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Geotechnical Evaluation of Landslide Risks in Bali's Tourism Zones – A Case Study from Candidasa, Bali, Indonesia

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ABSTRACT

Tourism in Bali has surged post-COVID-19, with a 74.60% rise in arrivals from September 2022 to 2023, driving infrastructure development, notably in areas like Candidasa. However, safety concerns arise, especially in steep slope regions prone to landslides. This study employs cone penetration testing (CPT) data to assess its suitability for slope stability analysis amidst tourism development. By interpreting CPT data based on prior research, it shows obtaining ample soil parameters for such analysis is feasible. The research site, a Candidasa resort, exemplifies risks in hilly terrains. Fellenius-Morgenstern analysis reveals varying safety factors, indicating landslide susceptibility in certain scenarios. While CPT testing offers valuable insights, comprehensive geotechnical investigations are recommended for critical infrastructure projects to mitigate risks effectively. This study highlights the importance of comprehensive soil analysis and safety measures in the development of tourism infrastructure, especially in areas prone to geological hazards.

Keywords: tourism, slope stability analysis, cone penetration testing, Fellenius-Morgenstern analysis, landslide, geological hazards.

INTRODUCTION

Tourism activities in Bali after the Covid 19 pandemic have started to show an increase. This can be seen by comparing the number of foreign tourists visiting Bali for the period of September 2022, which was 291,115 people, and for September 2023, which was 508,297 people. There is a significant increase of 74.60% (BPS Bali Province, 2023). After a long time, about 2 years of tourism activities in Bali experiencing a very severe blow, in 2023 the arrival of tourists in Bali gradually increased. Various kinds of buildings related to the provision of tourism facilities have also begun to be built in Bali. This has made investors start to get interested in investing in tourism again. This condition can be seen from the hotel room occupancy in September 2023 which reached 59.25% compared to September 2022 which was only 46.45%, so there was an increase in occupancy of 12.80% in the same period for a year (BPS Bali Province, 2023).

Many tourism facilities have been rebuilt or are planned to be built. The use of land for the development of tourism facilities is carried out in various locations in Bali. Almost all land is used even though it is in a quite dangerous location, including on the edge of a cliff or in an area prone to landslides (Puja et al., 2021; Mihardja et al., 2023). The above conditions are caused by the desire to obtain attractive views and because of the limited land in Bali. One of the tourism facilities that is built and located in a hilly area or on a slope is a resort in Candidasa, Karangasem, Bali, so it is prone to landslides.

The development of tourism destinations in the Candidasa area is crucial for the growth of East Bali, promoting a balanced distribution of tourism development beyond the well-established destinations of Kuta, Sanur, and Nusa Dua (Arntz et al., 2015; Kartika et al., 2021). This resort development also aims to support the expansion of tourism in East Bali, facilitating connections to nearby islands such as Lombok, Gili, and Nusa Penida (Solidpixels, 2022).

Given the development in this region, an increase in tourism facilities is expected to be constructed in the Candidasa area in the future. This development should pay attention to the safety of buildings to be constructed, especially in areas with steep slopes. This is necessary because, according to several reports, landslide incidents have occurred in several regions in Bali where tourism facilities have been built, including in the Jimbaran area in March 2023, which caused damage to several buildings (Nv. 2023). Furthermore, in Jatiluwih in January and March 2024, which caused damage to villa buildings and resulted in loss of life (Hartik, 2024; AFP, 2024). Landslides that occurred in the above incidents were caused by high rainfall, which caused the soil layers on the slopes to become unstable. These incidents have resulted in material losses and casualties; therefore, an analysis of slope safety or stability is crucial before construction to ensure that the building is safe from landslides.

