U Karst
Volume 09 Number 02 Year 2025

ISSN (*Online*) 2581-0855
ISSN (*Print*) 2579-4620

Available Online at
https://ojs.unik-kediri.ac.id/index.php/ukarst/index

https://dx.doi.org/10.30737/ukarst.v9i2.7106

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Increasing the Safety Factor of Clay Shale Slopes Using Bored Pile by Limit Equilibrium Method

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A R T I C L E I N F O

Article History :
Article entry : 14 – 11 – 2025
Article revised : 17 – 11 – 2025
Article received : 08 – 12 – 2025

Keywords **:**
Clay Shale, Dam, Fellenius, Plaxis LE, Slope Stability

IEEE Style in citing this article :
M. A. Simanjuntak, R. Fathki and Sriyana, "Increasing the Safety Factor of Clay Shale Slopes Using Bored Pile by Limit Equilibrium Method," U Karst, vol 9, no. 2, pp 138 – 149, 2025, doi: 10.30737/ukarst.v9i2.7106

A B S T R A C T

The clay shale slopes of the Rukoh Dam Supplementary Structure exhibit high susceptibility to weathering and shear strength reduction, which directly impacts long-term stability. This vulnerability demonstrates the importance of slope reinforcement and the need to consider the fully softened condition that represents the long-term behavior of degraded clay shale material in the field. This study aims to determine the stability of the Rukoh Dam Supplementary Structure's clay shale slopes with bored pile reinforcement. Soil characteristic data were tested in the Laboratory to obtain shear strength. Evaluations were performed at peak and fully softened conditions using Fellenius and Plaxis LE calculations. The bored pile design was calculated based on the slope stability evaluation results and requirements to achieve a safety factor of 1.5. The results showed that slope stability was significantly reduced when the material was fully softened, with a safety factor of 0.74, thus not meeting long-term service requirements. Increasing the stability to FS 1.5 was achieved using a bored pile system with a diameter of 0.8 m and a total length of about 11 m, which can provide a moment capacity of about 364,818 kNm. These findings indicate that bored pile reinforcement can improve long-term slope stability under clay shale conditions.

1. Introduction

Clay shale is widely recognized as one of the most problematic geomaterials in geotechnical engineering due to its high plasticity, rapid weathering, and significant reduction in shear strength when exposed to moisture or environmental changes [1]. These characteristics strongly influence slope stability because weathering leads to a decrease in cohesion and internal friction angle, which are the primary parameters that control the resisting forces against sliding [2]. At the Rukoh Dam, an additional structure designed to increase reservoir inflow [3], geotechnical investigations show that the surrounding soils, particularly near the intake tunnel,

ISSN (*Online*) 2581-0855
ISSN (*Print*) 2579-4620

are composed of clay shale [4]. These cohesive materials typically exhibit low shear strength, high plasticity when saturated, and high compressibility [5]. Clay shale within this environment presents additional complexities because it rapidly transforms into softened clay when exposed to water, air, or sunlight [6], and its behavior is strongly influenced by microstructure and mineralogical composition [7]. Expansive clay minerals, such as smectite, illite, and mixed-layer variants, further increase susceptibility to degradation, causing swelling, spalling, and instability [8].

In hydraulic structures, prolonged seepage, saturation, and climatic exposure accelerate the softening of clay shale, gradually reducing its strength as it transitions from an intact to a fully softened state. Within dam infrastructure, studies emphasize the importance of addressing seepage-related reductions in stability [9], the performance of various reinforcement systems, including CCSP [10], slope reinforcement in tunnels [11], and soil nailing applications [12]. Numerical modeling has consistently demonstrated its significant influence on determining safety factors, and integration of Fellenius, Bishop, and PLAXIS has been used for slope evaluation and bored pile design [13].

Previous research on problematic soils has shown that weathering and saturation significantly reduce shear strength and facilitate progressive deformation [14]. FEM-based studies also indicate that long-term moisture exposure promotes softening and triggers failure along weakened zones [15]. Although comparisons between FEM and LEM show that both methods produce comparable safety factors, FEM better represents deformation behavior in weathered soils. Reinforcement techniques, such as geotextiles, sheet piles, and bored piles have been shown to improve stability. However, most evaluations focus on short-term conditions, with limited examination under fully softened parameters [16]. Additional research highlights challenges involving expansive and saturated soils [17], the broad application of numerical methods for evaluating slope stability [18], and the use of FEM-based software such as PLAXIS to assess potential failure zones [19].

