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EVALUATION OF SLOPE STABILITY PROBLEMS: A CASE STUDY OF SLOPE REINFORCEMENT ON EXPANSIVE SOIL FOR THE HIGH-VOLTAGE TRANSMISSION TOWER (SUTT) T80 MALINGPING–BAYAH, SUKABUMI

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Abstract

Expansive soils are highly susceptible to volumetric changes due to moisture fluctuations, which can significantly affect the stability and durability of structures. Therefore, their presence must be carefully considered during the planning and foundation design stages. Survey, field investigations, and lab tests show that soil up to 8 m deep has a plasticity index of 30%–65%. Swelling tests on samples from 1 m–3.5 m depths revealed swelling percentages of 0.545%–0.715% and pressures of 11.7 kPa–12.5 kPa, which are high for near-surface soil. XRD tests identified montmorillonite minerals, known for high activity and shrinkage, contributing to slope cracks and movement. Geotechnical analysis using finite element method shows that slope stability safety factors of 0.84 (static) and 0.62 (earthquake), below required thresholds of 1.5 and 1.1, respectively. The proposed reinforcement includes double-row soldier piles, connected by a capping beam. The slope surface will be graded downstream and reinforced with 1 m thick stone masonry. These measures are expected to increase safety factors to 1.72 (static) and 1.1 (earthquake), meeting safety standards.

Keywords: Finite Element Method, Geotechnical Analysis, Reinforcement, Slope Stability

Introduction

Expansive soil refers to a type of clay with high plasticity, known for its distinctive properties like significant swelling when it absorbs water and noticeable shrinkage when it dries out (Zhang et al., 2022; Tiwari et al., 2021; Budianta, 2024). Expansive soils are characterized by their tendency to undergo volume changes in response to moisture variations, leading to a decline in their engineering performance. These soils expand upon wetting and contract when they lose moisture—a behavior commonly linked to seasonal changes in water content (Barman & Dash, 2022). Expansive soils contain a high concentration of water-attracting minerals, particularly montmorillonite. Due to its exceptionally large specific surface area, montmorillonite readily absorbs substantial amounts of water. As a result, expansive soils typically exhibit a high free swell index (Luo & Ma, 2024). Expansive soils can undergo significant deformation in both ground surfaces and slopes, potentially compromising their stability. Such instability poses substantial risks to human safety and can lead to considerable damage to infrastructure and property (Hou et al., 2013; Aga, 2021). Expansive soil is a unique category of clay distinguished by its high plasticity, tendency to lose strength, pronounced volume fluctuations, and the frequent development of surface cracks (Zhao et al., 2020). Additionally, the material demonstrates heightened sensitivity to moisture, which amplifies its tendency to undergo volume fluctuations under alternating wet and dry conditions (Liu, 2025; Zada et al., 2023). Identifying and mitigating the effects of expansive soils is vital for maintaining structural stability and ensuring durability over time, making it a key factor in geotechnical assessments as well as in the design of foundations and structural systems.

The highly moisture-sensitive nature of expansive soils makes them particularly vulnerable to volumetric changes during rainfall events (Cai & Ugai, 2004), which can reduce shear strength and trigger slope instability or failure. During rainfall, water infiltrates into the soil from the top and can cause shallow or deep failures (Rahardjo et al., 2007; C. H. Wu & Chen, 2009). It is evident that deep-seated failures generally result in greater damage and carry more serious consequences. As such, the impacts of shallow and deep failures should be evaluated separately to accurately reflect their differing levels of risk (Gallage et al., 2021). The triggering mechanisms for rainfall-induced landslides (Sorbino & Nicotera, 2013; Lee et al., 2009) are directly linked to changes in pore water pressure: as rain infiltrates the slope, matric suction decreases and pore water pressure increases, thereby reducing the soil's effective stress and shear strength, which destabilizes the slope and initiates failure. Failures triggered by generation of positive pore water pressure typically pose a greater risk compared to those resulting from the reduction or loss of matric suction. (Ali et al., 2014).

The Bayah transmission line tower is one of the subsystems of the Java-Bali network that connects the substations around Sukabumi. During its construction, several towers span across forests, plantations, residential areas, rice fields, etc. The morphology of the towers in Bayah is mostly hilly, with some of the towers located on hilltops and slopes. The topography of the tower location consists of a hillside with an approximate 30° slope, which critically influences soil stability (Shukla, 2014; Beddoe & Andy Take, 2015). As the slope steepens, the driving shear stresses on the soil mass increase relative to its shear resistance, making the slope more susceptible to failure, especially during rainfall events (Huang et al., 2021). Moisture infiltration during precipitation further reduces soil cohesion and friction angle, elevates pore water pressures, and decreases effective stress, thereby significantly lowering the factor of safety and increasing the risk of slope instability (Tiwari & Satyam, 2022). The issue of expansive soils is typically associated with variations in moisture content near the ground surface, primarily driven by environmental factors. This susceptible region is referred to as the active zone, with the most pronounced effects occurring within the soil layer situated above the groundwater table (Alihudien et al., 2022; Bambang Siswanto & Wijaya, 2023). During construction, the tower site was excavated and filled with variations of up to 2 m.

Based on field inspections, the slopes around the tower have experienced ground settlement. Additionally, soil cracks approximately 50 cm deep were observed around the tower, and the structure has experienced a tilt of about 1°, indicating potential ground movement and instability. To assess the extent and progression of this displacement, periodic monitoring was conducted using Real-Time Kinematic (RTK) GPS. This method enables high-precision positioning to detect even subtle shifts in the coordinates of the reference points, particularly at the tower footing, over time. Such observations are critical in understanding the nature and rate of ground deformation (Jamei et al., 2015) that may compromise the stability of the tower. Therefore, a comprehensive evaluation is required to identify the underlying causes of the observed movement, which may include slope instability, soil weakening due to moisture variations, or progressive failure mechanisms. Based on the results, appropriate mitigation measures must be designed, such as slope reinforcement, drainage improvements, or foundation retrofitting, to restore stability and ensure the structural integrity and safety of the tower over its service life. The formation of cracks resulting from the shrink–swell behavior of soils subjected to repeated drying and wetting cycles is a prevalent concern in expansive soil slopes. Such cracking is a characteristic manifestation of cyclic fluctuations in soil moisture content (Wang et al., 2019; Yang et al., 2019).