To thoroughly understand slope stability in sloping terrains, a comprehensive slope stability analysis is essential. For a relatively quick and reliable slope stability assessment, the widely used limit equilibrium method, a relatively simple approach, can be employed. This analysis necessitates supporting data, particularly soil foundation data, encompassing both physical and mechanical soil properties. Physical soil properties include grain size and soil unit weight, which are related to the soil type at the research site. Mechanical soil properties, on the other hand, are related to the soil's friction angle. However, in this study, the only available data is from CPT, which provides limited information, including cone resistance and sleeve friction values. Therefore, to address the scarcity of data and obtain more adequate data, this study involves converting CPT data into the necessary soil parameters by interpreting CPT data based on theories from previous research.

This study aims to demonstrate that by performing proper conversion of CPT data, it will be possible to obtain data that is sufficiently good and adequate for slope stability analysis. This is done to obtain the required safety factor, so that an adequate foundation can be planned (Huang, 2014; Pangemanan et al., 2014; Jain et al., 2023).

METHOD

Study site

This study was conducted to review the slope stability of the resort development project in the Candidasa tourist area, Karangasem, Bali, which is located at coordinates 8°30'57.9"S and 115°34'54.5"E (Figure 1). The area of the resort development is approximately 1.7 ha, with a varying contour with the lowest and the highest-level difference being 19 m. The landslope is varied with the highest level up to 30° which categorize as steep (Sikdar et al., 2004; Setyawan et al., 2019).

Data collection

To perform a slope stability analysis, initial assessments require soil investigations. Soil data can be acquired through direct field investigations and laboratory testing. The main goal of soil investigations is to determine the location and depth of soil layers with sufficient bearing capacity to support stable building construction and minimize excessive settlement (Kyakula et al., 2006; Prayogo and Saptowati, 2017).

In this study, soil data was obtained from field testing, specifically utilizing the cone penetration test. During the CPT, a pressure gauge (manometer) measures the force exerted during penetration, providing cone resistance values in kg/cm². These cone values represent the relative density of the tested soil layers. The strength characteristics of each soil layer at the research site were identified through the use of CPT (Kim et al., 2006; Indriasari et al., 2016; Ma et al., 2016). Field soil testing was conducted at five locations

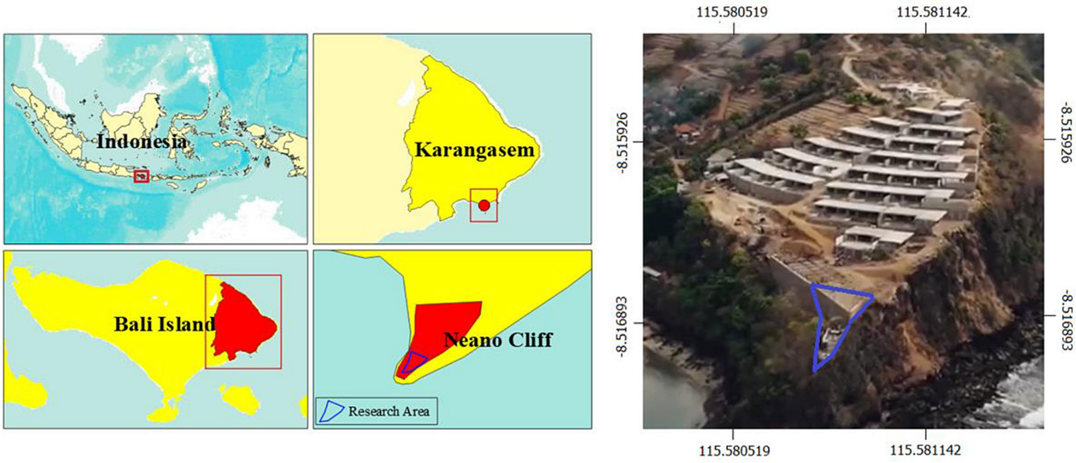

Figure 1. Area of research

strategically chosen on the most critical slope face at the lower end of the site, marked by the green slope cut in Figure 2. The slope angle data obtained from field mapping is depicted in Figure 2. This data was subsequently utilized to generate a slope angle model, a crucial element in slope stability analyses. The stability of the slope was assessed under two scenarios: at 0–31.09 m and 0–60.14 m from the edge of the slope.