Although numerous studies have examined weathering mechanisms, mineralogical influences, and short-term geomechanical behavior [20], long-term strength degradation under field conditions remains insufficiently understood, especially in slopes supporting dam auxiliary structures [21]. The interaction between long-term strength loss in high-plasticity clay shale, changes in the global factor of safety, and the required performance of bored-pile systems has not been comprehensively quantified for dam-related slopes [22]. This study aims to determine the slope stability of shale clay in the Rukoh Additional Structure with bored pile

https://dx.doi.org/10.30737/ukarst.v9i2.7106

ISSN (*Online*) 2581-0855
M. A. Simanjuntak/ U Karst Vol 09 No.02 Year 2025
ISSN (*Print*) 2579-4620

reinforcement. Slope stability evaluations were conducted at peak and fully softened conditions using Fellenius calculations and Plaxis LE. The expected outcomes are a clearer understanding of degradation-driven failure mechanisms and guiding for designing reinforcement systems under moisture-sensitive conditions. Furthermore, these findings support more informed decision-making for reinforcement design in infrastructure exposed to long-term weathering and seepage.

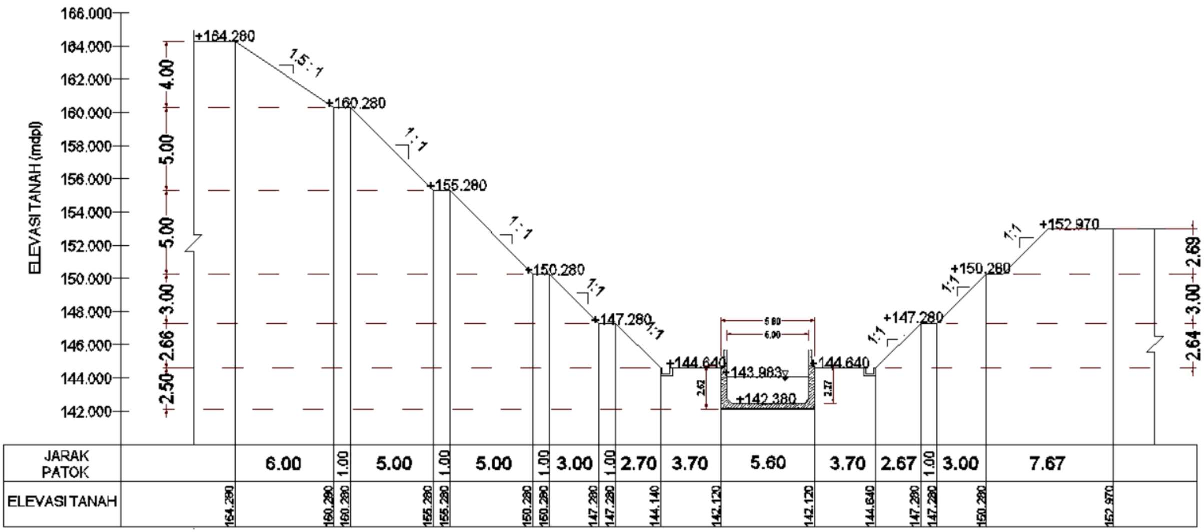
2. Research Method

2.1 Research Location

This research was conducted on the slope area of Rin Alue Village, Titeue Subdistrict, Pidie Regency, Aceh Province, Indonesia. Geographically, the site is located between approximately 5°11'55" to 5°12'28" N latitude and 95°20'20" to 95°53'59" E longitude. The area is accessible by traveling approximately 114 km from Banda Aceh City to Pidie Regency, followed by approximately 24 km from the Pidie town center to the dam area via paved village roads in good condition, and an additional 2 km on unpaved roads leading to the dam.

2.2 Data

The data used include the results of mechanical soil property tests conducted at the Soil Mechanics Laboratory of the Faculty of Civil Engineering. Additionally, slope geometry data was obtained from the dam management, as shown in **Figure 1**. The slope at the Rukoh Dam site is characterized by a geotechnical condition dominated by clay shale, which is highly susceptible to weathering and strength degradation.



Source: Author Research Results (2025).

Figure 1. Existing Slope Geometry

ISSN (*Online*) 2581-0855
ISSN (*Print*) 2579-4620

Figure 1 illustrates the slope geometry consisting of several elevation segments with varying inclinations, where the main slope has a gradient of approximately 1.5:1 at the crest and 1:1 along the descending sections. The slope height ranges from elevation +164.280 m to +144.000 m before reaching the channel bottom at elevation +142.380 m. The channel width is approximately 5.60–6.00 meters with a depth of about 2.25 m from the channel edge. The slopes on both sides of the channel rise again with a 1:1 gradient, reaching elevations around +150.280 m and +152.970 m. Overall, the profile shows a sequence of stepped slopes with structured inclinations and consistent elevations designed to ensure slope stability and adequate channel capacity.