Research Methods

Slope stability issues are commonly observed during the construction of roads, canals, and dams, and natural slopes may also become unstable due to water infiltration (Pokkunuri et al., 2023) which deteriorates soil strength—or as a result of excavation activities. Slope failure can have catastrophic consequences, leading not only to loss of human life but also to extensive damage to infrastructure such as roads, buildings, utility networks, and communication towers, as well as triggering environmental degradation through soil erosion, vegetation loss, and disruption of natural drainage systems (Fawaz, 2014).

The three predominant deterministic techniques used for slope stability analysis are the limit equilibrium method, the finite element method, and the limit analysis method. While these methods share broadly comparable conceptual interpretations of the factor of safety (FS), distinctions arise due to the unique computational frameworks and analytical procedures inherent to each technique (Qi, 2017).

Numerical modeling techniques, such as finite element analysis, have shown that swelling pressures in expansive soils contribute significantly to slope instability. The findings indicate that even moderate moisture variations can induce forces strong enough to cause slope deformation and eventual failure, highlighting the importance of incorporating swelling behavior in slope stability models (Olivares & Damiano, 2007). The swelling pressure generated by expansive clay soils is a crucial factor influencing slope stability. During periods of wetting, these soils expand, applying upward pressure that can lift the slope, leading to cracking and potential failure. Expansive soils, due to their high swelling potential, are a major factor in slope instability. Laboratory testing demonstrated that the volume change in these soils, when exposed to moisture variations, can exert significant pressure on the surrounding soil matrix, often resulting in slope deformation and failure.

A proper understanding of swelling behavior is critical for designing stable slopes in expansive soil regions. The soil parameters used in the evaluation for this study were obtained from field and laboratory tests, both for drained and undrained conditions. Interpretation based on commonly used correlations was also conducted as a supplementary information. This ensures that representative values can be used in the analysis. This research employs Plaxis 2D CE V20 (basic), a finite element-based software, to conduct numerical simulations and analyze the mechanical behavior of soil and geotechnical structures (Cho, 2016). Considering that the predominant soil type is cohesive and the analysis focuses on long-term behavior both during and after construction, the stability analysis was primarily conducted under drained conditions.

However, for capturing short-term response immediately after loading, a supplementary undrained analysis was also considered to evaluate the initial undrained shear strength.

A geoelectrical survey was carried out to examine and delineate the subsurface resistivity distribution of the site. This geophysical technique involves the use of electrical currents to assess the characteristics of underground formations. Typically, it determines subsurface conditions by recording the resistivity values of geological materials (Putranto et al., 2021). The method operates by injecting electrical current into the ground and measuring the corresponding voltage differences that arise.

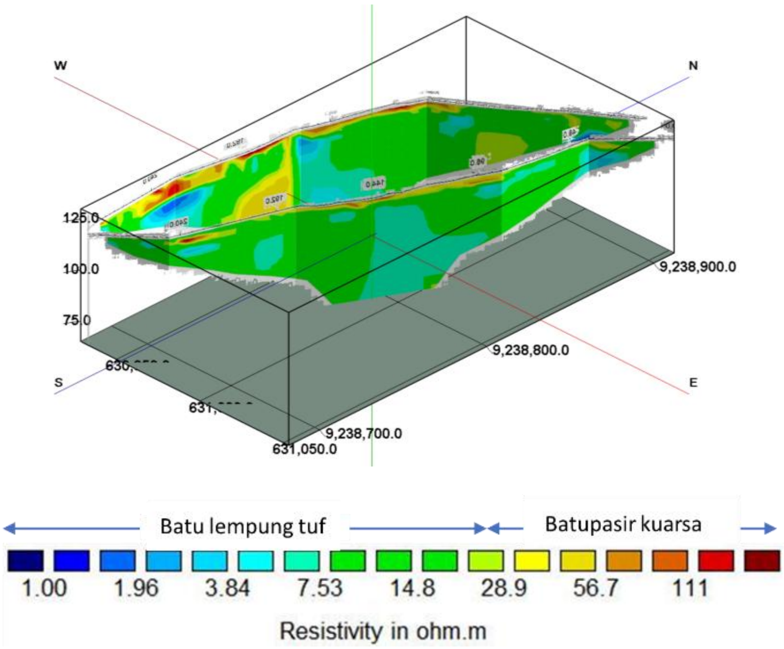


Figure 1. The results of the geoelectric survey integration from the measurement location

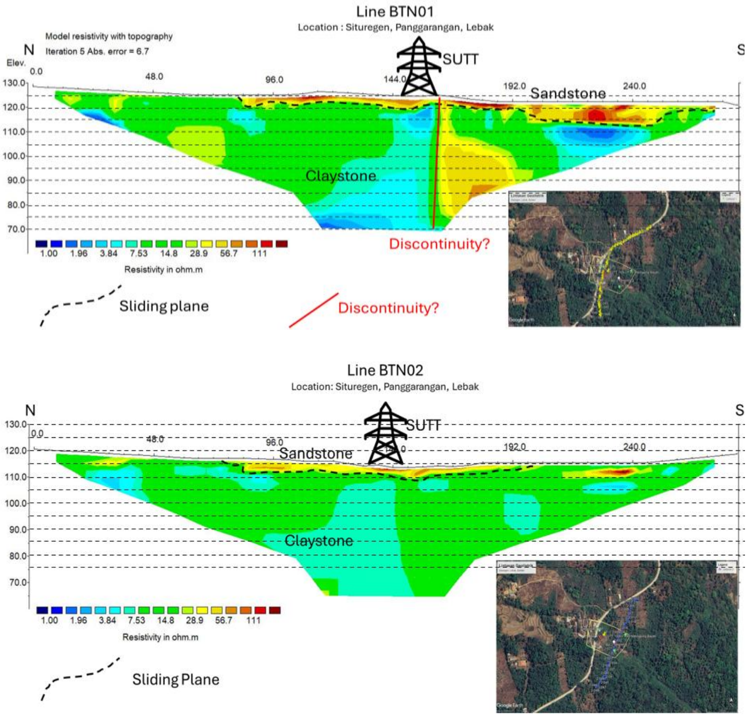


Figure 2. Cross-sections for line BTN01 (above) and BTN02 (below)

