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Slope Stability Analysis with Bore Piles for Landslide Prevention Using Plaxis LE 2D

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Abstract

The Rukoh Diversion Channel is an integral part of the Rukoh Dam, with the purpose of providing additional supply (supplement) to the Rukoh Dam reservoir of 15 m³/second. One of the components of the Rukoh Control Structure is a tunnel. The soil at the location of the Rukoh Diversion Channel tunnel consists of clay shale. Clay shale soil is a primary factor that causes landslides. Clay shale is a part of sedimentary rock, where this type of soil can undergo weathering in a short period when exposed to water, air, and sunlight. Several landslides have occurred at the inlet of the tunnel. Construction activities such as excavation and embankment can expose the soil, which may lead to a reduction in the shear angle of that soil. Landslide events at the inlet of the tunnel require management through soil reinforcement with bore piles using Plaxis LE 2D. This study aims to analyze the stability conditions of the slope in its existing state and with the reinforcement provided by bore piles. The factor of safety for the existing slope condition is 1.440, which is categorized as less than the required safety factor. The bore piles are planned to be 0.6 m wide and 8 m long. The bearing capacity analysis for the bore piles is 16147.21 kN, with the allowable lateral force provided by the bore piles using broms method being 54.348 kN. After the installation of the bore piles, the factor of safety for the slope is 1.868, which meets the minimum required threshold of 1.5.

Keywords: *slope stability; Plaxis LE 2D; bore pile; clay shale; broms*

1. Introduction

The Rukoh Diversion Structure is an integrated component of the Rukoh Dam. The soil characteristics at the tunnel site of the Rukoh Diversion Structure are classified as cohesive soil.

Cohesive soil includes clay, silty clay, or sandy clay, which generally exhibit low shear strength, plasticity when wet, and high compressibility. Their shear strength decreases when the soil structure is disturbed. Construction activities such as excavation and embankment can expose the soil, potentially leading to a reduction in its shear angle.

Landslides are a common natural disaster in hilly areas, involving soil movement in the form of deep-seated slope failures (Islam et al., 2017). Slope failures occur due to the disruption of stability in the materials composing the slope, whether soil or rock (Susanto & Putranto, 2016). In Indonesia, frequent slope failures are caused by various factors, one of which is the presence of clay shale (Sagitaningrum et al., 2022).

Clay shale constitutes approximately 50% to 70% of sedimentary rock (Diana et al., 2019). It is a type of sedimentary rock formed through weathering, which compacts under the pressure of overlying layers and is bound by minerals such as quartz, dolomite, and calcite. The typical particle size of clay shale is less than 1/16 mm or 0.0625 mm (Das & Sobhan, 2014). Clay shale exhibits unique behavior, as it can rapidly transition from rock to soil (Agung et al., 2017). It undergoes weathering and transforms into soft clay when exposed to water, air, or sunlight within a short period (Alatas et al., 2015).

The presence of montmorillonite, smectite, illite, and mixed-layer clay minerals of illite and smectite in clay shale actively contributes to instability, leading to issues such as exfoliation and slope failure (Wilson & Wilson, 2014; Khan et al., 2016). Clay shale is highly sensitive to environmental changes, exhibiting time-dependent behavior. The geological history of a site and the microstructure of this material significantly influence its characteristic behavior (Corkum & Martin, 2007).

This research aims to determine the slope stability of clay shale soil under existing conditions and after slope improvement using bore piles. This study is expected to provide valuable input regarding the use of

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bore piles to address slope failure issues encountered in the field.

2. Materials and Methods

The location of the Rukoh Slope Stabilization structure is situated in Blang Rikui Village and Panton Bunot Village, Tiroe Truseb District, Pidie Regency, Aceh Province, approximately 140 km from Banda Aceh City. The location of the landslide discussed in this study can be seen in Figure 1.

2.1 Slope Stability

Landslides on slopes can be influenced by many factors, including weather changes, the topography of the slope, and the local climate. Excavation processes carried out on a slope can cause a landslide. Stability analysis is conducted to determine the factor of safety value of a slope, in accordance with the established regulations. The factor of safety of a slope is the ratio between the forces resisting movement and the forces promoting movement. Generally, slope design requires a factor of safety (FS) value of 1.5 (National Standardization Agency, 2017). In cases of landslide estimates that have the potential to cause significant economic loss and loss of human life, the factor of safety may be greater than 1.5 (Holtz & Schuster, 1996).

