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Analysis of the impact of soil excavation stages on slope stability case study of road and bridge construction projects in bts. Singaraja-Mengwitani at point 7E, Bali

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ABSTRACT

The Singaraja - Pengayaman BTS Road Section is a national road located in the central corridor of Bali Island and includes several critical locations in terms of road geometry. Geometric adjustments are being addressed through the BTS Singaraja - Mengwitani Road and Bridge Construction Project Section 7E, involving excavation work up to 64 meters high at STA. 0+119.87. This study aims to analyze slope stability based on existing conditions, evaluate the impact of excavation method variations on slope stability, and determine effective excavation methods both with and without the influence of water on slope stability using Plaxis 2D program. The research results indicate that the safety factor (SF) value of the existing slope prior to excavation was 1.337, whereas it decreased to 1.034 after the final excavation stage. According to the SNI 8460:2017 standard (SF < 1.5), the slope condition in the final excavation stage is deemed unsafe. Excavations with depth variations of 1 meter, 2 meters, and 3 meters, as well as at slope angles of 45˚, 55˚, and 65˚, showed similar impacts on slope stability. A significant decrease in the safety factor occurred from the 7th excavation bench downward, where the safety factor fell below 1.3. At the end of the excavation process, the deepest sliding surface reached a depth of 20.11 meters. At an elevation of +36.5 meters, where the groundwater level reaches 56.40% of the total slope height, which marks the boundary between soil and rock layers, the safety factor drops to 1.040. Further increases in groundwater levels above +36.5 meters could render the slope unstable and potentially lead to collapse.

Keywords : slope, soil excavation, groundwater table, safety factor.

INTRODUCTION

The Bts. Singaraja - Pengayaman Road Section features several critical locations in terms of road geometry. To address these geometric issues, the Bts. Singaraja - Mengwitani Road and Bridge Construction Project Section 7E has been implemented, which includes excavation work up to a height of 64 meters at STA. 0+119.87.

Figure 1 The project location for the Road and Bridge Construction of Bts. Kota Singaraja Mengwitani at Points 7D and 7E.
Source : Satker PJN Wilayah III Province Bali, 2024

The Road and Bridge Construction Project of Bts. Kota Singaraja – Mengwitani at Points 7D and 7E is located in Wanagiri Village, Sukasada Sub-district, Buleleng Regency, on the Bedugul – Singaraja Highway. The construction site for Point 7D is situated at KM 60+350 to KM 60+600, while Point 7E is located at KM 60+950 to KM 61+300. The location of the Bts. Kota Singaraja – Mengwitani Road and Bridge Construction Project at Points 7D and 7E is illustrated in Figure 1.

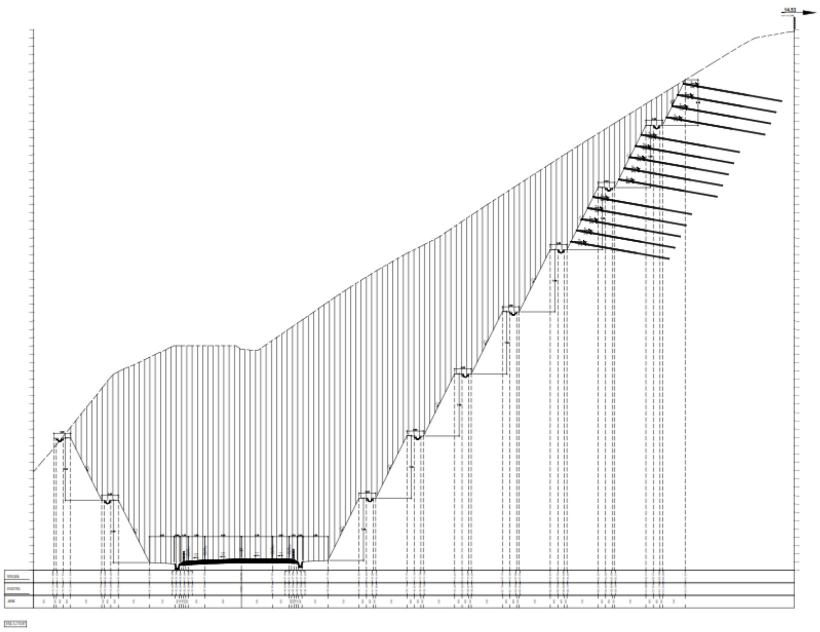

Figure 2. Cross section of Point 7E Sta. 0+119
Source : Satker PJN Wilayah III Province Bali, 2024

Figure 2 shows the cross-section of the soil at Point 7E STA. 0+119. As illustrated, soil excavation up to a height of 64 meters will be conducted. In the initial design, the slope was planned to have an inclination of 63˚ with 8 steps (traps), and soil nailing reinforcement was provided on traps 6, 7, and 8. Following technical assessments in the field and recalculations of slope stability, the slope inclination was adjusted to 45˚ for traps 6, 7, and 8, with soil nailing reinforcement applied to traps 7 and 8. Based on the soil investigation data, the following soil layers were identified:

1. At a depth of 0–4 meters, the soil consists of sandy clay with soft consistency (NSPT = 2–4).
2. At a depth of 4–18 meters, the soil is sandy silt with medium consistency (NSPT = 4–8).
3. At a depth of 18–30 meters, the soil comprises silty sand with medium consistency (NSPT = 24).
4. At a depth of 30–50 meters, andesite rock and volcanic sand with very hard consistency were found (NSPT = 50).

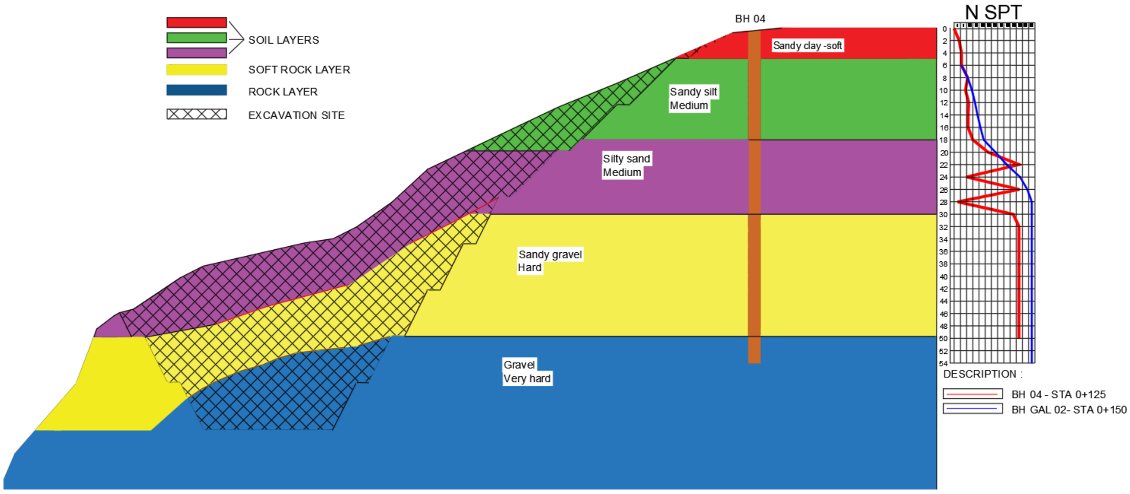

Figure 3. Description, consistency and stratification of slope soil Sta. 0+119
Source : Processed by the Author