Based on the geoelectric survey lines for cross-sections BTN01 and BTN02, a depth of approximately 60 m was identified over a span of 282 m in the N-S direction. In general, the rock dominating the surface is quartz sandstone and conglomerate, indicated by resistivity values greater than 25 Ohm.m. The slip surface is estimated to lie between the quartz sandstone and conglomerate layers and the tuff claystone. The tuff claystone is indicated by resistivity values between 0–25 Ohm.m, which continue to the bottom of the geoelectric measurement cross-section. A discontinuity plane was identified, indicating a shear fault zone, as evidenced by a shear fault located in the southeast of the study area.

The inclinometer is an instrument installed in areas prone to landslides or soil movement. This instrument is used to determine the magnitude of lateral displacement or shifting that occurs in soil layers, from the surface down to the base layer. Inclinometers are typically installed at or close to the toe of embankments to monitor their behavior, as well as that of natural or man-made slopes, since this area is often prone to significant lateral displacement (Indraratna et al., 2015).

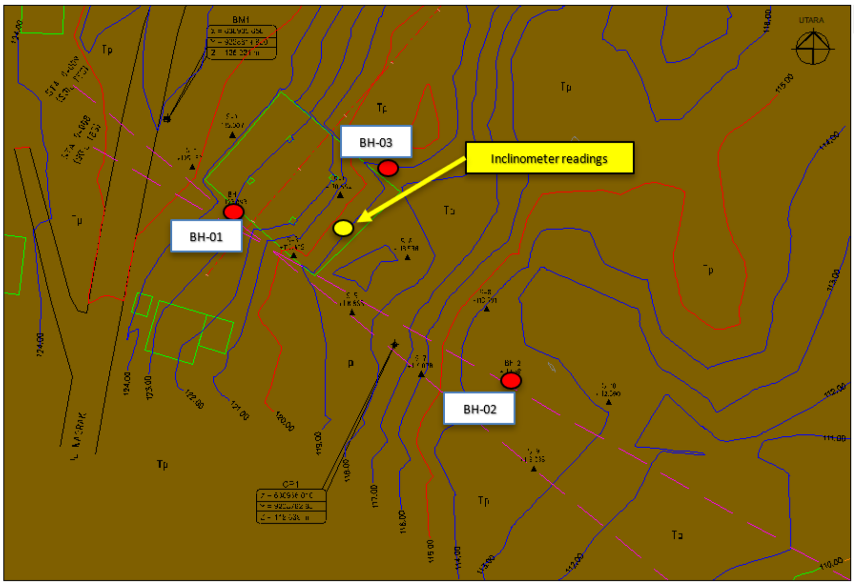


Figure 3. Soil investigations and inclinometer monitoring location

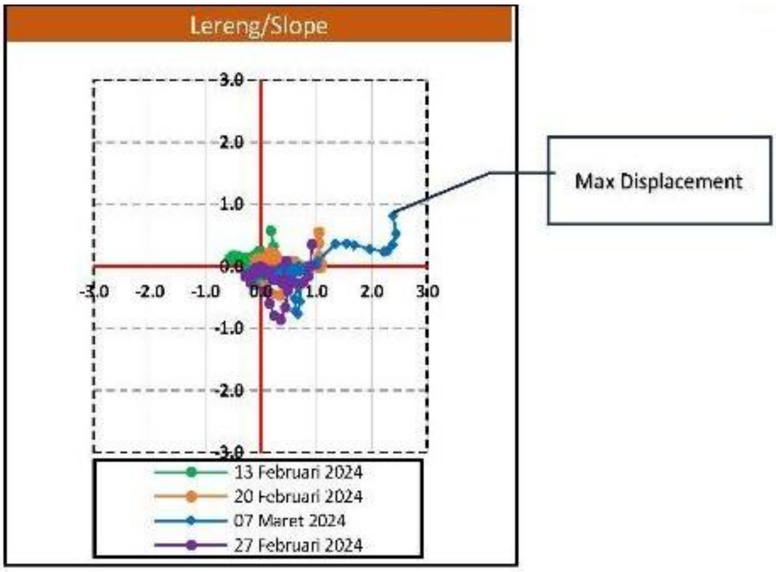
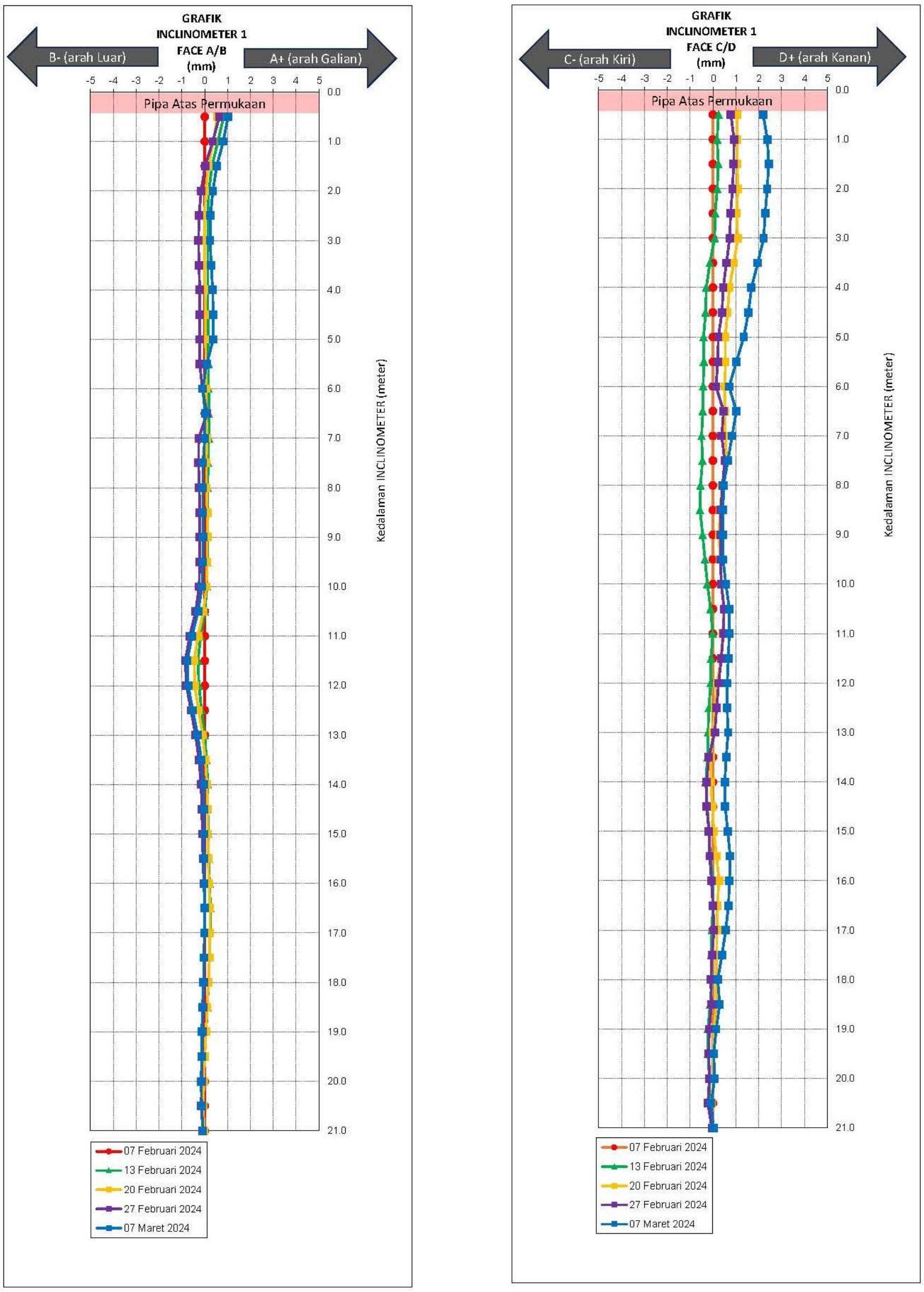


