanisms of landslides and offers recommendations for improving the management of geotechnical risks in similar projects.

III. RESULTS

A. *Field Monitoring Data*

The on-site investigations provided valuable data on the evolution of the landslide at PK 208. The inclinometers installed in the slopes recorded progressive displacements, particularly after periods of heavy rainfall and immediately following the initiation of construction activities in early August (excavation works). The detected movements were primarily horizontal, indicating a slow but continuous landslide, observed in Figures 5 and 6. A direct correlation was noted between climatic fluctuations and slope deformations.

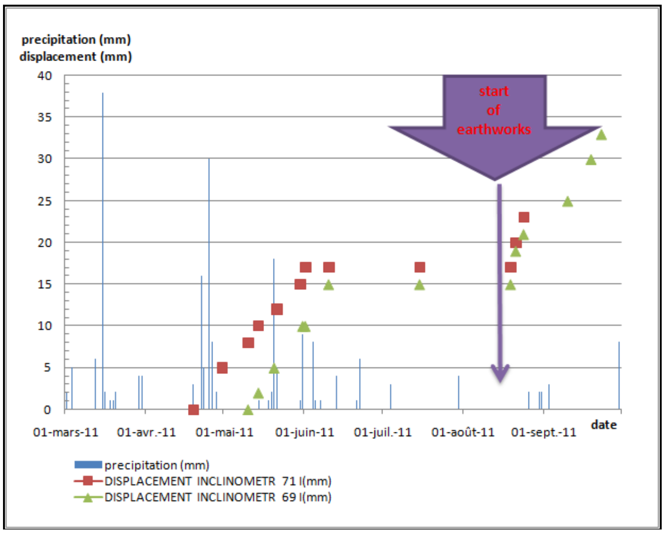


Fig. 5. Deformations measured by inclinometers as a function of precipitation.

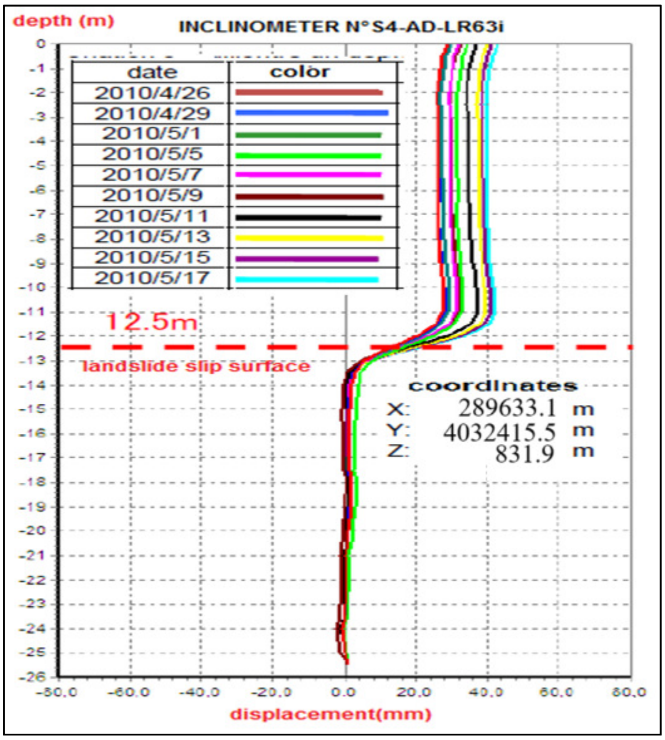


Fig. 6. Example of displacement evolution in the landslide area.

B. *Stability of Natural Slope Before and After Construction*

Stability simulations were also conducted to analyze the state of the natural slope before and after the construction of the highway, as can be seen in Figures 7 and 8.

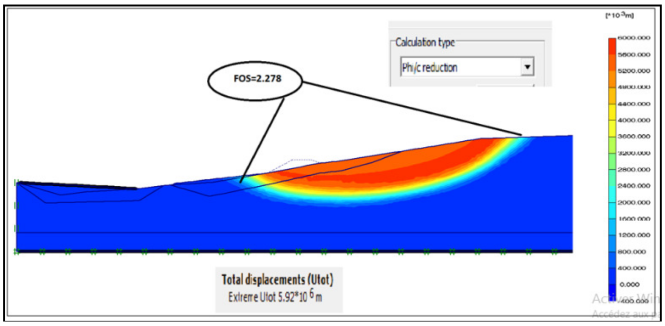


Fig. 7. Deformations and critical slip before construction works.

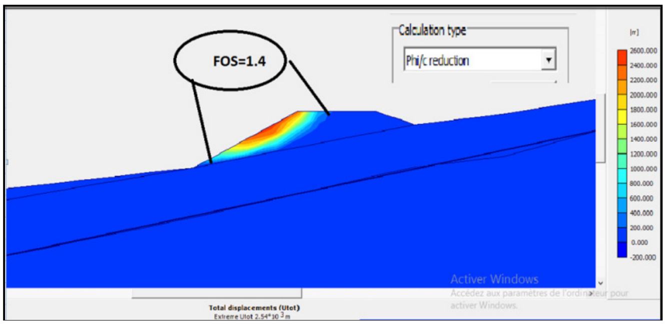


Fig. 8. Deformations and critical slip after construction works.