The safety factor criteria for soil slopes with high levels of uncertainty in analysis conditions and significant slope repair costs require a minimum safety factor value of 1.5, as specified in SNI 8460:2017. At the project site, soil samples were collected only from boreholes at the peak slope elevation, and soil testing data were obtained from borehole samples at STA. 0+150. The limited availability of secondary data contributes to a high level of uncertainty in the analysis conditions.

The Ministry of Public Works and Housing has emphasized construction safety by issuing Regulation No. 10 of 2021 on Guidelines for the Construction Safety Management System (SMKK). One key element of SMKK, as outlined in the regulation, focuses on construction safety planning, which includes: hazard identification, risk assessment, risk control. Planning and implementing control measures to mitigate or eliminate assessed risks, including the use of personal protective equipment (PPE), safe work procedures, and workplace management.

The execution of high excavation work to form a slope reaching a height of 64 meters requires thorough investigation, as it may lead to slope instability and increase the risk of landslides. To ensure effective safety management for workers and slope stability, soil excavation to shape the slope gradient according to the design must be carried out with caution and adhere to geotechnical studies and guidelines.

Lili Wu, et al (2022) states that the results of the slope stability analysis from the soil excavation stages of seven benches with four variations of slope inclination indicate that as the slope angle increases, the factor of safety decreases. Each bench has an optimum slope angle to achieve a factor of safety of 1.5. In the first bench, the optimum slope angle ranges from 62˚ to 65˚; in the second bench, it is 64˚ to 67˚; in the third bench, 67˚ to 69˚; in the fourth bench, 70˚ to 71˚; in the fifth bench, 73˚; in the sixth bench, 75˚ to 76˚; and in the last bench, the seventh, it ranges from 77˚ to 80˚. As the excavation depth increases, the optimal angle that still meets the safety factor standard becomes larger.

Several slope excavation methods include vertical column excavation, horizontal column excavation, and inclined column excavation. Each method has a different impact on the number of cracks that occur on the slope. Wang ZY, et al (2020) report that in an experiment involving a slope of 5 meters in height, three variations of excavation methods resulted in the highest number of cracks due to horizontal excavation, followed by vertical column excavation. Meanwhile, excavation with an inclined angle resulted in the fewest cracks on the slope.

Based on the problems outlined previously, it is necessary to conduct an analysis of the impact of excavation stages on slope stability and the influence of groundwater levels on slope stability. Differences in excavation methods can result in variations in safety factor values. The slope stability analysis is performed using Plaxis 2D software. The outputs of this analysis include graphs showing the relationship of safety factors for each type of soil layer and combinations of soil layers with varying slope angles, graphs depicting the relationship of safety factors with variations in excavation depth for horizontal column schemes, graphs illustrating the relationship of safety factors with variations in excavation angle for sloped column schemes, and graphs showing the relationship of safety factors with variations in groundwater levels after excavation completion. By determining the safety factor values for each excavation variation, effective excavation methods can be identified to maintain slope stability.

LITERATUR REVIEW

Slope Stability

Slope stability analysis is an important aspect of geotechnical engineering that involves assessing the stability of natural and artificial slopes. The main objective is to evaluate the possibility of slope failure and ensure the safety of structures built on or near the slope. Several factors contribute to slope instability, including soil properties, groundwater conditions, slope geometry, and external loads.

Soft Soil Parameters

1. Cohesion

   Cohesion is one of the important factors that influences the shear strength of soil. Cohesion refers to the attraction between soil particles caused by molecular bonds. The higher the soil cohesion, the greater the soil's ability to withstand loads without shearing. In the context of shear strength, cohesion increases soil stability, especially in clay soils, where soil particles are tightly bound together. On the other hand, soils with low cohesion, such as sand, tend to have lower shear strength, making them more susceptible to shifting when loaded. Thus, cohesion plays a crucial role in determining the strength and stability of soil.

Table 1. Relationship between undrained shear strength and N-SPT

Cohesive Soil						
N-SPT	< 2,5	2,5 – 5	5 - 10	10 – 20	20 – 40	>40
State	Very soft	Soft	Medium	Stiff	Verry Stiff	Hard
Cu (KPa)	0 – 12,5	12,5 – 25	25 – 50	50 – 100	100 – 200	>200

Source : Mochtar, 2012

2. Internal Friction Angle

The internal friction angle is one of the important parameters that influences the shear strength of the soil. This angle reflects the ability of soil particles to rub against each other when subjected to load. The greater the internal shear angle, the higher the shear strength of the soil, which means the soil can withstand a greater load before experiencing shear failure. Sandy soil generally has a higher internal friction angle compared to clay soil, so it is more stable when under pressure. In contrast, soils with low internal friction angles tend to be more susceptible to displacement and failure, especially in saturated conditions or when exposed to sudden loads. Estimate the value of the internal shear angle from the NSPT value for cohesionless soil can be seen in Table 2.

Table 2. Relationship between Internal Shear Angle and N-SPT

Cohesionless Soil					
N-SPT	< 4	4 – 10	10 - 30	30 – 50	>50
State	Very loose	Loose	Medium	Dense	Verry Dense
φ (˚)	0 – 28	28 – 30	30 – 36	36 – 41	>41

Source : Mochtar, 2012

3. Geological Strength Index (GSI)

Geological Strength Index (GSI) is a parameter used to evaluate the strength and stability of rock slopes based on geological conditions and material characteristics. GSI combines factors such as texture, structure and surface condition of the rock to provide an overview of the slope's ability to withstand loads. The higher the GSI value, the better the quality of the rock and the more stable the slope, because rocks that have a high GSI tend to have better bearing capacity and resistance to movement. On the other hand, a low GSI value indicates that the rock condition is weaker and potentially more susceptible to landslides or ground movement. Estimate the value of the Geological Strength Index value can be seen in Table 3.