Figure 4. Soil movement from inclinometer readings

Table 1. Inclinometer measurement result



Cuaca : *Cerah*
Incl : *Pembacaan Indikator*
Kum : *Pembacaan Kumulatif*
Dev : *Pergerakan/Deviasi*

The results of observations and inclinometer readings for the period from January to the end of February in a specific year are presented as follows: The maximum movement value for face AB is 0.81 mm at a depth of 1.0 m, with the movement direction toward the downstream side of the slope. The maximum movement value for face CD is 2.44 mm at a depth of 2.0 m, with the movement direction to the right of the tower (when the observer is facing the slope).

The results of boring activity and the estimated soil layer cross-section, as well as the cross-section based on N-SPT values, can be seen as follows:

Table 2. Resume of Soil Mechanics Survey

Point	Depth (m)	Layers	N_{SPT} /30 cm	Consistency
BH.01	0.00 – 0.20	Concrete	-	-
	0.20 – 2.45	Silty Clay	N.3	Soft
	2.45 – 3.50	Clay	N.3	Soft
	3.50 – 4.00	Sand	N.3	Soft
	4.00 – 12.00	Clay	N.8 – N.23	Very Stiff
	12.00 – 19.00	Sand	N.22 – N.49	Medium - Dense
	19.00 – 30.00	Clayey Sand	N.31 – N>60	Dense-Very Dense
BH.02	0.00 – 2.45	Silty Clay	N.6	Medium
	2.45 – 10.00	Clay	N.10 – N.25	Stiff-Very Stiff
	10.00 – 13.50	Sand	N.45 – N.48	Dense
	13.50 – 23.50	Clay	N.30 – N>60	Hard-Very Hard
	23.50 – 30.00	Clayey Sand	N. >60	Very Dense
BH.03	0.00 – 2.45	Silty Clay	N.4	Medium
	2.45 – 11.00	Clay	N.9 – N.24	Stiff-Very Stiff
	11.00 – 17.00	Sand	N.27 – N.42	Dense
	17.00 – 26.00	Clay	N.50 – N>60	Hard-Very Hard
	26.00 – 30.00	Clayey Sand	N.47 – N>60	Very Dense

