Slope stability analysis using Bishop and Finite Element Methods

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Abstract. Analysis of slope stability in this study aims to determine the safety factor (SF) of the landslide for the existing and the reinforcement condition. The study case was in STA 84+910 of national road Meulaboh-Geumpang, West Aceh Regency in Aceh Province. The condition of the Meulaboh-Geumpang road often causes landslides due to the topography of the area and is also triggered by rainfall. The analysis of safety factor for the existing condition was calculated by using the Bishop method that assumes a circular failure surface and the calculation was also validated by the finite element method using 2D Plaxis version 8.6 software. However, computation requires iterative procedures because of the nonlinear relationship for the safety factors. The result obtained from calculations using the Bishop method for the existing condition is 1.08, while by using Plaxis software, the result is 1.10, which means the slopes are in unstable conditions and need to be reinforced to prevent landslides. Alternative reinforcement was conducted by using sheet pile and calculations performed using 2D Plaxis version 8.6 software. Variations in the placement of sheet piles are at the upper and middle of the slope. The results obtained from the calculation of the safety factor after reinforcement are 1.57 (with a 12m sheet pile depth at the upper slope) and 1.48 (with a 10m sheet pile depth in the middle of the slope).

1. Introduction

The development of transportation encourages humans to make the best use of existing land, such as in hilly and sloped areas, whose topography tends to be diverse. Slope stability analysis is required from the planning or design stage to create a safe, comfortable, and durable construction in the slope area. Object location for this study is Meulaboh-Geumpang national road, which often causes landslides due to the topography of the area and is also triggered by rainfall. The landslide that occurred on Wednesday (10/5/2017) night around 11.00 p.m caused the disruption to the Meulaboh-Geumpang national road, which experienced a landslide and failure. The case study located in Lancong Village, Sungai Mas District, West Aceh Regency (figure 1).

Natural factors causing landslides are topography or slope, rock conditions and slope subgrade, as well as hydrological conditions or groundwater conditions on slopes. The heavy rainfall, which flushed most of the high area of Lancong Village, Sungai Mas District, West Aceh Regency, applies landslides and erosion of most of the main roads that have quite steep cliffs on STA 84 + 910 as shown in figure 2.

The objectives of slope stability analyses are: (1) Understanding the development and formation of natural slopes and processes that occur under different natural conditions; (2) Determine the slope stability in the short-term and long-term conditions; (3) Determine the possibility of failure on natural
or artificial slopes; and (4) Analyzing and understanding the mechanism of failure and the factors that cause it [1].

Slopes can occur naturally or be formed by humans for certain purposes. If the surface forms a slope, the soil mass component above the slip plane tends to move downward due to gravity. If the gravity component that occurs is large enough, it can cause landslides on the slope [2].

![Map of case study locations in West Aceh Regency.](image1)

**Figure 1.** Map of case study locations in West Aceh Regency.

![The latest condition of Meulaboh-Geumpang Road (December 2018).](image2)

**Figure 2.** The latest condition of Meulaboh-Geumpang Road (December 2018).

The concept of slope stability is very much needed in developing the current use of slopes. Because the use of slopes for the benefit of humans increases, it is necessary to develop the concept of slope stability aimed to overcome the problem of slope landslide [3]. There are many solutions for landslide remediation. Common principles used are unloading, drainage, reinforcement, retaining structures, and
surface vegetation [4]. However, [1] and [4] indicate that not all stabilization methods are appropriate for every type of slope failure; the most expensive treatment may not always be the most effective. Therefore, the determination of treatment for landslide appears to have no definitive rule to follow.

Reinforcement by installing sheet pile has been used for decades to meet engineering purposes: considering safety, economic, and uncomplicated approach [5]. Many similar studies using sheet pile reinforcement have been done before, as in research [5] using sheet pile wall for bridge pile foundation, and [6] describe the effect of seismic reinforcement of sheet pile quay wall using the ground anchor. This study describes the result of the safety factor that has been calculated to anticipate slope failure by the installation of the sheet pile.

The purpose of the slope stability analysis is to obtain the value of safety factor (SF) from the landslide area in the existing and reinforcement condition. Calculations for the existing condition is performed using the Bishop method and validated by the finite element method using 2D Plaxis version 8.6 software. Whereas for conditions with reinforcement, calculations are only performed using Plaxis software for 2 (two) variations of the placement of sheet piles, namely at the upper slope and in the middle of the slope. Then, the next calculation is varying depth of the sheet pile.