Table 3. Geological Strength Index For Jointed Rocks

Geological Strength Index For Jointed Rocks					
Surface Condition	Verry Good	Good	Fair	Poor	Verry Poor
Intact or massive	80 – 90			N/A	N/A
Blocky		60 – 70			
Very blocky		40 – 70			
Blocky/disturbed			30 – 40		
Disintegrated				20	
Laminated/sheared	N/A	N/A			10

Source : Hoek,2006

4. Uniaxial Compressive Strength (UCS)

Uniaxial Compressive Strength (UCS) of rocks is an important parameter that influences the stability of rock slopes. UCS measures a rock's ability to withstand pressure without deforming or collapsing, giving an indication of how strong the rock is. The higher the UCS value, the greater the rock's bearing capacity against external loads, which means the slope is more stable and less susceptible to ground movement or landslides. Estimate the value of the Uniaxial Compressive Strength value can be seen in Table 4.

Table 4. Uniaxial Compressive Strength of rocks

Uniaxial Compressive Strength of rocks					
Examples	Fresh basalt, chert, granite	Sandstone, basalt, limestone, tuff	Mable, sandstone, limestone	Claystone,siltstone, coal, concrete	Chalk, rocksalt, potash
Uniaxial Compressive Strength (MPa)	>250	100 – 250	50 – 100	25 – 50	5 – 25

Source : Hoek,2006

5. Estimated disturbance factor (D)

Estimated disturbance factor (D) according to Hoek is a parameter used to assess the impact of geological and environmental conditions on rock strength and slope stability. These disturbance factors include the influence of cracks, weathering, and changes in hydrogeological conditions which can reduce the effective strength of rocks. The higher the D value, the greater the disturbance experienced by the rock, which can cause a decrease in slope stability and increase the risk of landslides or ground movement. Estimate the value of the disturbance factor value can be seen in Table 5.

Table 5. Disturbance factor of rocks

Disturbance factor of rocks					
Description of rock mass	Exelent quality controlled blasting or excavation	Mechanical or hand excavation in poor quality	Verry poor quality blasting	Small scale blasting	Very large open pit mine slopes suffer significant disturbance
Suggested value of D	D = 0	D = 0,5 No invert	D = 0,8	D = 0,7 Good blasting D = 1,0 Poor blasting	D = 1,0 Production blasting D = 0,7 Mechanical excavation

Source : Hoek,2006

Safety Factor

The safety factor for slope stability is the ratio between the available soil strength and the force that causes failure, where a safety factor value above 1 indicates adequate stability, while a value below 1 indicates a landslide risk. Safety factors employed in traditional geotechnical practice are grounded in solid experience (Duncan, 2000). In summary, the following equation is utilized to calculate the safety factor value.

$$\text{Factor of Safety (FS)} = \frac{(\sum \text{Retaining Force})}{(\sum \textit{Pushing Force})} \quad \text{... (1)}$$

Safety factor criteria for soil slopes according to SNI 8460:2017 are shown in Table 6.

Table 6. Safety factor criteria for land slopes

Costs and consequences of slope failure	The level of uncertainty of the analysis conditions	
	Low	High
The repair costs are worth the additional costs of designing more conservative slopes	1,25	1,5
The repair costs outweigh the additional costs of designing more conservative slopes	1,5	2,0 or more

Source: SNI 8460:2017

RESEARCH METHOD

The methodology employed in this study involves initially gathering secondary data, including detailed engineering designs, shop drawings, soil bore test results, soil stratification profiles, and soil investigation reports, among others. Once the necessary data is collected, the next step is to model the slope according to the soil stratification using the Plaxis 2D software, incorporating various factors as variables in this research. The slope is first modeled at Station 0+119 prior to excavation, followed by an analysis to determine the safety factor before and after the excavation is completed. Subsequently, variations in slope angles of 65˚, 55˚, and 45˚ are applied at each excavation stage, creating specific inclinations for each bench. The excavation depths considered are 1 m, 2 m, and 3 m, with the excavation process progressing from the top of the slope to its base. After analyzing the slope stability in response to the different excavation variations, the influence of groundwater level is assessed at the end of the excavation process. The groundwater level variations include scenarios with no groundwater, groundwater at the surface level, and groundwater levels lowered by 2 m and 4 m. Additionally, the study seeks to determine the groundwater elevation that leads to slope failure. All experiments conducted will yield the safety factor values for the slopes, allowing for an understanding of the impact of soil excavation on slope stability. Finally, a nomogram will be developed to illustrate the relationships among all these variables.

DATA COLLECTION

In this study, the soil and rock data utilized are representative of the conditions at the case study site, specifically the Road and Bridge Construction Project at the Singaraja - Mengwitani boundary, at Point 7E. After categorizing the soil layers based on the borehole test results, the thickness of each soil layer, along with their respective physical and mechanical properties, will serve as parameters for the slope stability analysis. These parameters will be input into the Plaxis 2D software for further calculations. The following data were employed in this research.

Table 7a. Physical and mechanical parameters of each layer

Parameters	Symbol	Soil			Rock		Unit
		sandy clay	sandy silt	Silty sand	Sandy gravel	gravel	
Model		Hardening soil	Hardening soil	Hardening soil	Hoek-Brown	Hoek-Brown	
Types of behavior		Undrained B	Undrained B	Drained	Non-porous	Non-porous	
Thickness	h	4	14	12	22	25	m

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Table 8b. Physical and mechanical parameters of each layer

Parameters	Symbol	Soil			Rock		Unit
		sandy clay	**sandy silt**	**Silty sand**	**Sandy gravel**	**gravel**	
Unsaturated volume weight	ɣ unsat	13,98	16,01	14,37	22	28	kN/m^3
Saturated volume weight	ɣ sat	18,86	19,86	18,73	22	28	kN/m^3
Corrected SPT value	$N_{1(60)}$	4	8	24	50	50	
Consistency		Soft	Medium	Medium	Very hard	Very hard	
Void ratio	e	0,866	0,652	0,851	0,25	0,05	
Porosity	n	0,4641	0,3947	0,4599	0,2	0,04762	
Young's modulus	E^0	15000	20000	25000	100000	150000	kN/m^2
Effective young's modulus	E'	10500	14000	17500	-	-	kN/m^2
	E50	10500	14000	17500	-	-	kN/m^2
	Eoed	10500	14000	17500	-	-	
	Eur	31500	42000	52500	-	-	
Poisson's ratio	v	0,2	0,2	0,2	0,2	0,27	-
Cohesion	c	25,00	50,00	-	-	-	kN/m^2
Effective Cohesion	c'	-	-	22,75	-	-	
Effective internal friction angle	ϕ'	-	-	25,20	-	-	
Unaxial compressive strenght	σc	-	-	-	175000	175000	kN/m^2
	mi	-	-	-	13	25,00	
	GSI	-	-	-	20	30,00	
	D	-	-	-	1,00	1,00	

Source : Processed by the Author

RESEARCH ANALYSIS

Safety Factors For The Natural Slope And The End Of The Excavation Without Additional Reinforcement

After gathering all the necessary data for input into the Plaxis 2D auxiliary program, the initial modeling was conducted under natural slope conditions and after the excavation process was completed. The number of layers and soil parameters are listed in Table 7. Once the data input process was completed, an analysis was performed to determine the safety factor value.