Figure 1. Landslide Location at the Inlet of the Rukoh Directional Structure, Aceh Province.

2.2 Bearing Capacity of Bore Piles on Cohesive Soil

The shear strength of clay soil can change due to the boring process. The resistance at the tip of the pile may decrease during the drilling process. The shear strength of clay soil can also decrease due to the concreting process, which softens the clay. The bearing capacity of the bore pile can be calculated using the approach provided by Skempton (Hardiyatmo, 2014).

The unit end resistance of the bore pile is calculated using Equation 1, the cross-sectional area of the pile tip is calculated using Equation 2, and the ultimate end resistance is calculated using Equation 3.

$$f_b = \mu \, . \, c_b \, . \, N_c \qquad (1)$$

$$A_b = \frac{1}{4} \, . \, \pi \, . \, d^2 \qquad (2)$$

$$Q_b = f_b \, . \, A_b \qquad (3)$$

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where Q_b = ultimate end resistance (kN), μ = correction factor, μ = 0.8 for d < 1m, A_b= cross-sectional area of the lower end pile (m^2), c_b = undrained soil cohesion beneath the lower end pile (kN/m^2), N_c = bearing capacity factor ($N_c = 9$), dan d = pile diameter (m).

The surface area of the pile is calculated using Equation 4, the ultimate friction resistance is calculated using Equation 5, the weight of the pile is calculated using Equation 6, the ultimate bearing capacity is calculated using Equation 7, and the allowable bearing capacity is calculated using Equation 8.

$$A_s = \pi \,.\, d \quad (4)$$
$$Q_s = 0.45 \,.\, c_u \,.\, A_s \quad (5)$$
$$W_p = \frac{1}{4} \,.\, \pi \,.\, d^2 \,.\, L \,.\, \gamma \quad (6)$$
$$Q_u = Q_b + Q_s - W_p \quad (7)$$
$$Q_a = \frac{Q_u}{2.5} \quad (8)$$

where Q_s = Ultimate friction resistance (kN), A_s= surface area of the pile (m^2), c_u = undrained soil cohesion at the pile (kN/m^2).

2.3 Allowable Lateral Force in Cohesive Soil Using the Broms Method

The ultimate soil resistance of a pile embedded in cohesive soil increases with depth (Hardiyatmo, 2020). The Broms method is one of the approaches that can be utilized to calculate the allowable lateral force in cohesive soils (Santoso & Kawanda, 2022). A simplified approach proposed by Broms allows for the determination of the distribution of soil pressure in clay resisting the pile. Soil depth from the surface up to 1.5 times the pile diameter (1.5d) is considered to provide zero resistance, and for depths greater than 1.5d, the soil resistance remains constant at 9cu. The failure of a pile with a free head in cohesive soil is illustrated in Figure 2.

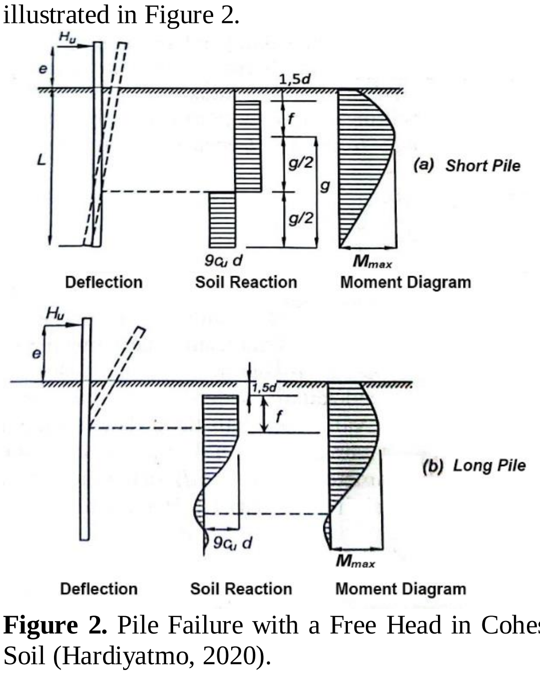

Figure 2. Pile Failure with a Free Head in Cohesive Soil (Hardiyatmo, 2020).