2.3 Data Anaylisis

The analysis in this research was carried out using the Limit Equilibrium Method (LEM), consisting of manual calculations with the Fellenius Method and numerical analysis using the Plaxis LE application. Two shear strength parameters (internal friction angle and cohesion) were used at the peak condition, representing the maximum intact soil strength, and at the fully softened condition, representing soil weakened by weathering, reshaping, and saturation. The fully softened parameters were applied for long-term slope stability analysis. Peak shear strength parameters were obtained using empirical characteristic values based on Empfehlungen des Arbeitsausschusses Ufereinfassungen (EAU) 2004 [12], while fully softened internal friction angles were determined using the correlation between fully softened shear strength and Liquid Limit (LL) [15].

Analysis using Plaxis LE is carried out by creating a slope model, inputting soil material properties, creating a slope reinforcement model, inputting reinforcement material properties, and running the program to obtain the Safety Factor (FS). Meanwhile, manual analysis using the Fellenius Method is performed by drawing a slope model, plotting the failure surface with the center and radius of the shear circle based on the results of Plaxis LE, dividing the failure mass into several slices, and calculating the slope stability using Equation 1 [23].

$$F_s = \frac{\sum c' \, \Delta L \, cos\alpha + (W \, cos\alpha) \tan \phi'}{\sum W \sin \alpha} \quad (1)$$

Where $\sum c' \, \Delta L \, cos\alpha + (W \, cos\alpha) \tan \phi'$, Is the resisting (passive) moment, and $\sum(\text{W} \sin \alpha)$ is the driving (active) force. In the Fellenius Method, interslice force distribution is neglected, resulting in simpler calculations. Meanwhile, Plaxis LE uses a numerical, iterative computer based analysis with more slices and more detailed consideration of interslice force interactions.

Reinforcement with bored piles is carried out by determining the location and depth of the pile installation above the shear plane based on the radius and center point obtained from

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the Fellenius critical safety factor analysis. Then, calculate the applied forces and the required resisting moment. The analysis of the moment required to be resisted by the bored pile is carried out until it reaches FS ≥ 1.5. Equations 2, 3, and 4 provide the mathematical framework for determining the load-carrying capacity of bored piles (drilled shafts) of diameter d utilized for slope stabilization in unstable terrain conditions. Equation 2 calculates the eccentricity ratio e/d, where e signifies the vertical distance from the neutral axis to the point of lateral load application on the pile, and d represents the nominal pile diameter, thereby defining the load eccentricity relative to the pile's geometric properties.

$$ed\ ratio = \frac{e}{d} \tag{2}$$

Equation 3 evaluates the coefficient of passive earth pressure (Kp) as a function of the residual friction angle (φ') under fully softened soil conditions, thereby quantifying the passive earth pressure mobilization capacity surrounding the pile structure when the soil has undergone significant long-term degradation and weathering.

$$K_p = \frac{1+\sin\phi'}{1-\sin\phi'} \tag{3}$$

Equation 4 calculates the ratio that correlates the lateral pile force (H) with soil parameters and pile geometry to determine the required embedment length of the pile below the slip surface. This value is subsequently utilized on a design chart to obtain the necessary pile depth. γ = 17.65 kN/m³ represents the unit weight of soil (bulk density) at the research location.

$$\frac{h}{k} ratio = \frac{H_{pile}}{K_p^2 \gamma d^3} \tag{4}$$

Equation 5 calculates the maximum moment resistance of the pile (Mp). This Mp value represents the minimum moment resistance that a bored pile with diameter d must possess in order to withstand lateral loading and stabilize the slope with a safety factor of 1.5.

$$M_\mathrm{p} = 9{,}338.\, K_p^2 \gamma d^4 \tag{5}$$

3. Results and Discussions

3.1 Atterberg Limit Test Result

Laboratory Atterberg limit testing on the clay shale at the Rukoh Supplementary Structure yielded a liquid limit (LL) of 70.53%, a plastic limit (PL) of 34.31%, and a plasticity index (PI) of 36.12%. These values classify the material as a highly plastic clay that is strongly cohesive and highly sensitive to changes in moisture content. For the stability analyses, the soil unit weight (γ) was 17.65 kN/m³, with peak shear strength parameters ϕ_{peak} 25° and c_{peak} 10

https://dx.doi.org/10.30737/ukarst.v9i2.7106

ISSN (*Online*) 2581-0855
ISSN (*Print*) 2579-4620

kPa, and fully softened parameters ϕ'_{FS} 23.479° and c'_{FS} 0 kPa. The fully softened friction angle was derived empirically from the correlation between LL and drained shear strength proposed for high-plasticity clays, ensuring that the long-term behavior of the clay shale is realistically represented.