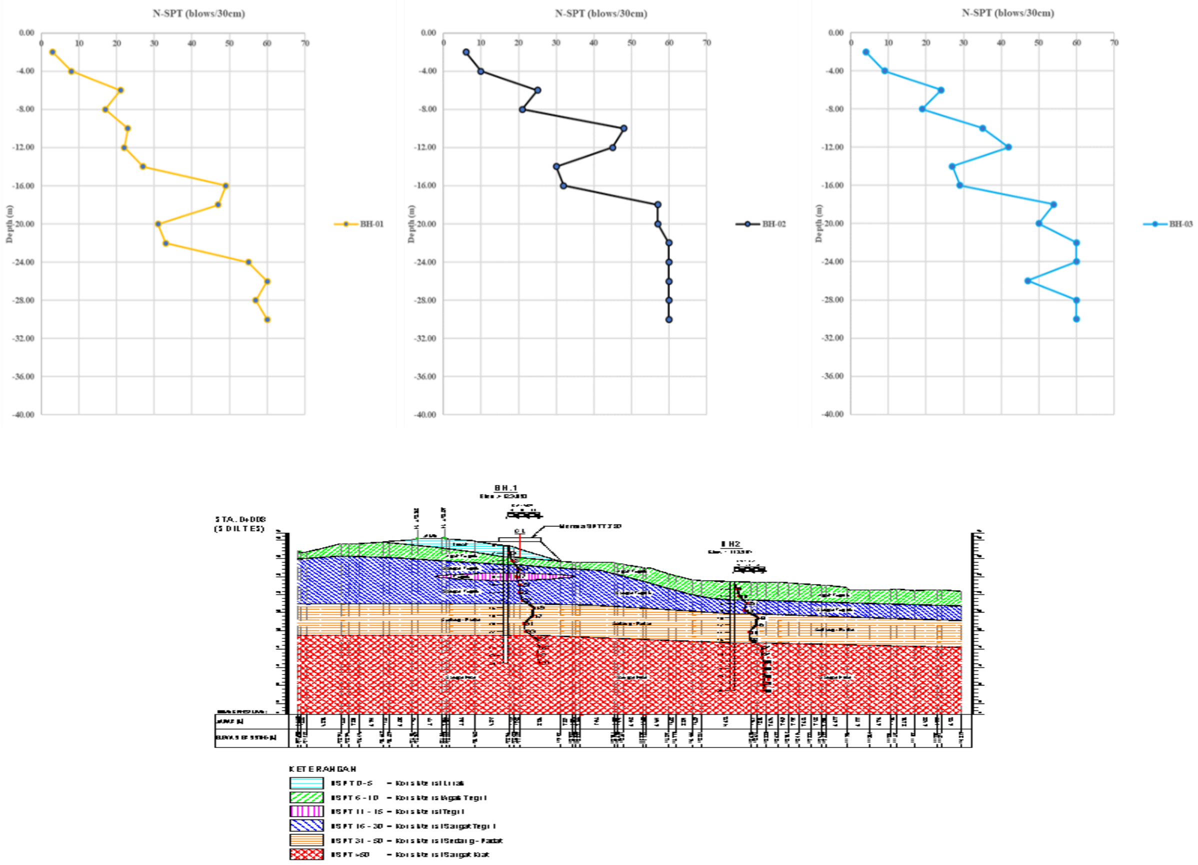


Figure 5. Soil profile based on NSPT value

The results of laboratory tests, showing the variation of soil parameters with depth, are presented in the following graphs and tables.

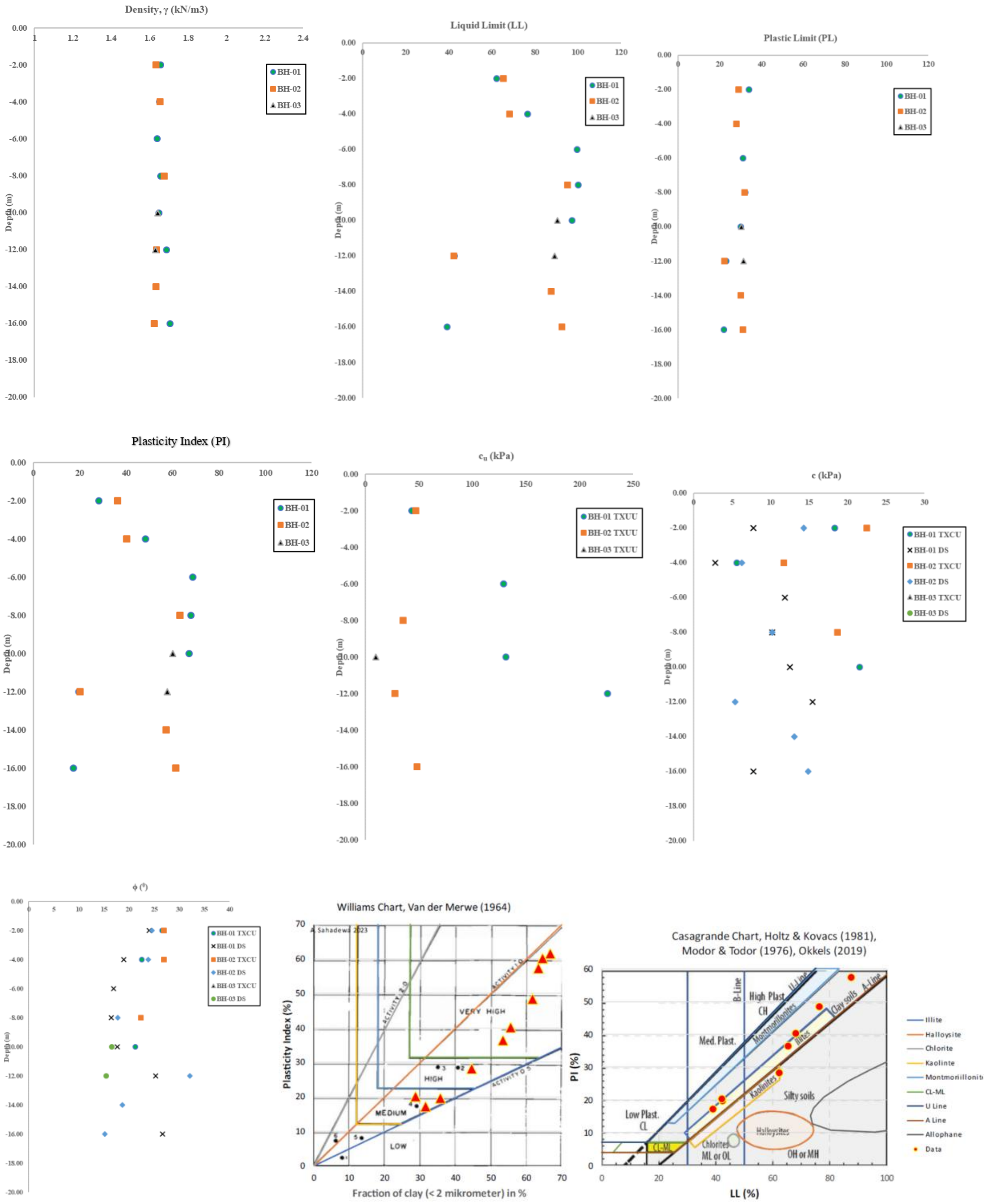


Figure 6. Laboratory results

The soil at the study location has the potential for soil activity ranging from moderate (2% – 4%) to very high (> 8%). Another evaluation was also conducted by incorporating the PI and LL values into the modified Cassagrande chart based on (Holtz & Kovacs, 1981), Modor & Todor (1976), and (Okkels, 2019).