A pile with a free head that behaves like a long pile, the lateral force that can be resisted by the pile is determined by the maximum moment that the pile itself can withstand (My). Equation 9 is used to calculate the maximum moment (Mmax) on the pile.

$$M_{max} = H_u \left(e + \frac{3}{2}D + \frac{1}{2}f\right) \quad (9)$$

where f is the distance of the maximum moment from the surface, calculated using Equation 10.

$$f = \frac{H_u}{9 \,.\, c_u \,.\, D} \quad (10)$$

The maximum moment can also be calculated using Equation 11, and the pile length can be calculated using Equation 12.

$$M_{max} = \frac{9}{4} D \; x \; g^2 \; x \; c_u \quad (11)$$
$$L = \frac{3}{2} D + f \; x \; g \quad (12)$$

where D = pile diameter (m), H_u = lateral load (kN), c_u = undrained soil cohesion (kN/m^2), f = distance of the maximum moment from the ground surface (m), dan g = distance from the location of the maximum moment to the pile's base (m).

The value of M_y is considered equal to the value of M_{Max}, the value of M_y can be determined based on the strength of a pile in resisting the moment. The pile moment is calculated using Equation 13, the bending strength of the pile load is calculated using Equation 14, the moment resistance is calculated using Equation 15, the moment of inertia is calculated using Equation 16. To determine the criteria for a short or long pile, it can be calculated using Equation 17. The modulus of elasticity is calculated using Equation 18, and the horizontal subgrade modulus is calculated using Equation 19.

$$M_y = F_b \,.\, W \quad (13)$$
$$F_b = 0.40 \,.\, F'c \quad (14)$$
$$W = \frac{I_p}{D/2} \quad (15)$$
$$I_p = \frac{1}{4} \,.\, \pi \,.\, (r^4) \quad (16)$$
$$\beta = \left(\frac{K_h \,.\, D}{4 \; x \; E_p \,.\, I_p}\right)^{1/4} \quad (17)$$
$$E_p = 4700 \,.\, \sqrt{F'c} \quad (18)$$
$$K_h = \frac{k1}{1.5} \quad (19)$$

where D = bore pile diameter (m), F'c = concrete strength kg/cm^2, π = 3.14, k1 = Terzaghi subgrade modulus value, dan r = radius of the bore pile (cm).

2.4 Research Methodology

The research flow diagram is shown in Figure 3. The secondary data used includes soil parameters and slope geometry obtained from the research site. The soil parameters collected are cohesion value, internal friction angle, and soil bulk density.

The bearing capacity of the bore pile is calculated using the Skempton equation. The Broms method is used to calculate the allowable lateral resistance of the pile, which is then used as a parameter in the Plaxis LE 2D program input.

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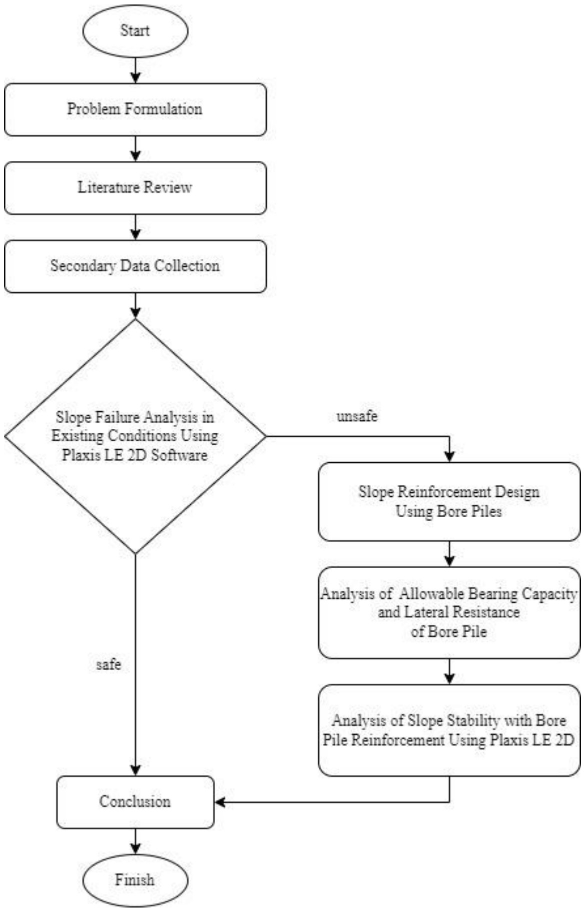

Figure 3. Flowchart of Slope Stability Analysis with Bore Piles for Landslide Prevention Using Plaxis LE 2D.