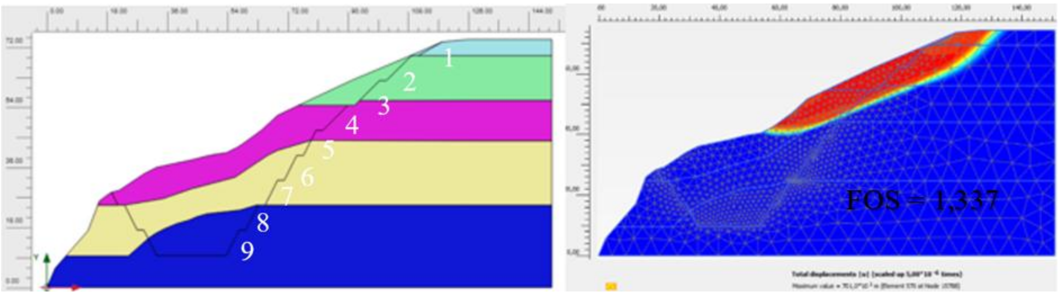

Figure 4. Nature slope before excavation

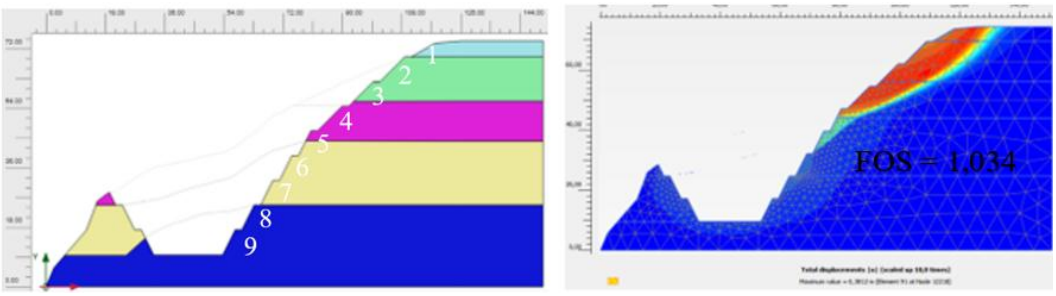

Figure 5. The end of excavation

The factor of safety for the natural slope conditions before excavation was 1.337, while after excavation it decreased to 1.034. According to SNI 8460:2017, slopes with a high level of analytical uncertainty indicate that the slope condition after excavation falls into the unsafe category (FOS < 1.5).

The stability of slopes at various angles of inclination for each type of excavated material is analyzed through single slope simulations

In this section, each type of excavated material is simulated to obtain the factor of safety at inclinations of 65˚, 55˚, and 45˚ with a slope height of 7.5 meters. Subsequently, an analysis is conducted to determine the safety factor values.

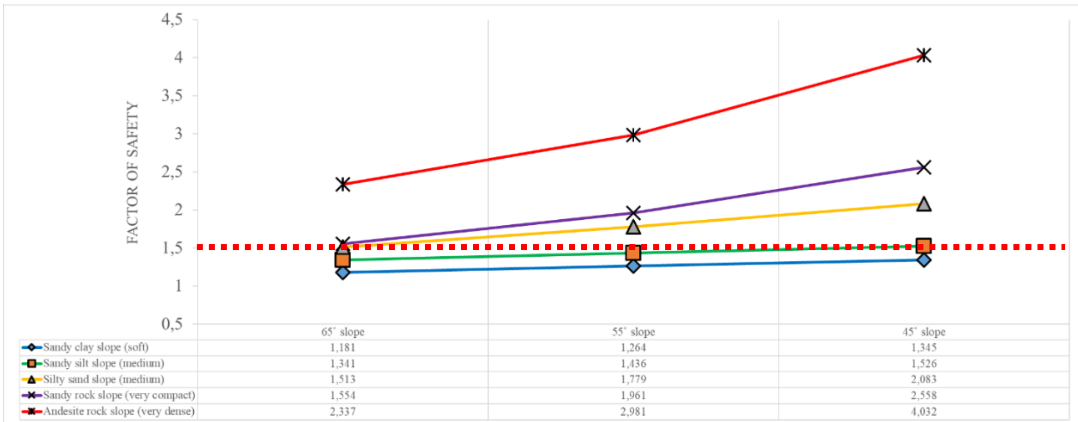

Figure 6. The factor of safety at various slope angles (single slope)

Figure 6 shows the safety of the slope improves as the angle of inclination decreases from 65˚ to 55˚ and 45˚. Slopes composed of soft sandy clay are deemed unsafe at all three angles, while slopes composed of medium silt-sand are considered safe at an inclination of 45˚ according to SNI 8460:2017 (FOS ≥ 1.5).

Simulation of single slope horizontal and inclined excavation method

In this section, first, a simulation was conducted using a horizontal excavation method

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with a slope height of 7.5 meters to create a slope angle of 45˚. Excavation begins at the top of the slope and continues to the final depth at the base of the slope. The variations in excavation depth applied are 1 m, 2 m, and 3 m. Each stage of excavation is analyzed to obtain the factor of safety values.

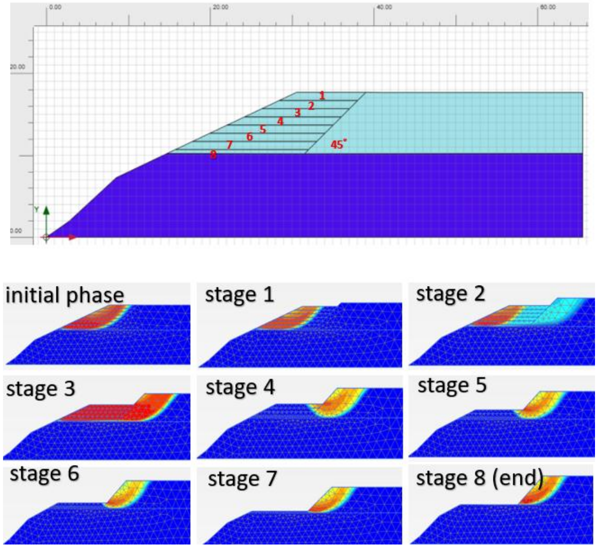

Figure 7. Horizontal excavation method stages

Furthermore, a simulation was conducted using the inclined excavation method. The excavation process was carried out in stages, starting from the outer side of the slope, with excavation angles of 65˚, 55˚, and 45˚. Excavation was performed incrementally at a distance of 1 meter until the slope inclination conformed to the design specifications. The factor of safety was calculated for each stage of excavation.