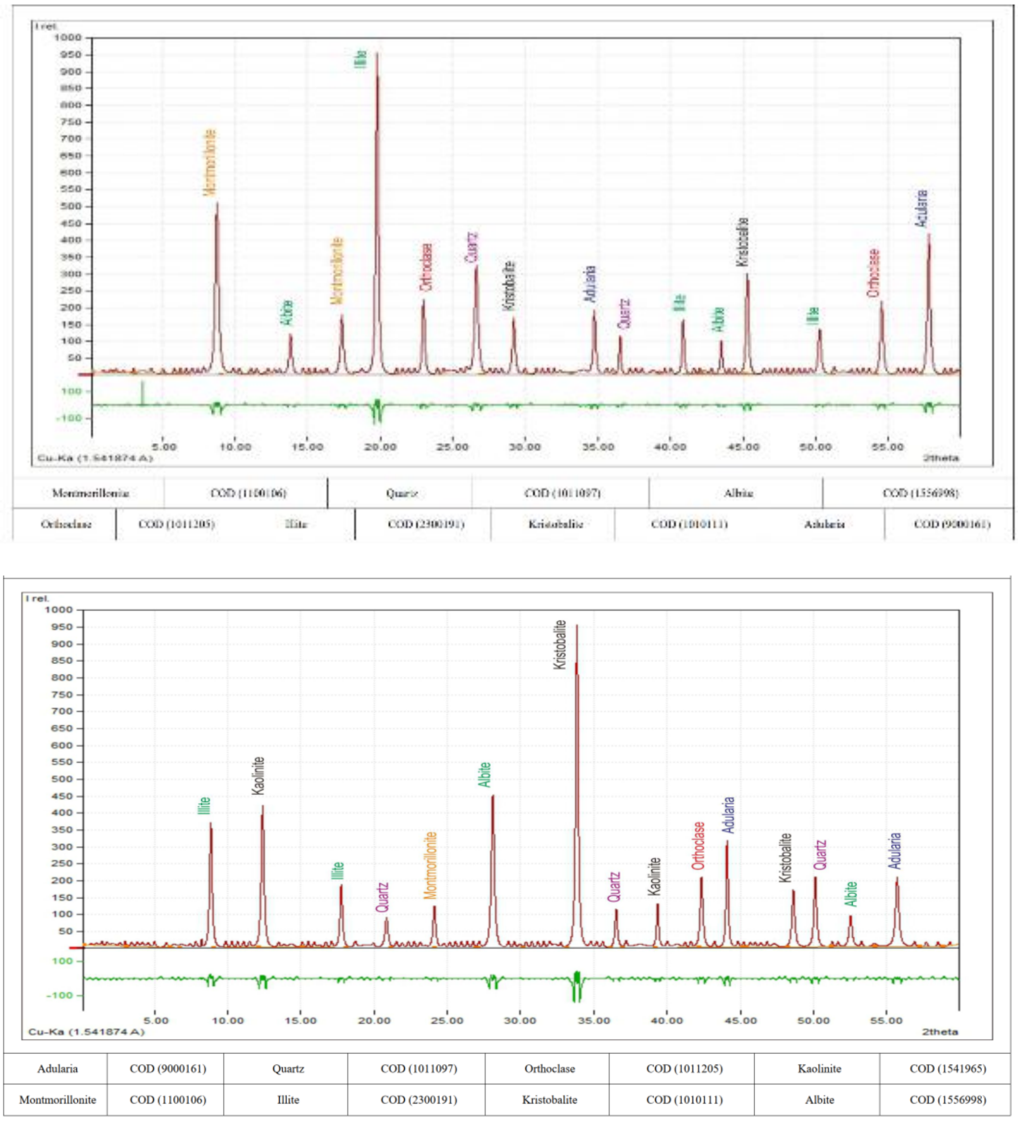


Figure 7. Laboratory results (XRD test)

From the graph, it can be estimated that the soil at the project site contains Illite and Kaolinite minerals. The clay mineral content was also evaluated through XRD testing. The XRD test even revealed the presence of Montmorillonite clay minerals, which are the most active clay minerals with high swell-shrink properties. Expansive soils present significant challenges in construction projects, particularly during the rainy season. Increased rainfall elevates the soil's moisture content, which subsequently reduces its cohesion, internal friction angle, and matric suction, thereby compromising the mechanical integrity and stability of the soil (Y. Wu & Wang, 2014).

The results of field investigations and laboratory tests are used to create soil stratification along with its parameters, which are utilized in the analysis. These soil parameters are presented in the following table.

Table 3. Summary of design soil parameters

No.	**Soil type**	**N-SPT (blows/ft)**	**γ (kN/m³)**	**c' (kPa)**	**ϕ'**	**C_u (kPa)**	**E (kPa)**
1	CH Soft	3	16.5	3	19	18	2,700