3. Result and Discussion

3.1 Slope Stability in Existing Conditions

The FS value from the slope stability analysis was calculated using soil test data obtained from the site, which includes Soil Cohesion = 15.887 kPa, Soil Unit Weight = 17.475 kN/m³, and Internal Friction Angle = 17.210°.

The FS value for the initial condition (without bore piles), analyzed using the Plaxis LE 2D program, is 1.440, as shown in Figure 4. This result aligns with direct field observations, where the slope was found to be unstable and experiencing landslides. The obtained FS value is below the minimum requirement specified in SNI 8460:2017 (National Standardization Agency, 2017), which mandates a slope Factor of Safety of 1.5. Therefore, slope reinforcement is necessary to increase the existing slope stability factor.

3.2 Bearing Capacity of Bore Pile

The bore pile is designed with a diameter *of* 0.6 m and a length of 8m, using concrete with a compressive strength of F'c 26.4 Mpa (K-300).

The unit end resistance of the bore pile (f_b)

$$f_b = \mu \,.\, c_b \,.\, N_c$$
$$= 3.14 \,.\, 15886.77 \,.\, 9$$
$$= 114384.8 \text{ kN/m}^2$$

The Cross-Sectional Area of the Lower End Pile

$$A_b = \frac{1}{4} \,.\, \pi \,.\, d^2$$
$$= \frac{1}{4} \,.\, 3.14 \,.\, 0.6^2$$
$$= 0.2826 \text{ m}^2$$

The Ultimate End Resistance (Q_b)

$$Q_b = f_b \,.\, A_b$$
$$= 114384{,}8 \,.\, 0{,}2826$$
$$= 32325.13 \text{ kN}$$

The surface area of the pile

$$A_s = \pi \,.\, d$$
$$= 3.14 \,.\, 0.2826$$
$$= 1.884 \text{ m}^2$$

The Ultimate Friction Resistance (Q_s)

$$Q_s = 0{,}45 \,.\, c_u \,.\, A_s$$
$$= 0.45 \,.\, 15886.77 \,.\, 1.884$$
$$= 13468.81 \text{ kN}$$