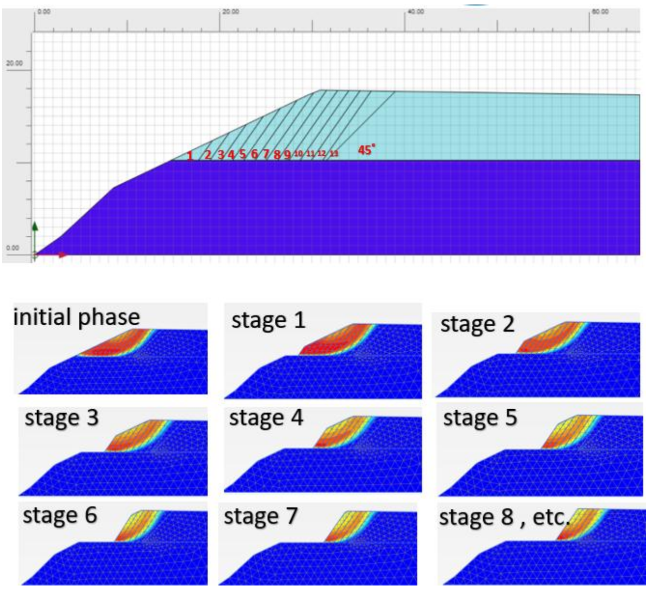

Figure 8. Stages of the inclined excavation method

Each type of soil, based on the previously identified layers, was analyzed using simulations of both the horizontal excavation method and the inclined excavation method. The results of the safety factor analysis are presented in the following graph:

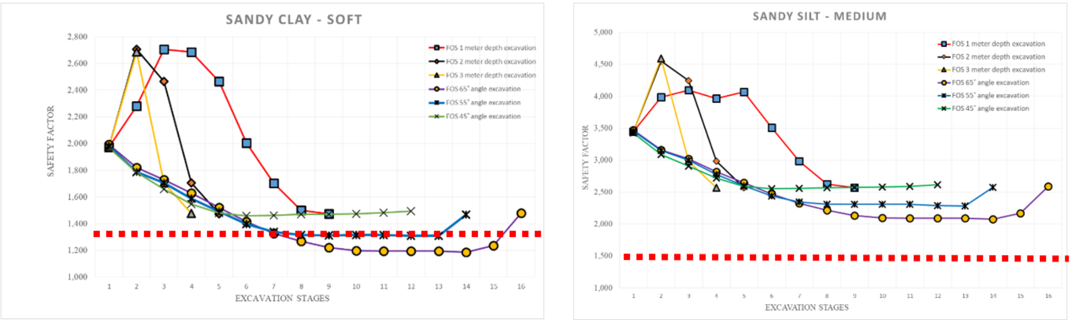

Figure 9. Impact of excavation on safety factors for soft sandy clay slopes and medium sandy silt slopes

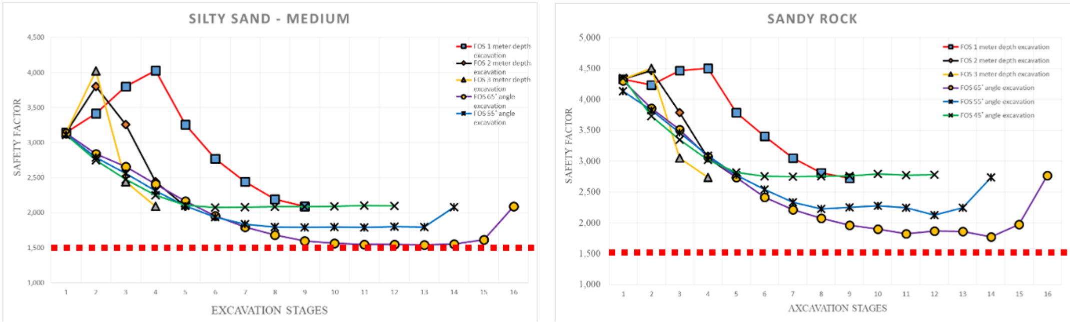

Figure 10. Impact of excavation on safety factors for medium silty sand slopes and sandy rock slopes

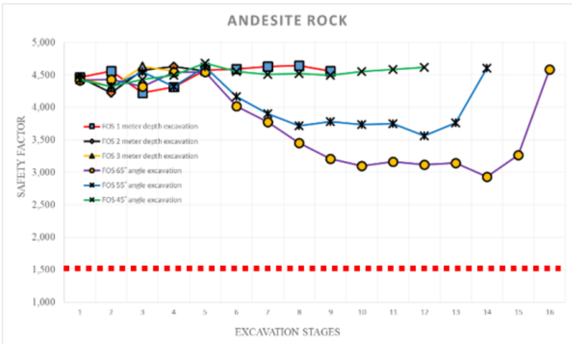

Figure 11. Impact of excavation on safety factors for andesite rock slopes

Based on the stability analysis of slopes for all variations, the factor of safety at the end of excavation for soft sandy clay slopes does not meet the safety criteria for soil slopes according to SNI 8460:2017. Although both have medium consistency, the silt-sand soil at the end of excavation exhibits a higher factor of safety compared to the sandy silt soil. The following is a graph illustrating the grouping of the relationship between excavation stages and the factor of safety based on the same excavation method.