The results of the Safety Factors (FOS) for the natural slope before and after the highway construction, regarding the water table levels, are presented in Figure 9.

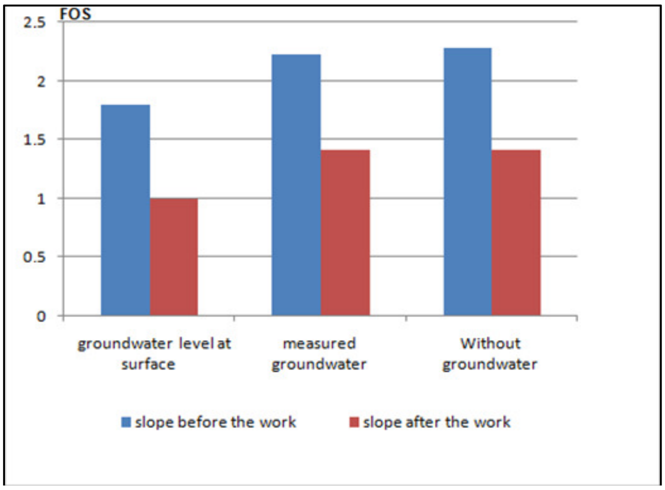


Fig. 9. Relationship between slope FOS and water table fluctuations before and after construction works.

Before the works, the FOS of the natural slopes were relatively high, indicating overall satisfactory stability. However, after the works, a significant decrease in these factors was observed, particularly when the water table was at the surface, with FOS having dropped to 1.14, suggesting a critical post-construction stability state.

C. Safety Factor of Construction Phases and Water Table Position

The results of the numerical modeling with PLAXIS revealed significant variations in slope stability depending on the construction phases and the position of the water table.

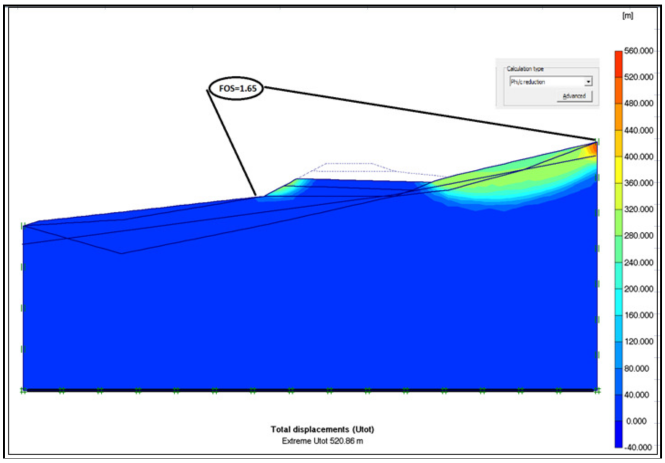


Fig. 10. Deformations and critical slip during construction works.

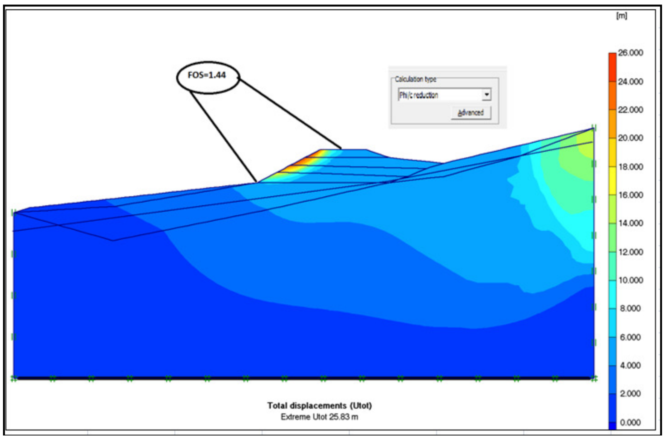


Fig. 11. Deformations and critical slip at the end of construction works.

Figure 12 presents the FOS obtained for the three main modeling scenarios. The results highlight the critical influence of the water table on slope stability. When the water table is at its actual position, Case 1, FOS remains relatively stable although it slightly decrease with each construction phase. However, when the water table is simulated at the surface, Case 2, FOS significantly drops, reaching 0.80 during preparatory earthworks, indicating a high risk of instability. Conversely, in the absence of a water table, Case 3, the FOS increases, demonstrating that the slopes would be more stable under dry conditions.