2. Methodology
This study was based on experimental works in Soil Mechanics Laboratory in University of Syiah Kuala, Indonesia. The soil sample was taken from two test pits in STA 84+910 namely B1 and B2. Some physical and mechanical properties of the soil were then performed; the tests were unit weight of soil, water content, Atterberg limit test, grain size distribution test, and specific gravity. Mechanical tests of soil were also conducted to obtained soil cohesion and friction angle. All of the soil testing to obtain physical and mechanical properties of soil were follow the ASTM standard [7]. Soil classification is done by two methods specifically the AASHTO and USCS soil classification system [8]. Physical and mechanical soil properties are used for designing or calculating reinforcement by the installation of sheet pile and as input parameters for 2D Plaxis software.

Sheet pile is a relatively thin, long flat vertical wall, usually made of steel or concrete material that serves to restrain the soil and also water entering the digging hole [9]. This study uses the steel sheet pile, as shown in figure 3.

![Figure 3. Steel sheet pile.](image)

The type of sheet pile can be divided in terms of construction (sheet pile without anchor and anchored sheet pile), and type of sheet pile according to the material (wood, steel, and reinforced concrete sheet pile). [10] Sheet pile without anchor is used for differences in soil height (h) that are not too large and are often used for semi-permanent work. Anchored sheet pile is used for quite a large difference in the height of the retained soil (h). The stability of construction is obtained apart from soil clamps in the sheet pile construction section embedded underground.

In general, the value of safety factor (SF) ≥ 1.25 was used for normal design in slope stability analysis. This is important to ensure that the slope design is safe and prevents unexpected factors during analysis, construction such as incorrect data, analysis errors, work skills, and the lack of field supervision.
[10]. Safety factor values for design [11] and based on slope failure studies [12] are shown in Table 1 and Table 2.

Table 1. Value of safety factors for design [11].

| No. | Safety Factor (SF) | Description                          |
|-----|-------------------|--------------------------------------|
| 1   | < 1.0             | Unsafe                               |
| 2   | 1.0 – 1.2         | Query safety                         |
| 3   | 1.25 – 1.4        | Safe for excavation, embankment, query for dam |
| 4   | 1.5 – 1.75        | Safe for dam/reinforcement           |

Table 2. Safety factors based on study of slope landslide [12].

| No. | Safety Factor (SF) | Description |
|-----|-------------------|-------------|
| 1   | < 1.07            | Unstable    |
| 2   | 1.07 – 1.25       | Critical    |
| 3   | > 1.25            | Stable      |

The safety factor (SF) is defined as the comparison between the maximum shear resistance (τ) and the shear stress due to gravity of the soil will failure (τd) as shown in equation (1).

$$SF = \frac{\tau}{\tau_d}$$  \hspace{1cm} (1)

Where:

τ = maximum shear resistance (kN/m²); and

τd = shear stress due to the gravity of the soil that will failure (kN/m²).

2.1. Simplified Bishop Method

The Bishop method assumes that the forces acting on the slice have zero resultant in the vertical direction. The system of forces in the Bishop method is shown in figure 4 [9].

Figure 4. Forces acting on segments by the Bishop method [12].

By calculating the entire balance of forces, the formula for the safety factor (SF) of the Bishop method is obtained as follows [13].
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\[ SF = \frac{\sum_{i=1}^{n}[c_b i + (W_i - u_i b_i) \tan \phi'] \left( \frac{1}{\cos \alpha_i (1 + tan \alpha_i \tan \phi')^2} \right)}{\sum_{i=1}^{n} W_i \sin \alpha_i} \]  

Where:
- \( SF \) = safety factor;
- \( c' \) = effective soil cohesion (kN/m²);
- \( \phi' \) = effective friction angle (°);
- \( b_i \) = width of the \( i \) slice (m);
- \( W_i \) = weight of the \( i \) slice (kN);
- \( \gamma \) = unit weight of soil (kN/m³);
- \( h \) = average slice height (kN/m³);
- \( \alpha_i \) = slope angle of the tangent on point in the middle of the base of the slice with respect to the horizontal plane;
- The slope angle is positive if it is in the direction of the slope and negative if it is in the opposite direction to the slope (°); and
- \( u_i \) = pore pressure of the \( i \) slice (kN/m²).