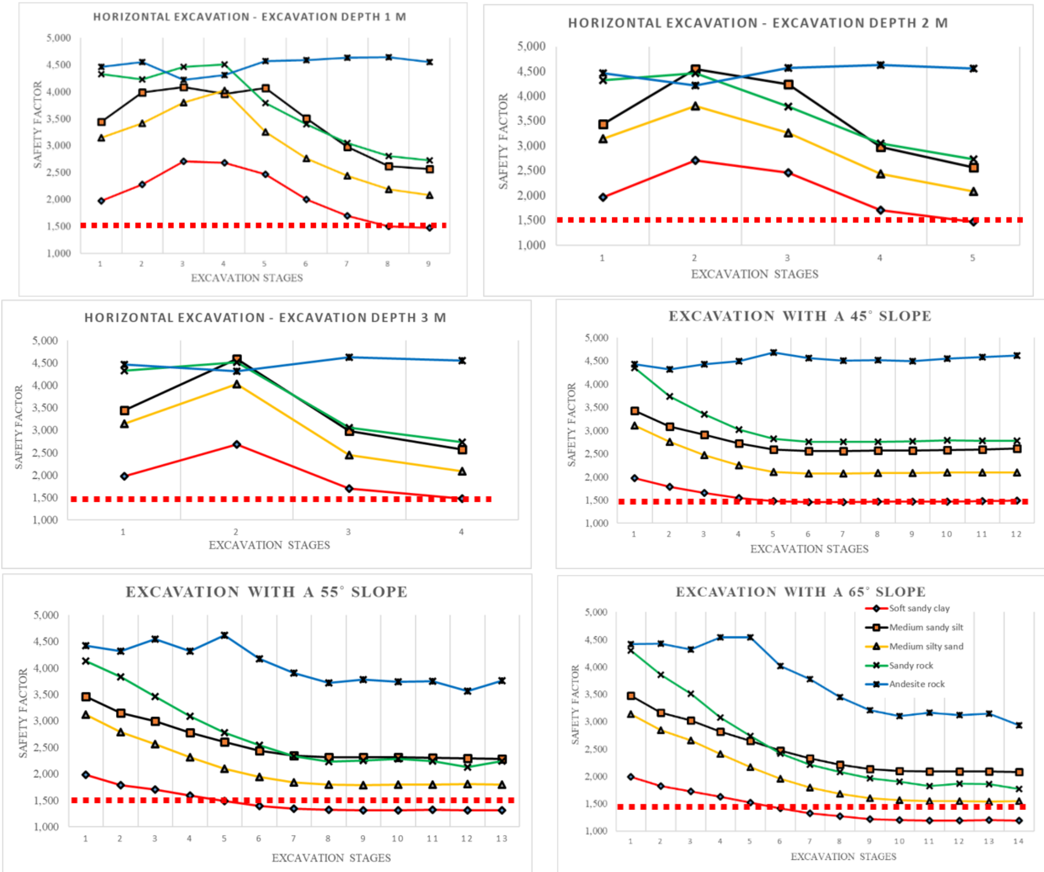

Figure 12. Comparison of slope stability in the same excavation method

Changes in slope stability due to differences in excavation methods at slope Sta. 0+119

To assess the impact of different excavation methods on slope stability at Sta. 0+119, an analysis was conducted based on the previously mentioned soil stratification. Subsequently, calculations were performed to determine the factor of safety of the slope when the soil volume decreases, both through horizontal excavation methods with depth variations of 1 m, 2 m, and 3 m, and by calculating the factor of safety when the soil volume of the existing slope decreases through excavation methods that create inclination angles of 65˚, 55˚, and 45˚. The following presents the calculations of the slope factor of safety using the Plaxis 2D. The following is a modeling of the horizontal excavation method of the Sta. 0+119 slope in the Plaxis 2D program.

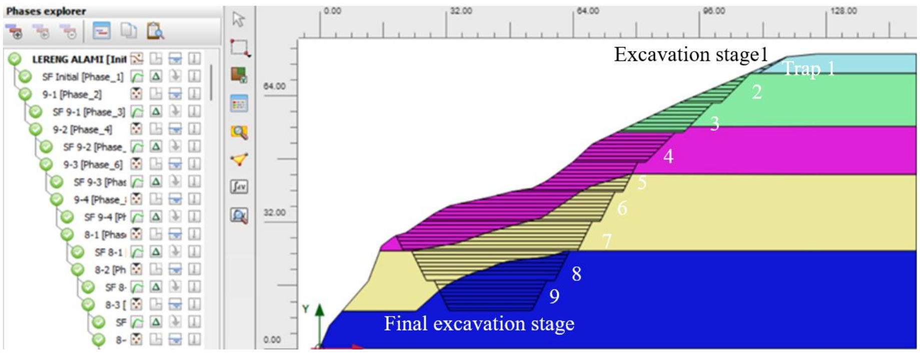

Figure 13. Modeling of the horizontal excavation method

The factor of safety was calculated at each stage of excavation by reducing the soil volume from top to bottom until reaching the base of the slope at the end of the excavation process. Once all stages reached the conclusion of the excavation plan, the factor of safety values for each stage were obtained as follows:

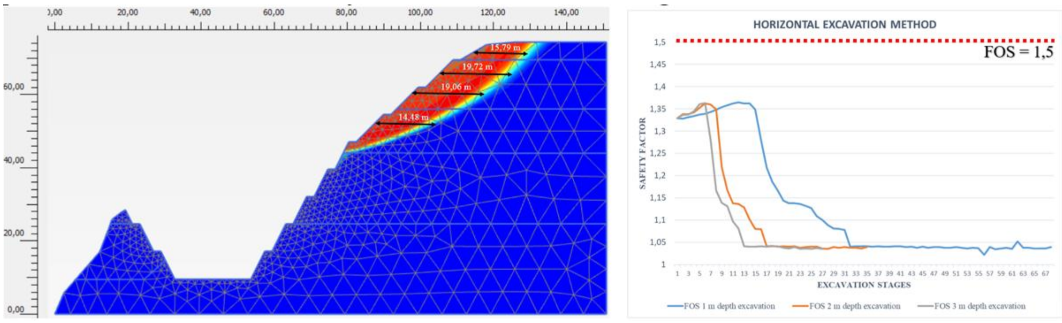

Figure 14. Landslide depth and changes in the factor of safety of the slope using the horizontal excavation method

The failure plane of the slope at the end of one stage of excavation using the horizontal excavation method is as follows:

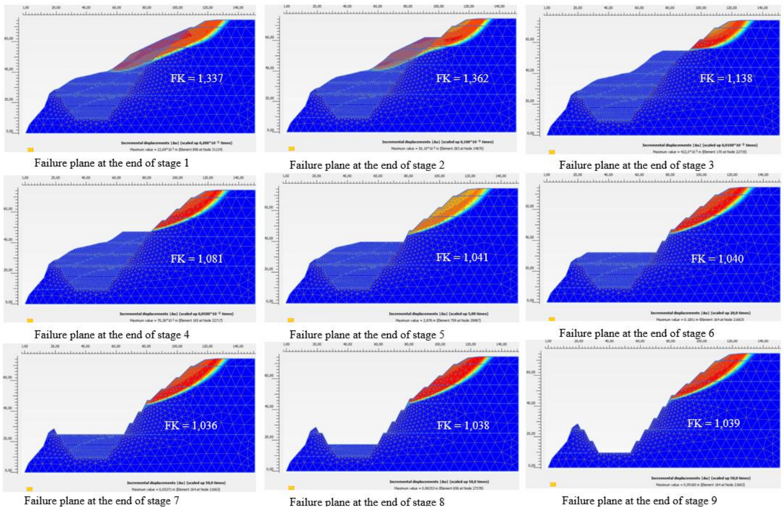

Figure 15. Changes in the slope failure area due to horizontal excavation methods

For excavation that creates an inclination angle, it is modeled that the reduction in soil volume is based on the shape of the inclined column with angle variations of 65˚, 55˚, and 45˚. The excavation stages are carried out by dividing the areas into 1-meter intervals with the same inclination in one slope stage. The factor of safety of the slope is calculated starting from the reduction of soil volume at the outer edge of the slope and gradually progressing inward according to the design inclination plan. The following is a modeling of the inclined excavation method of the Sta. 0+119 slope in the Plaxis 2D program.