These index and strength parameters confirm that the clay shale behaves as a strain-softening material whose shear resistance can degrade significantly under weathering, wetting–drying cycles, and structural disturbance. The relatively high LL and PI indicate a substantial content of expansive clay minerals, leading to volume changes and progressive softening when the soil becomes saturated. The decision to adopt a fully softened condition with zero cohesion and a reduced friction angle for long-term analysis reflects the expectation that bonding and apparent cohesion in the clay shale will be lost in the field, so that only frictional resistance along reoriented clay particles remains mobilized over time. This distinction between peak and fully softened strengths is critical for slope design, because relying solely on peak parameters would overestimate stability under in-service conditions in which the material has already undergone degradation [24].

The characterization obtained in this study is consistent with previous research on clay shale and highly plastic clays, which has shown that short-term intact strengths can decrease markedly after exposure and remolding. Another study reported significant shear strength degradation of Semarang–Bawen clay shale due to weathering, highlighting a rapid transition from stiff, bonded material to soft clay with much lower strength [6]. Similarly another result, as well as subsequent work on fully softened shear strength, emphasized that high-plasticity clays, clay shales, and mudstones should be analyzed using fully softened parameters for first-time failures in cuts and embankments [18].

3.2 Slope Stability under Peak and Fully Softened Conditions

Limit equilibrium analyses using PLAXIS LE showed that under peak conditions, the factor of safety (FS) of the existing slope is 1.355, whereas under fully softened conditions, the FS decreases to 0.740. Manual Fellenius slice calculations using the same slip surface geometry produced FS values of 1.354 for the peak case and 0.741 for the fully softened case. These results indicate that the slope is nominally stable in the short term, but becomes unstable in the long term once the clay shale has degraded and its shear strength has softened. The close agreement between PLAXIS LE and Fellenius (differences $< 1\%$) demonstrates that the chosen slip surface and material parameters are internally consistent and that both methods capture a

https://dx.doi.org/10.30737/ukarst.v9i2.7106

ISSN (*Online*) 2581-0855
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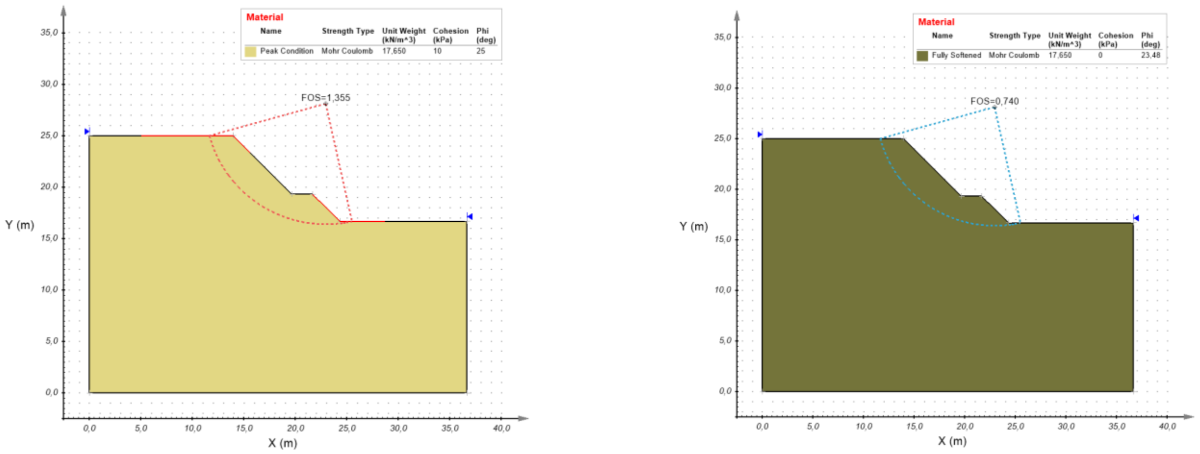
similar critical mechanism. The safety factor at peak and fully softened conditions is shown in **Figure 2**.