2.2. Finite element method

The finite element method (FEM) represents a powerful alternative approach for slope stability analyses. This method is accurate, versatile, and requires fewer prior assumptions, especially regarding the failure mechanism. The FEM is powerful in solving problems with irregular boundaries and complex variation of potential and flow lines [14].

The reduction in cohesion parameters (c) of the friction angle (\( \phi \)) and SRF (strength reduction factor) can be stated in Equation (3) and Equation (4) below [15].

\[ c_f = \frac{C_f}{SRF} \]  

\[ \phi_f = \tan^{-1} \left( \frac{\tan \phi}{SRF} \right) \]  

Where:
- \( C_f \) = certain factor;
- \( c \) = cohesion;
- \( \phi \) = friction angle; and
- SRF = strength reduction factor.

With SRF (strength reduction factor) is a shear strength reduction factor, so the safety factor (SF) is the same as the SRF value at the time of failure.

2.3. Plaxis software

The Plaxis software for Windows was first released in 1998 at Delft Technical University, the Netherlands. According to [16] the Mohr-Coloumb model is highly recommended to be used as an initial analysis of a problem. Mohr-Coloumb can be used to calculate realistic supporting stresses on tunnel faces, foundation boundary loads, and others. This model can also be used to calculate the safety factor with the '\( \phi \)-c Reduction' approach.

The Mohr-Coloumb model is included in the elastoplastic model with two shear strength parameters namely cohesion (c) and friction angle (\( \phi \)). 2D Plaxis version 8.6 software can handle models with parameter values of cohesion (c) of zero, friction angle (\( \phi \)), dilatation angle (\( \Psi \)), where in the sand soil,
the angle of dilation depends on the density and friction angle, Young modulus/modulus elasticity (E), and Poisson's ratio (v).

In general, Poisson's ratio values range from 0.3-0.4 depending on the type and condition of the soil. In soil mechanics, two types of analysis are used, namely undrained analysis and drained analysis. In 2D Plaxis software, the calculation used undrained analysis. The modulus of elasticity of the soil in an undrained condition, according to [17], can be calculated by Equation (5).

\[ E_u = \frac{15,000 \times C_u}{IP} \]  

Where:
- \( E_u \) = modulus of elasticity for undrained condition (kN/m²);
- \( C_u \) = undrained shear strength (kN/m²);
- \( IP \) = index of plasticity (%).

The calculation of safety factors (SF) in the 2D Plaxis software can be done by selecting \( \phi-c \) reduction. This option is only available in plastic calculations in the manual setting procedure or load advancement number of steps. ‘\( \phi-c \) reduction’ approaches the shear angle parameters (\( \phi \)) and cohesion (c) by reducing shear parameters to failure. The total multiplier (\( \Sigma Msf \)) is used to determine the parameters given at the analysis stage [16] can be calculated by Equation (6).

\[ \Sigma Msf = \frac{\tan \phi_{\text{input}}}{\tan \phi_{\text{reduced}}} = \frac{c_{\text{input}}}{c_{\text{reduced}}} \]  

The advantages of the 2D Plaxis version 8.6 software in analyzing slope stability are:
1. Provides a clear picture, both at the time of failure and slope stability and provides an effective safety chart according to safety criteria;
2. Able to simulate construction in stages, as is usually done in embankment construction;
3. Can model reinforcement elements, such as retaining walls, geogrids, geotextiles, anchors, and their interfaces

According to [9], the research method is the steps carried out systematically with a clear frame of reference in solving problems starting from the stage of collecting information on landslides, looking for literature studies related to landslides, primary and secondary data collection. Then proceed with analyzing the stability of the existing slope conditions using the Bishop method and the 2D Plaxis software. If these conditions do not meet the safety factor (SF), proceed with analyzing the stability of the slope with steel sheet pile reinforcement to obtain a safety factor (SF) ≥ 1.5. Furthermore, analyzed using the 2D Plaxis software has three stages, namely the data input stage, the calculation stage, and the data output stage.

In analyzing slope stability with the 2D Plaxis software requires modeling the slope in accordance with the actual conditions so that accurate results are obtained to determine the value of the safety factor of these conditions. However, if after analyzing the natural slope conditions but the safety factor value is not required, slope stability is reinforced by installing sheet piles.