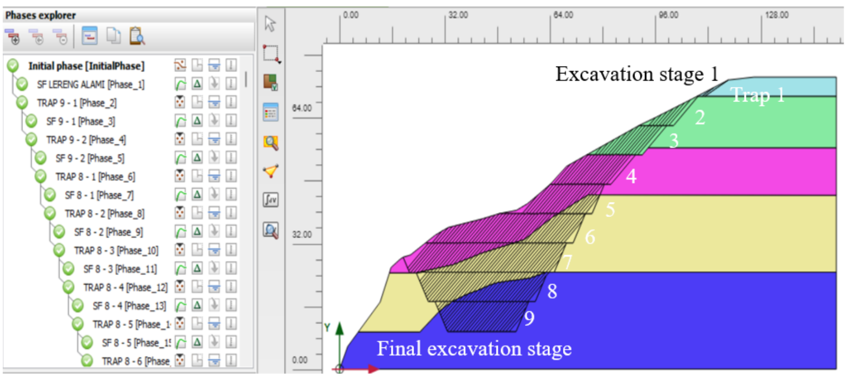

Figure 16. Modeling of the inclined excavation method

After all stages have reached the conclusion of the excavation plan, the factor of safety values for each stage are obtained as follows:

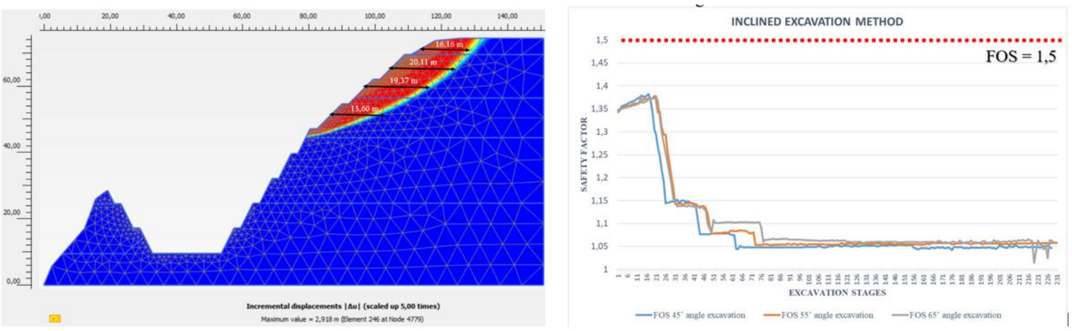

Figure 17. Landslide depth and changes and changes in the factor of safety of the slope using the inclined excavation method

The failure plane of the slope at the end of one stage of excavation using the inclined excavation method is as follows:

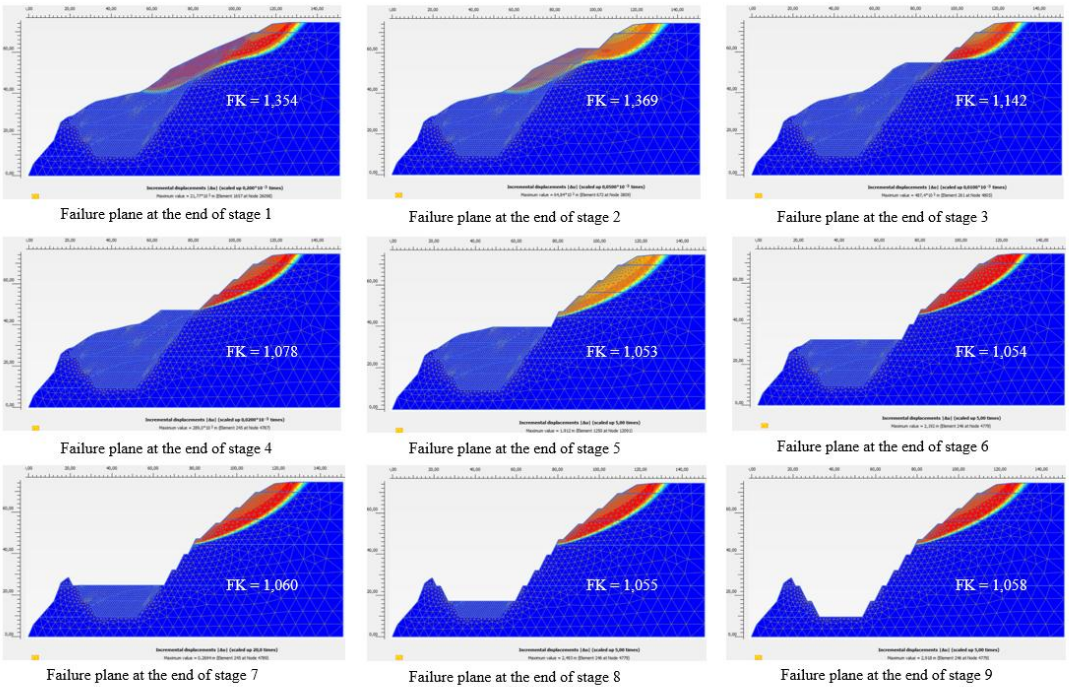

Figure 18. Changes in the slope failure area due to inclined excavation methods

Changes in slope stability due to the influence of groundwater levels on slope Sta. 0+119

To assess the impact of the groundwater level on slope stability, the groundwater level is modeled at the interface between soil and rock layers. Subsequently, a simulation is conducted by raising the groundwater level by 2 meters until the slope reaches a condition of failure or instability (FOS < 1). The following presents the modeling of the groundwater level using the Plaxis 2D software :