(a) (b)

Source: Author Research Results (2025).

Figure 2. Safety Factor at (a) Peak and (b) Fully Softened Condition

This finding aligns with previous research showing that comparisons between limit equilibrium methods and Plaxis LE software results report similar FS values when the same shear strength model and sliding surface family are used [25], [26]. So the difference in values in the two slope stability methods in the study is still acceptable [27].

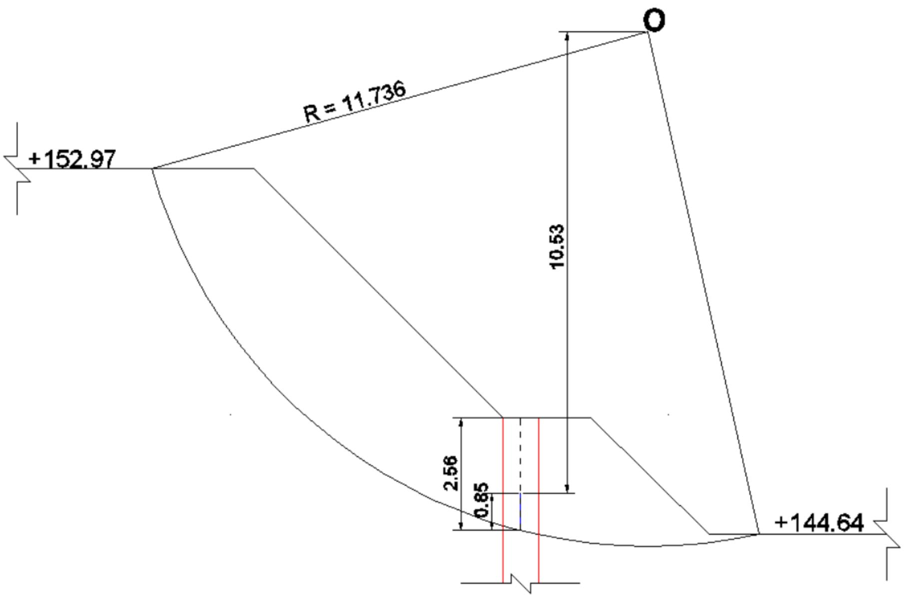
3.3 Bored Pile Reinforcement

Slope stability analysis under fully softened conditions showed a significant decline in the geotechnical performance of the clay shale, reflected in a factor of safety below the safe limit. This occurred due to decreased cohesion and internal friction angle after long-term weathering. Calculations using the Fellenius method yielded a driving moment of 319.099 kN and a resisting moment of 236.383 kN. The difference between these two components indicates that the soil's resistive capacity is no longer able to offset the driving force caused by long-term weathering of the clay shale. Based on these results, the need for additional moments was determined using a moment balance formulation to achieve FS 1.5, resulting in a required stabilizing moment of approximately 2843.232 kN m.

This stabilizing moment contribution is planned to come from the lateral force of the bored pile. Based on the geometric configuration of the slope system, the lateral force of 270.012 kN acts on a moment arm 11.736 m from the center of the slip plane, resulting in a moment of 2843.232 kN m. This value corresponds to the moment required to achieve the design target increase in FS. Therefore, the pile force and position are directly related to the global slope stability, as reflected in **Figure 3**.

https://dx.doi.org/10.30737/ukarst.v9i2.7106

ISSN (*Online*) 2581-0855
ISSN (*Print*) 2579-4620



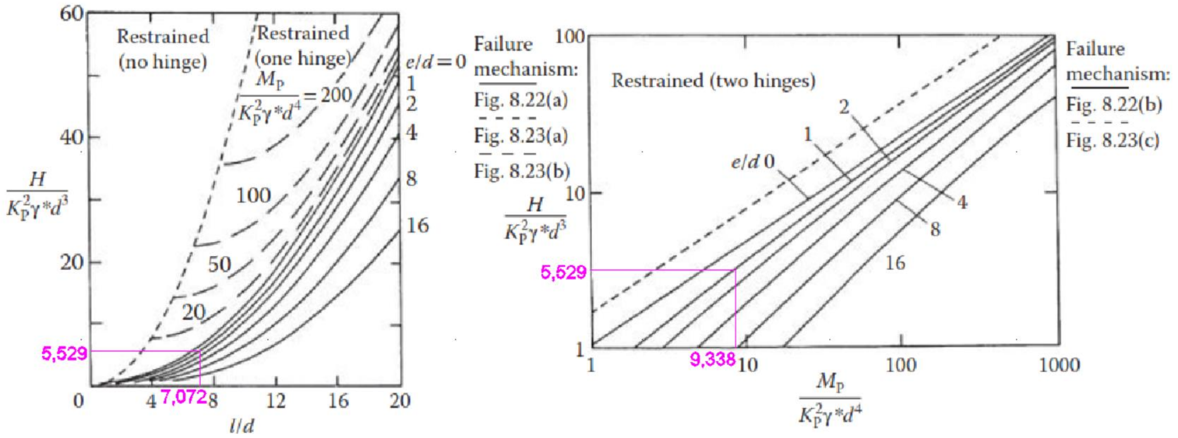
Source: Author Research Results (2025).