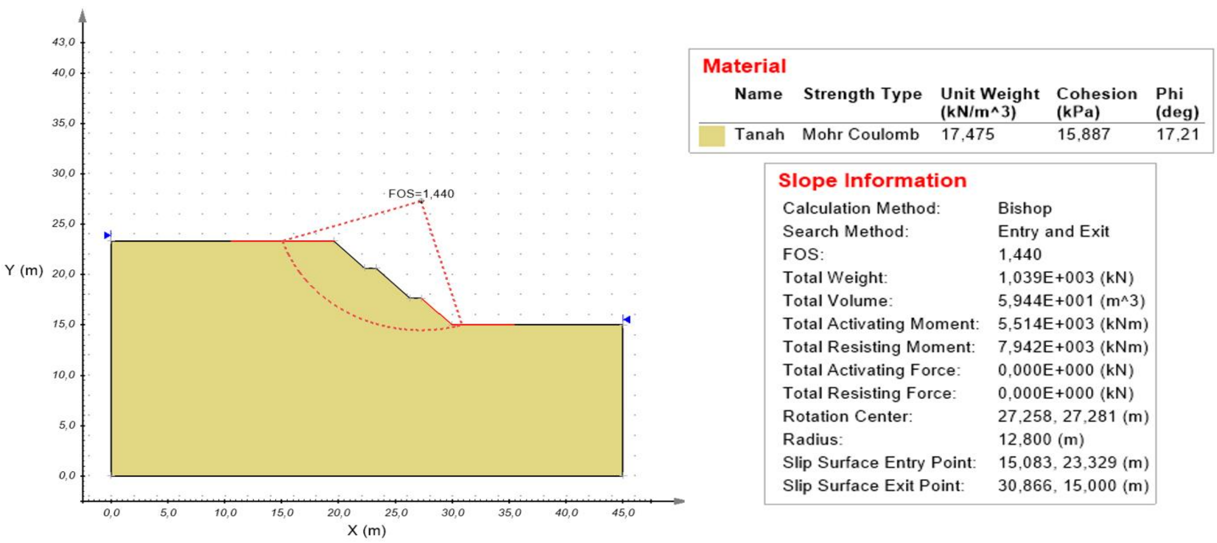

Figure 4. FS of the Slope in Initial Condition (Without Bore Piles).

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The Pile Weight

$W_p \quad = \frac{1}{4} . \pi . \ d^2 . L . \gamma$

$= \frac{1}{4} . 3.14 . 0.6^2 . 8 . 24$

= 5425.92 kN

The Ultimate Bearing Capacity (Q_u)

$Q_u \quad = Q_b + Q_s - W_p$

$= 32325.13 + 13468.81 - 5425.92$

= 40368.02 kN

The Allowable Bearing Capacity (Q_a)

$Q_a \quad = \frac{Q_u}{2,5}$

$= \frac{40368.02}{2.5}$

= 16147.21 kN

3.3 Lateral Bearing Capacity of Bore Pile

The lateral resistance of the bore pile is calculated based on the Broms approach for cohesive soil.

D = 60 cm = 0.6 m

L = 8 m

SF : 2.5

F'c : 26.4 Mpa = 269.205 kg/cm^2

Elasticity Modulus(E_p)

$E_p \quad = 4700 . \sqrt{F'c}$

$= 4700 . \sqrt{269.205}$ = 77115.113 kg/cm^2

Moment of Inertia (I_p)

$I_p \quad = \frac{1}{4} . \pi . \ (r^4)$

$= \frac{1}{4} . 3.14 . (30^4)$

= 635850 cm^4

Horizontal Subgrade Modulus (K_h)

$K_h \quad = \frac{k1}{1,5}$ (k1 from the terzaghi subgrade modulus table)

$= \frac{2,7}{1,5}$

= 1.8 kg/cm^3

K = 1.8 x 80

= 144 kg/cm^2

Constant Soil Modulus(R) for cohesive soil

$R \quad = \sqrt[4]{\frac{E_p . I_p}{K_h}}$

$= \sqrt[4]{\frac{77115.113 \ . \ 635850}{1.8}}$

= 145.971 cm

Determining the criteria for rigid (short) and non-rigid (long) piles

$\beta \quad = \left(\frac{K_h . \ D}{4 \ x \ E_p . I_p}\right)^{1/4}$

$\beta \quad = \left(\frac{1.8 . \ 60}{4 . \ 77115.113 \ . \ 635850}\right)^{1/4}$

= 0.0048

Behaves as a long (non-rigid) pile

$\beta . L \geq 2.5$

$0.0048 . 800 \geq 2.5$

$3.875 \geq 2.5$

Calculating the load capacity of the pile in resisting moments(M_y)

Bending Strength of The Pile Load (F_b)

$F_b \quad = 0.40 . F'c$

$F_b \quad = 0.40 . 269.205$

= 107.682 kg/cm^2

The Moment Resistance (W)

$W \quad = \frac{I_p}{D/2}$

$= \frac{635850}{60/2}$

= 21195 cm^3

The Pile Moment (M_y)

$M_y \quad = F_b . W$

= 107.682 . 21195

= 2282302.838 kg.cm

The Lateral Force on a Long Pile with a Free Head

$H \quad = 9 . c_u . D$

$f \quad = \frac{H_u}{9 \ . \ 0.162 \ . \ 60}$

$= \frac{\boldsymbol{H_u}}{\mathbf{87.48}}$

$= \frac{\mathbf{1}}{\mathbf{87.48}} . \boldsymbol{H_u}$

$f \quad = \ 0.011431 H_u$

Menggunakan Persamaan 9 dan Persamaan 11 untuk mendapatkan nilai g^2

$H_u \ (e + \frac{3}{2} D + \frac{1}{2} F) = \frac{9}{4} D \ x \ g^2 \ x \ c_u$

$H_u \ (0 + \frac{3}{2} 60 + \frac{1}{2} 0.011431 H_u) = \frac{9}{4} 60 \ x \ g^2 \ x \ 0.162$