3. Results and discussion
The results of soil laboratory testing and slope stability analyses for the study case in Meulaboh–Geumpang national road located in Lancong Village, Sungai Mas District, West Aceh Regency are shown below.

3.1. Results of soil laboratory testing and slope geometry
Results of soil laboratory testing regarding the physical and mechanical properties of the soil are shown in Table 3 and slope geometry in STA 84+910 is shown in figure 5.
Table 3. Results of soil laboratory testing.

| No. | Description                              | B1     | B2     |
|-----|------------------------------------------|--------|--------|
| 1   | Unit weight of soil (gr/cm³)             | 1.645  | 1.65   |
| 2   | Dry soil weight (gr/cm³)                 | 1.235  | 1.10   |
| 3   | Water content (%)                        | 33.15  | 49.43  |
| 4   | Liquid Limit, LL %                      | 89.85  | 65.79  |
| 5   | Plastic Limit, PL %                     | 35.95  | 40.79  |
| 6   | Index of Plasticity, IP %               | 53.90  | 25.01  |
| 7   | Specific gravity, Gs                    | 2.44   | 2.46   |
| 8   | Friction angle, $\phi$ (°)              | 25.6   | 27.9   |
| 9   | Cohesion, c (kg/cm³)                    | 0.175  | 0.14   |
| 10  | AASHTO Classification System            | A-7-6  | A-7-6  |
| 11  | USCS                                     | CH     | MH     |

Figure 5. Slope geometry in STA 84+910.

The obtained soil properties values are used for calculation of safety factor by using Bishop method for the existing condition. Specification of steel sheet pile is used for slope reinforcement and as the input parameter for 2D Plaxis calculation as shown in Table 4. In addition, the physical and mechanical properties of soil (input parameters) also used in calculation by using 2D Plaxis software, as shown in Table 5.

Table 4. Specification of Steel Sheet pile [14].

| Sheet pile specification (Steel) |                |
|---------------------------------|----------------|
| EA                              | 1.200E + 07 KN/m |
| EI                              | 1.200E + 05 KNm²/m |
| d                               | 0.346 m         |
| w                               | 8.300 KNm       |
| $\nu$                           | 0.15            |
| Mp                              | 1.000E + 15 KNm/m |
| Np                              | 1.000E + 15 KNm/m |
Table 5. Input Parameters on the Meulaboh-Geumpang STA 84 + 910 Road Section.

| Description                        | Unit | STA 84+910 |
|------------------------------------|------|------------|
|                                    |      | B1         |
| Material model                     | -    | MC         |
| Type of behavior                   | -    | Drained    |
| Dry soil weight (γ_dry)            | kN/m³| 12.99      |
| Wet soil weight (γ_wet)            | kN/m³| 16.13      |
| Saturated Soil (γ_sat)             | kN/m³| 23.95      |
| Horizontal permeability (k_h)      | m/day| 0.00864    |
| Vertical permeability (k_v)        | m/day| 0.00864    |
| Young’s modulus (E_ref)            | kN/m²| 6376.5     |
| Poisson’s ratio (ν)                | -    | 0.3        |
| Cohesion (c)                       | kN/m²| 17.27      |
| Friction angle (ϕ)                 | °    | 25.6       |
| Dilatancy angle (Ψ)                | °    | 0          |

3.2. Slope stability analyses results

The results of the safety factor for the existing condition as shown in figure 6 is used to see the location of the slope failure pattern which is then used to calculate the Bishop method and also the calculation for reinforcement using the sheet pile in the 2D Plaxis software.

![Figure 6](image)

Figure 6. Slope failure pattern for existing conditions in STA 84 + 910 (SF = 1.10).