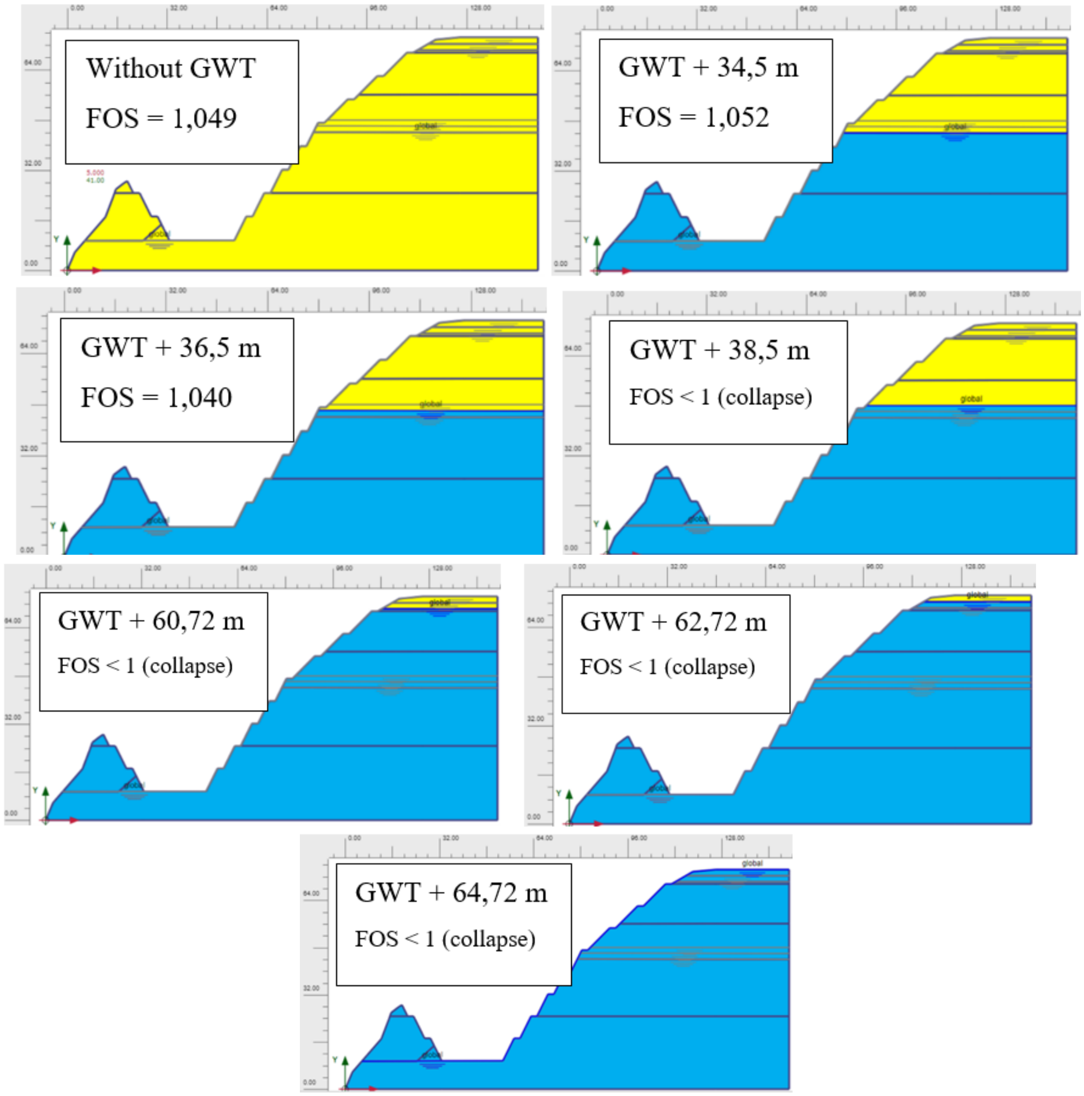

Figure 19. Modeling of variations in groundwater level on slope Sta. 0+119

CONCLUSIONS

Based on the results of the analysis and calculations presented in the previous chapter, several points can be concluded as follows:

1. According to SNI 8460:2017, for slopes with high uncertainty in analysis conditions, the minimum required safety factor is 1.5. Upon completion of the excavation, the slope at STA. 0+119 exhibited a safety factor of 1.034, indicating the need for reinforcement to ensure slope stability. The slope inclination that still meets safety criteria for soft sandy clay is a maximum slope angle of 30°, achieving a safety factor value of 1.615.
2. For sandy clay slopes with soft consistency, slope inclinations of 65˚, 55˚, and 45˚ do not meet the safety criteria based on SNI 8460:2017 (FOS < 1.5). For sandy silt slopes with medium consistency, the maximum safe slope inclination is 45˚. Apart from these types of slopes, all excavation methods meet the safety criteria for slopes (FOS ≥1.5).
3. The slope stability condition for excavation depth variations of 1 meter, 2 meters, and 3 meters shows a decrease in the safety factor beyond the 7th trap, rendering the slope critical. Therefore, it is recommended to implement reinforcement on the slope starting at the 7th trap stage. At the 5th trap, the safety factor begins to stabilize, with no significant decrease observed, as the excavation has reached the rock layer. At the end of the horizontal excavation, it was determined that the deepest slip plane reached a

depth of 19.72 meters.

4. Similar to the horizontal excavation method, excavations with inclined slopes exhibit similar stability conditions to horizontal excavations, where a decrease in the safety factor occurs beyond the 7th trap, making the slope critical. Therefore, it is recommended to implement reinforcement on the slope starting from the 7th trap stage. At the 5th trap, the safety factor begins to stabilize, with no significant decrease observed, as the excavation has reached the rock layer. At the end of the sloped excavation, it was determined that the deepest slip plane reached a depth of 20.11 meters.
5. The stability of the slope after excavation is affected by the groundwater table at elevations of +64.72 m, -2 m (+62.72 m), and -4 m (+60.72 m), leading to collapse conditions of the slope. The maximum acceptable groundwater table height for the slope is +36.5 m (at the fifth bench), which corresponds to a ratio of the groundwater table elevation to the slope height of 56.40%. At an elevation of +36.5 m (56.40% of the slope height), the factor of safety is calculated to be 1.040. An increase in the groundwater table beyond +36.5 m may result in unstable slope conditions.
6. An effective excavation method can be implemented using horizontal excavation with depths of 1 meter, 2 meters, or 3 meters, or by creating slopes with angles of 65˚, 55˚, and 45˚. For slopes composed of sandy clay with soft consistency, the maximum slope inclination should be less than 45˚ to meet the safety factor requirement of ≥ 1.5. For sandy silt slopes with medium consistency, the maximum slope inclination that meets the safety factor requirement is 45˚. The impact of soil excavation methods on slope stability is significantly influenced by the type of soil and its consistency. In particular, for soft-consistency soils, the use of horizontal excavation methods provides a more stable safety factor during the initial excavation stages compared to inclined excavation methods. The installation of reinforcement in the form of soil nailing should extend beyond the deepest failure plane, with a length exceeding 20.11 meters. The slope becomes more prone to instability when there is a groundwater table. When encountering a slope with the presence of a groundwater table, the installation of surface and subsurface drainage systems becomes crucial. The surface drainage channels are designed to direct rainwater, prevent excessive infiltration into the soil, and control water flow to avoid erosion. For subsurface drainage, drainage pipes can be installed within the slope to redirect groundwater, thereby reducing pore water pressure on the slope.

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