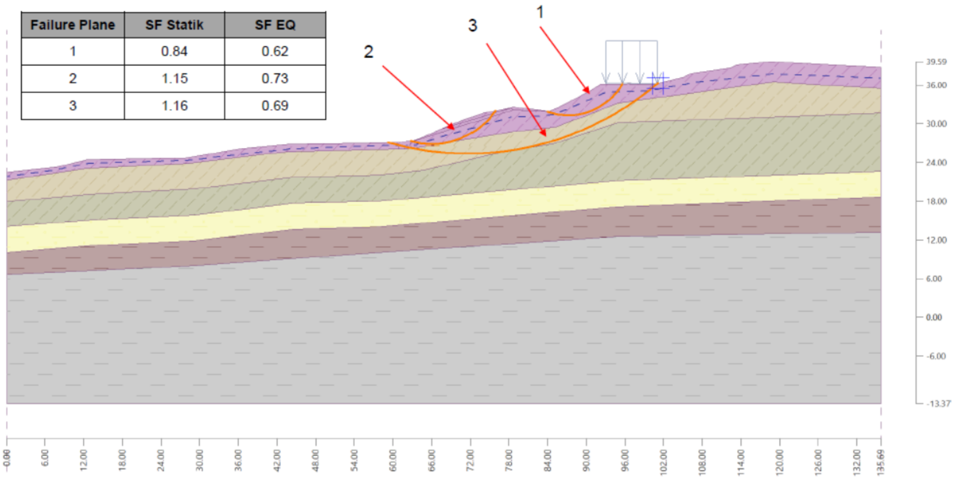
No.	Soil type	N-SPT (blows/ft)	γ (kN/m^3)	c' (kPa)	ϕ'	C_u (kPa)	E (kPa)
2	CH Firm to Stiff	6 – 10	16.5	4	22.5	42	6,300
3	CH Very Stiff	17 – 27	17	10	27	108	16,200
4	SC Dense	45 – 49	17	5	32		45,000
5	CH Hard	30 – 33	17	15	27	180	27,000
6	CH Very Hard	> 50	18	35	35	300	60,000

The design criteria for slope stability can refer to SNI 8460:2017 (Badan Standardisasi Nasional, 2017). The design criteria used in this study are: Slope Stability Safety Factor during static conditions static ≥ 1.5. Slope Stability Safety Factor during earthquake conditions ≥ 1.1.

Research Results and Discussion

The slope geometry is created based on cross-sections obtained from topographic survey work. Subsequently, the soil layer profile is estimated based on available soil investigation data. The slope stability analysis was conducted using the finite element method. The results of the analysis indicate that there are three potential slip surfaces that could occur at the tower location. Two slip surfaces were identified representing local stability under the most critical conditions, and one slip surface was observed representing the global stability of the entire slope. The presence of multiple slip surfaces in the analysis indicates that the stepped slope geometry plays a significant role in influencing slope stability, potentially increasing the risk of localized and global failures.

For all three slip surfaces, the safety factors obtained were lower than the design criteria, both under static conditions and seismic conditions. This aligns with field observations indicating that slope movement has already occurred.



Failure Plane	SF Statik	SF EQ
1	0.84	0.62
2	1.15	0.73
3	1.16	0.69

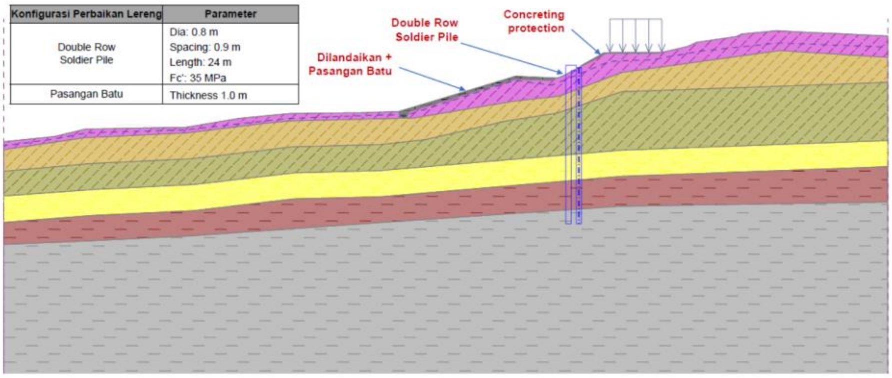
Figure 8. Analysis results for existing condition

The analysis of the existing slope stability indicates that the computed factor of safety (FoS) falls below the acceptable threshold defined by applicable design standards, thereby necessitating immediate slope mitigation and reinforcement measures. Slope reinforcement techniques encompass a range of methods, including anchor rods, stabilizing piles, geogrids, and other approaches (Liu, 2025; Pei et al., 2020). As a primary stabilization method, soldier piles are proposed to resist lateral soil movement and enhance global slope stability. The design configuration of the soldier piles, including their spacing, depth, diameter, and embedment length, is determined through a series of iterative slope stability analyses using finite element modeling in

PLAXIS. In each iteration, the geometry and mechanical properties of the piles are adjusted based on the computed FoS until the design meets or exceeds the minimum required value—typically FoS ≥ 1.5 under static conditions and FoS ≥ 1.1 under pseudo-static (seismic) conditions. The staged construction modeling also considers soil-structure interaction to ensure realistic simulation of pile performance under various loading scenarios.

In addition to the deep-seated reinforcement, surface protection measures are implemented. The upper section of the slope, which corresponds to slip surface 1, will be covered with reinforced concrete facing to prevent superficial erosion, reduce water infiltration, and mitigate localized failure. Meanwhile, the lower section (slip surface 2) is reinforced with stone masonry retaining structures to resist toe failure and improve slope toe stability.

The proposed reinforcement involves installing two rows of soldier piles downstream of the existing tower. Based on the study conducted by Akhmudiyanto et al. (2021), the addition of reinforcement with bore pile on the slope increase the factor of safety of the slopes. The soldier piles consist of bored piles with a diameter of 0.8 meters, spaced 0.9 meters apart, and embedded 24 meters below the ground surface. Furthermore, the slope area downstream of the tower must be flattened and reinforced with 1-meter-thick stone masonry. Concrete reinforcement is also required directly in front of the tower.