Figure 3. Simulation of Slip Plane Cutting by Bore Pile

Evaluation of the pile design parameters was performed for a 0.8 m diameter pile. The eccentricity value was 0.853 m, resulting in an e/d ratio of 1.067, which describes the relative position of the lateral force to the pile axis and determines the distribution of bending stresses along the structural element. The calculation results show a Kp value of 2.325. This value indicates the ability of the degraded clay shale soil to mobilize passive pressure around the pile. Therefore, based on Equation 4, the $\frac{H_{\text{pile}}}{K_p^2 \gamma d^3}$ ratio is 5.529. This ratio is used in the design graph that relates the force ratio to the pile embedment depth. The matching result in the graph (**Figure 4**) yields an $\frac{l}{d}$ value of 7.072, resulting in an embedment depth of 5.657 m from the point of force application. Taking into account the depth of the force relative to the ground surface, the theoretical pile length is 8.217 m. For field implementation purposes, this length was increased by 30%, resulting in a final pile length of 11 m. This adjustment is consistent with design practice to accommodate uncertain field soil conditions.

https://dx.doi.org/10.30737/ukarst.v9i2.7106

ISSN (*Online*) 2581-0855
ISSN (*Print*) 2579-4620



Source : Powrie (2014).

Figure 4. Pile Resistance Moment Calculation Graph

Based on **Figure 4**, a value of 9.338 is obtained for the moment ratio. Calculations using Equation (5) yield a minimum moment capacity Mp of 364.818 kNm. This capacity meets the previously calculated stabilization moment requirements, so the pile design is deemed adequate to withstand lateral forces and increase the slope FS.

Several recent case studies of bored pile or soldier pile reinforcement report post-reinforcement safety factors in the range of 1.5–1.9 for static loading, achieved with pile diameters of 0.8–1.0 m and embedment lengths optimized via limit equilibrium or finite-element analysis. The present design, which uses piles with a diameter 0.8 m and a total length of about 11 m to raise FS from approximately 0.74 to 1.5 under fully softened conditions, falls squarely within this observed range. Furthermore, the use of empirical charts for laterally loaded piles and the adoption of an increased field length relative to the theoretical requirement mirror recommendations from standard soil–structure interaction references, supporting the adopted bored pile solution reliability for ensuring long-term slope stability in clay shale.

4. Conclusion

Based on the integration of Fellenius limit equilibrium and Plaxis LE analysis, this study shows that the stability of the clay shale slope at the Rukoh Additional Structure is significantly reduced when the material is fully softened, with a safety factor of only about 0.74, thus not meeting long-term service requirements. This evaluation confirms that the fully softened parameter should be used to assess the performance of degraded clay shale slopes, as small differences in friction angle and loss of cohesion have been shown to drastically reduce stability. Stability improvements of up to FS 1.5 were achieved using a bored pile system with a diameter of 0.8 m and a total length of approximately 11 m, which can provide a moment

https://dx.doi.org/10.30737/ukarst.v9i2.7106

ISSN (*Online*) 2581-0855
ISSN (*Print*) 2579-4620

capacity of about 364.818 kNm. These findings demonstrate the need for the long-term reinforcement of bored piles on clay shale slopes. Furthermore, they provide a technical reference for reinforcement design practices in dam infrastructure and slopes with similar geological conditions.

5. Acknowledgement

The author would like to express sincere gratitude to the academic supervisor for the guidance and valuable input provided, the Directorate of Dams and Lakes, the Dam Engineering Center, and the Sumatera I River Basin Organization (BWS Sumatera I Banda Aceh) for their support and provision of data, and to colleagues of the Master Super Specialist Program in Dam Safety Retrofitting and Instrumentation, Universitas Diponegoro, Cohort V Year 2024, for their cooperation and support during the preparation of this article.

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