H_u (90 +0.005715H_u) = (21.87g^2) (20)

L $= \frac{3}{2} D + f \ x \ g$

$g \quad = \ 800 - \frac{3}{2} 60 - \ 0.011431 H_u$

$g^2 \quad = \ (710 - 0.011431 H_u)^2$

$g^2 \quad = \ 504100 - 16.23228 H_u + 0.00013 {H_u}^2$

Using Equation 20 to determine the value of H_u to obtain M_{max}

$H_u \ (90 + 0.005715 H_u) = 21.87 . \ (504100 - 16.23228 H_u + 0.00013 {H_u}^2)$

$90 H_u \ + 0.005715 {H_u}^2 = 11024667 - 355 H_u + 0.00286 {H_u}^2)$

$H_u \quad = \ 21739.462 \ kg$

Substituting the value of H_u into Equation 10 to determine f

$f \quad = \frac{H_u}{9 . c_u . D}$

$f \quad = \frac{21739.462}{9 \ . \ 0.162 \ . \ 60}$

$f \quad = 248.508 \ cm$

Using Equation 9, to calculate the value of M_{max} using the obtained H_u value

$\Sigma M_{max} \ = H_u \ (e + \frac{3}{2} D + \frac{1}{2} f)$

By assuming that the maximum moment is the moment resistance of the pile (M_y), the ultimate lateral resistance can be determined using Equation 9.

$\Sigma M_{max} \ = H_u \ (e + \frac{3}{2} D + \frac{1}{2} f)$

$H_u \quad = \frac{M_y}{e + \frac{3}{2} D + \frac{1}{2} f}$

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$$H_u = \frac{2282320.838}{0+\frac{3}{2}60+\frac{1}{2}0.011431H_u}$$

$$90H_u + 0.00572{H_u}^2 - 2282320.838 = 0$$

Thus, the ultimate resistance, H_u , is obtained as follows:

H_u = 13604.745 kg

Allowable Lateral Force

H_u allowable $= \frac{H_u}{SF}$

H_u allowable $= \frac{13604.745}{2.5}$

H_u allowable = 5441.898 kg

H_u allowable = 54.348 kN

3.4 Slope Stability with Bore Pile Reinforcement

The lateral resistance obtained using the Broms method for the bore pile is 54.348 kN, resulting in a slope Factor of Safety (FS) of 1.868. The lateral resistance input into the Plaxis LE 2D program is shown in Figure 5.

The results of the slope stability analysis with reinforcement using a bore pile with a 0.6 m diameter and an 8-meter length can be seen in Figure 6. A comparison between previous studies and the current research is presented in Table 1.

Table 1. Comparison with Previous Studies

Number	Researcher	Slope FS Value	
		With *Bore Pile*	***Without Bore Pile***
1	Redha	1.440	1.868
2	Himawan, Muhrozi, & Sadono, (2017)	1.011	1.436
3	Pratama, Muhibbi, Atmanto, & Hardiyati, (2014)	1.216	1.638