Konfigurasi Perbaikan Lereng	Parameter
Double Row Soldier Pile	Dia: 0.8 m Spacing: 0.9 m Length: 24 m Fc': 35 MPa
Pasangan Batu	Thickness 1.0 m

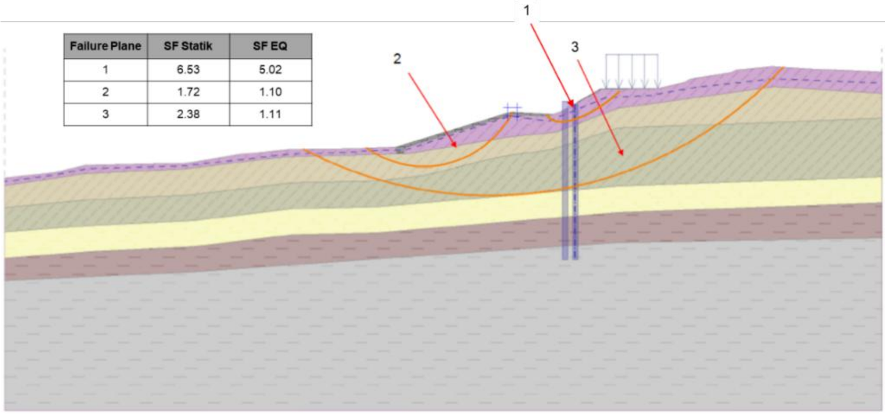
Figure 9. Reinforcement for the slope

Compared to other reinforcement methods, such as single row piles, ground anchors, or retaining walls, the double row system provides greater structural capacity and stability, particularly in cases where deep-seated failure mechanisms are present. This configuration allows for more effective distribution of earth pressures and improves resistance against both lateral movement and overturning. Additionally, the double row system offers better performance in complex slope geometries or in conditions with limited space for passive resistance, where conventional retaining structures may be less effective.

Furthermore, in the context of cohesive soil with low shear strength and multi-slip surface scenarios, as observed in this study, the double row soldier pile method enhances global and local stability while minimizing deformation. Its constructability and adaptability also make it a practical solution for staged construction or reinforcing the existing slopes.

The safety factor for slope stability on the existing slip surface has increased significantly due to the reinforcement. Meanwhile, the critical slip surface in the reinforced slope area has shifted, and the safety factor for slope stability has improved, meeting the design criteria. Based on the analysis conducted, the safety factor after reinforcement is estimated to be SF = 1.72 under static conditions, which exceeds the minimum allowable limit and indicates adequate slope stability (above the allowable safety factor, OK). Under seismic loading, the safety factor is SF = 1.1, which meets the minimum recommended value for pseudo-static conditions according to standard geotechnical design guidelines.

This relatively low safety factor for seismic conditions reflects a deliberate engineering decision made to balance safety requirements with economic feasibility. Given the owner's constraints and the necessity to implement a cost-efficient solution, the design was optimized to achieve the minimum acceptable safety threshold under seismic conditions without overdesigning the system. While the slope technically satisfies design standards, the narrow safety margin under dynamic loading suggests that the site may remain vulnerable under extreme or unforeseen seismic events. As a precaution, it is advisable to incorporate risk management strategies, such as slope monitoring or drainage improvements, to maintain long-term performance and reduce potential failure risks without significantly increasing construction costs.



Failure Plane	SF Statik	SF EQ
1	6.53	5.02
2	1.72	1.10
3	2.38	1.11

Figure 10. Analysis results of post reinforcement

The primary challenge in slope construction lies in the uncertainties associated with analysis methods and the soil parameters used. Several aspects need to be carefully considered to ensure the project proceeds smoothly with measurable risks, including design planning, construction processes, and monitoring and instrumentation. The monitoring and instrumentation system is used to oversee the implementation during construction and the maintenance of the reinforcement for the T.80 High-Voltage Transmission Line (SUTT) slope. This system also serves as an early warning mechanism during both construction and maintenance phases. Generally, referring to the Kimpraswil (2002), the scope of monitoring and instrumentation is required for: (a) Procedures or schedules for construction execution, (b) Guidance when design uncertainties are high and safety factors are limited, and (c) Evaluation of the appropriateness of the solutions and methods used, such as slope monitoring or drainage improvements.

The criteria for warning levels are based on displacement limits recommended by the Japanese Public Works Research Institute (PWRI, 2007), as shown in the table below. The planning of slope stability mitigation must be followed by the construction process. Both stages should be accompanied by instrumentation and monitoring.

Conclusion

Field survey and laboratory analysis results shows that from surface until -8 m (embedded pile position), the index plasticity value is ranging from 30% to 65%. The swelling test using samples at depths of -1m until -3,5m shows the swelling percentage and swelling pressure, respectively, ranging from 0.545%-0.715% and 11,7-12,5 kPa. These pressure values are quite high for soil near the surface. XRD testing confirmed that the soil contains highly active montmorillonite minerals, which exhibit significant shrinkage and swelling. These findings are one of the causes of cracking and soil movement on the slope at the tower site.

The results of the analysis shows that slope stability safety factors of 0.84 (static) and 0.62 (earthquake), below required thresholds of 1.5 and 1.1, respectively. The proposed reinforcement includes double-row soldier piles made of 0.8 m diameter bored piles, spaced 0.9 m apart and 24 m long, connected by a capping beam. Concrete with fc' 35 MPa will be used. The slope surface will be graded downstream and reinforced with 1 m thick stone masonry. These measures are expected to increase safety factors to 1.72 (static) and 1.1 (earthquake), meeting safety standards.

A practical approach to slope reinforcement design that carefully balances structural safety and economic feasibility is demonstrated through the analysis and discussion presented in the study above. Unlike many conventional studies that prioritize conservative safety margins, this work demonstrates how a minimum-threshold seismic safety factor (SF = 1.1) can still be considered acceptable when combined with a robust understanding of site conditions, failure mechanisms, and material behavior. By employing iterative numerical analysis, the configuration of soldier piles was optimized not to maximize safety arbitrarily, but to meet design criteria in the most cost-effective manner. This integrated approach highlights a real-world engineering solution where structural reliability is achieved without incurring unnecessary construction costs—a critical consideration in infrastructure projects with budget limitations. As such, the methodology and findings presented in this study offer valuable insights into how performance-based geotechnical design can be adapted for constrained settings, enhancing the ongoing scholarly dialogue on sustainable and economically viable slope stabilization strategies.

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