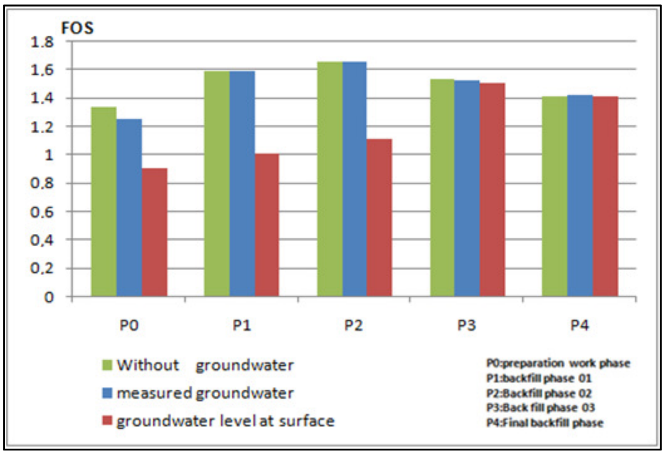


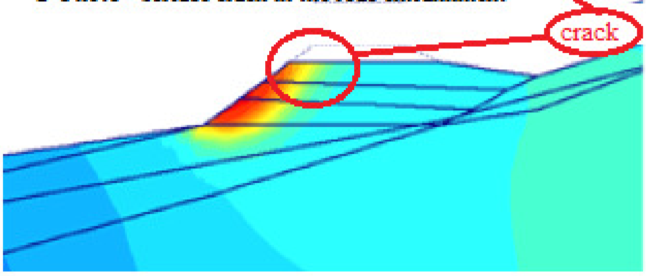
Fig. 12. Relationship between slope FOS and construction phases (about water table fluctuations).

D. *Validation by Field Observations*

Field observations confirm the predictions from the numerical simulations:

- The moments of acceleration on the ground due to construction or precipitation, as shown in Figure 6, are consistent with the modeling results evidenced in Figures 9 and 12.
- Significant cracks were observed in the road embankment, as Figure 13a depicts, confirming the areas identified as vulnerable by the modeling illustrated in Figure 13b.
- These cracks appeared during periods of high soil saturation, being in line with the modeling assumptions.

a- Photo - Surface crack in the road embankment



b- Landslide lines on the embankment [numerical model].

Fig. 13. Surface cracks and landslide lines in the road embankment.

IV. DISCUSSION

A. *Interpretation of Observed Displacements and Influence of Precipitation*

The field monitoring data (Results A) show progressive horizontal displacements of the slopes at PK 208, mainly after episodes of heavy rainfall. This behavior is typical of slow landslides, where soil saturation reduces cohesion and increases pore pressure, thereby promoting displacement. The observed correlation between climatic fluctuations and deformations underscores the importance of weather conditions in slope stability. These results are consistent with the findings in [12], where the significant impact of precipitation on landslide mechanisms was demonstrated.

B. *Impact of Construction Works on Natural Slope Stability*

The simulations of natural slope stability before and after construction (Results B) revealed a significant decrease in FOS post-construction, particularly when the water table was at the surface. This suggests that the construction activities disturbed the hydrogeological conditions, thereby increasing the risk of landslides, which aligns with the observations in [12]. The modification of drainage conditions and the increase in pore pressure are key factors responsible for this degradation in stability.

C. *Influence of the Water Table on Slope Stability*

The analysis of FOS concerning the construction phases and water table position (Results C) reveals that the presence and position of the water table play a decisive role in slope stability.

- Case 1 (Actual water table): The stable FOS around 1.25 to 1.65 indicates maintained relative stability despite embankment phases. This confirms the conclusions drawn in [12], regarding the stabilizing effect of adequate drainage when the water table is properly managed.
- Case 2 (Water table at the surface): The drastic decrease of FOS to 0.80 during preparatory earthworks suggests increased instability, aligned with the principles of [21] concerning the adverse influence of high pore pressure on shear resistance.
- Case 3 (No water table): The increase of FOS to 1.33 demonstrates that the absence of a water table improves stability.

These results stress the importance of managing the water table during construction phases, by providing recommendations on water control to maintain slope stability, according to [12].

D. *Validation of Numerical Models by Field Observations*

The cracks observed in the field (Results D) validate the predictions of the numerical models, thereby confirming the accuracy of the simulations performed with PLAXIS. This correlation between the observations and models strengthens the credibility of the results and underscores the importance of validating numerical models with field data, as proposed in the literature.

V. CONCLUSION

This study highlights the critical influence of the groundwater level, construction activities, and complex geological factors on slope stability, an aspect often overlooked in geotechnical engineering. The presence of clays and marls, with their inherent sensitivity to moisture changes, adds another layer of complexity. Numerical simulations, validated by field observations, demonstrate that the position of the Groundwater table, construction-related disturbances, and the geological characteristics of these soils significantly impact stability, particularly during construction. The present study's findings indicate that:

- A high groundwater level, combined with construction activities, substantially reduces the safety factor of slopes composed of clays and marl, thus increasing the risk of landslides.
- The absence of a groundwater table and minimal construction activities enhance stability in these soil types.

This study for the first time quantitatively assesses the combined impact of the aforementioned factors, including the geological complexity of clays and marls, making a significant contribution to understanding slope stability during construction in diverse geological settings. The drawn conclusions can guide the design and construction of future projects in similar geological contexts. The importance of incorporating the effects of groundwater, construction, and soil type into stability analyses is also emphasized. Further research could focus on developing more sophisticated predictive models that account for the specific behavioral characteristics of clays and marls under varying moisture conditions and construction-related stresses.

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