The results of slope stability analyses obtained by reviewing 2 (two) slope conditions, namely the existing conditions and the condition of sheet pile reinforcement with different sheet pile depths and placement. The existing conditions are calculated using the Bishop method and also using the 2D Plaxis software (as shown in Table 6) while the sheet pile reinforcement is performed by simulating the 2D Plaxis software to obtain a safety factor that matches the safe and stable conditions.
Table 6. Results of Analysis of Safety Factors in Existing Conditions Using the Bishop’s Method and the Plaxis Software.

| No. | Location (STA) | Safety Factor (Bishop) | Description | Safety Factor (2D Plaxis 8.6) | Description |
|-----|----------------|------------------------|-------------|-------------------------------|-------------|
| 1   | STA 84+910     | 1.08                   | Unstable    | 1.10                          | Unstable    |

In the existing condition, two calculation models are used: the Bishop method, which obtains a safety factor value of 1.08, and the 2D Plaxis software, which obtains a safety factor of 1.10. In addition to the influence of the slope angle, the depth of the sheet pile also has a great influence on the value of the safety factor obtained after the reinforcement is performed. STA 84 + 910 has a slope angle of 69° so it has different safety factors for various conditions of placement and depth of sheet pile.

Slope stability analysis using sheet pile reinforcement was carried out by changing the sheet pile depth from 8m, 9m, 10m, 11m, 12m, for the location of the upper slope, and 6m, 7m, 8m, 9m, 10m, for the location of the middle of the slope. Results of the safety factor obtained from 2D Plaxis software for various placement and depth of the sheet pile are shown in Table 7.

Table 7 shows that at STA 84 + 910, reinforcement by sheet pile installation gets the highest safety factor value of 1.57 for 12m sheet pile depth for upper slope. It can be seen very clearly from figure 7, the influence of the pattern of slope failure, if the sheet pile is installed, does not pass through the failure plane, then it does not increase the value of the safety factor. Slope stability analysis using sheet pile reinforcement in the 2D Plaxis software shows that the results obtained will be better if the sheet pile is installed at a depth that passes through the failed plane. If the installation of sheet pile on the soil layer located in the failed plane, so it does not have the contribution of reinforcement due to the weight of the sheet pile itself.

Table 7. Results of Safety Factor for Variation in Placement and Depth of Sheet Pile (STA 84 + 910).

| No. | Location of Sheet Pile | Position | Slope angle | Sheet Pile depth (m) | Safety Factor (SF) |
|-----|------------------------|----------|-------------|----------------------|--------------------|
| 1   | Upper slope            | A        | 69°         | 8                    | 1.19               |
|     |                        |          |             | 9                    | 1.12               |
|     |                        |          |             | 10                   | 1.33               |
|     |                        |          |             | 11                   | 1.42               |
|     |                        |          |             | 12                   | 1.57               |
| 2   | Middle of slope        | B        | 69°         | 6                    | 1.18               |
|     |                        |          |             | 7                    | 1.25               |
|     |                        |          |             | 8                    | 1.34               |
|     |                        |          |             | 9                    | 1.42               |
|     |                        |          |             | 10                   | 1.48               |

On the other hand, figures 8 shows the results of the slope failure pattern after reinforcement by installing sheet pile with various placement and depth of the sheet pile. The results obtained from the calculation of the safety factor after reinforcement is 1.48 with a 10m sheet pile depth in the middle of the slope.
Figure 7. Analysis of Slope Stability at STA 84 + 910 with Sheet Pile Installation of 12m depth (upper slope), SF = 1.57.

Figure 8. Analysis of Slope Stability at STA 84 + 910 by Installing a Sheet Pile Depth of 10m (the middle of the slope), SF = 1.48

4. Conclusion

Based on the results of slope stability analyses using the Bishop method and 2D Plaxis software on the Meulaboh-Geumpang road section, Sungai Mas District, West Aceh Regency, it can be concluded that the safety factor obtained for existing condition by using Bishop method for is 1.08 while using 2D Plaxis software the safety factor is 1.10.

The results of the safety factor values for after reinforcement condition vary greatly, the position of sheet pile installation also greatly influences the value of the safety factor. The results of the safety factors that meet the safety requirements for STA 84 + 910 are for the position of upper slope, sheet pile with a depth of 12m SF is 1.57, on the other hand, the placement of sheet pile in the middle of the slope with a depth of 10m SF is 1.48. Those indicate that sheet pile reinforcement for a 12 m sheet pile depth meets the required safety factor (SF ≥ 1.5).

It is generally obtained that the longer the sheet pile, the value of the safety factor in the upper slope will increase. However, the addition of a certain depth of the sheet pile will decrease the value of the safety factor. Placement of sheet piles must be located below the slope failure plane if the sheet pile has not influenced the safety factor or if the sheet pile only increases the soil overburden pressure resulting in the landslide even worse.

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