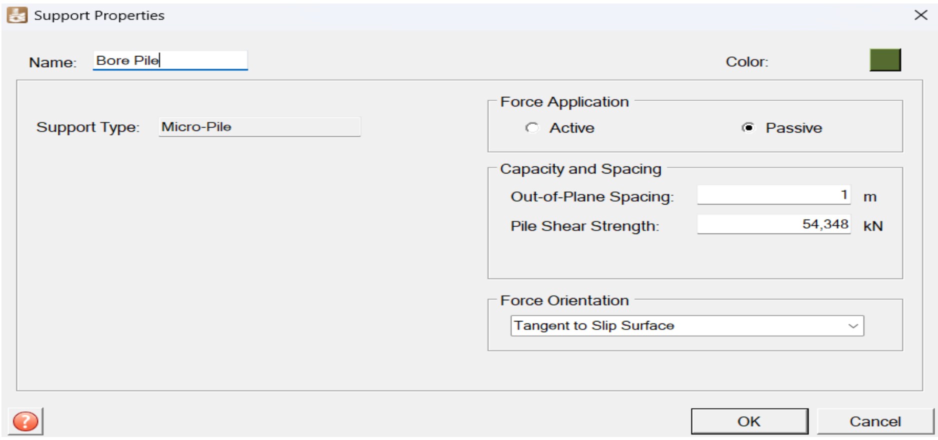

Figure 5. Input of Lateral Resistance Values for Bore Piles in the Plaxis LE 2D Program.

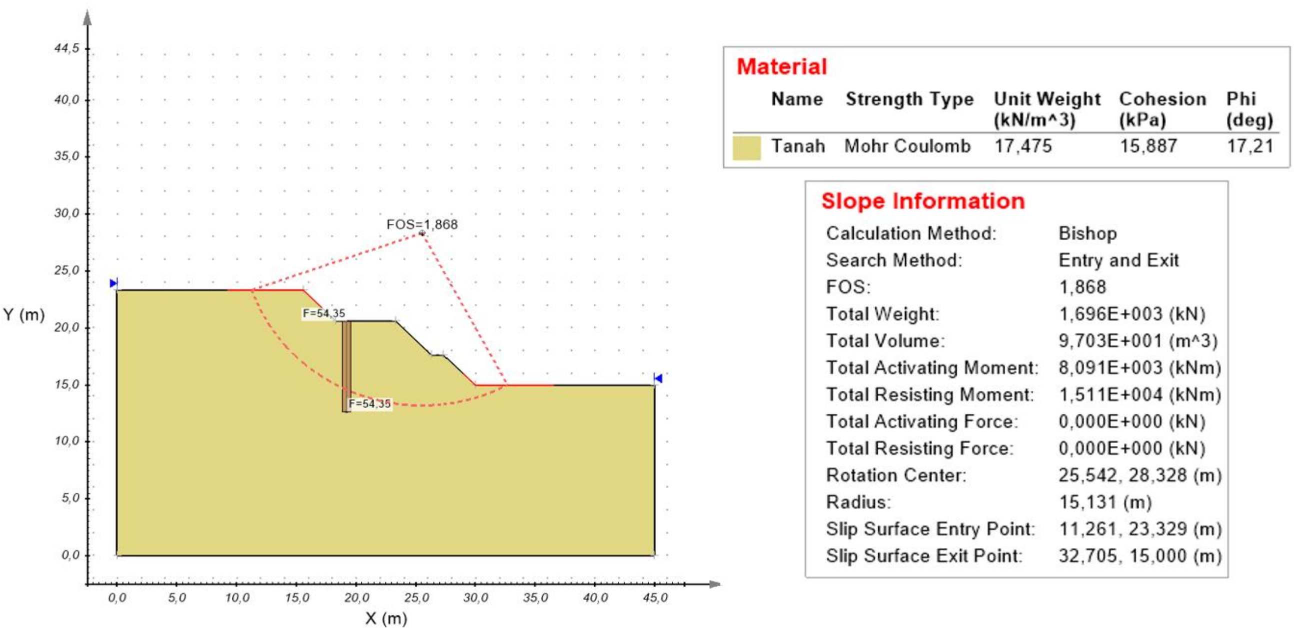

Figure 6. FS of the Slope with Bore Pile Reinforcement.

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The bore pile is considered effective in addressing landslide issues on slopes, as evidenced by the increase in the FS value after the installation of bore piles.

4. Conclusion

The slope stability analysis using Plaxis LE 2D for the existing condition resulted in an FS value of 1.440. which is below the required safety factor for slopes as per SNI 8460:2017. Therefore, slope reinforcement using bore piles is necessary to enhance the safety factor and ensure long-term slope stability. The slope reinforcement was designed using bore piles with a diameter of 0.6 m and a length of 8 m, yielding an ultimate bearing capacity of 16147.21 kN and an allowable lateral force of 54.348 kN. After implementing bore pile reinforcement, the FS increased to 1.868, which meets the minimum required safety factor of 1.5.

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