Data analysis

Several in-situ testing methods are employed for soil investigation in structural design planning. These methods include cone penetration testing and standard penetration testing (SPT), alongside borehole sampling for laboratory testing. However, CPT has become the most prevalent in-situ testing method for building design in

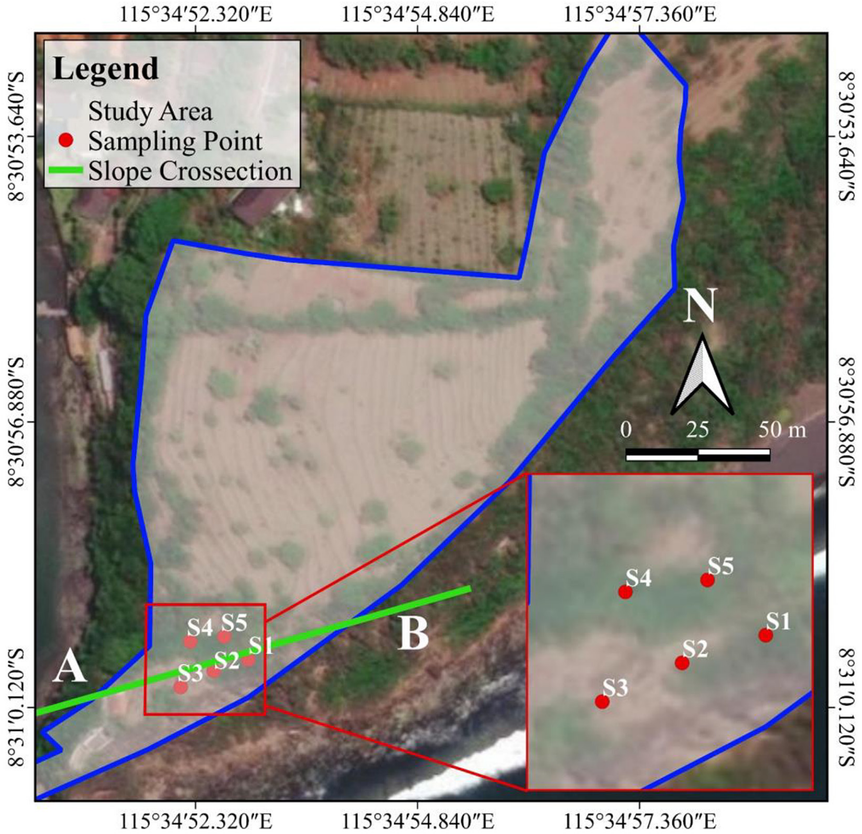

Figure 2. Location of CPT test points and slope angle map

Indonesia, including Bali. The widespread adoption of CPT testing can be attributed to its relative economic efficiency, speed, and repeatability with comparable results (Harimei, 2018; Miller et al., 2018; Hakam et al., 2019). Nevertheless, CPT testing also possesses limitations. Notably, it cannot retrieve soil samples and has a restricted penetration depth, hindering its ability to penetrate through dense soil layers (Miller et al., 2018). Although CPT testing only yields cone resistance data from the probing tool, slope stability analysis requires additional soil parameters such as unit weight, friction angle, and volume weight. Therefore, to utilize CPT data for slope stability analysis, it becomes crucial to employ various interpretational approaches to derive these necessary soil parameters.

Slope stability analysis commences with an evaluation of field soil testing data. Notably, the cone penetration test provides valuable insights into cone resistance values and depths of hard soil layers at the test location (Robertson, 1991; Bela and Sianto, 2022). To establish the physical soil parameters of each layer, a diagram relating cone resistance values to the friction ratio obtained during testing is employed.

Several researchers have developed charts to estimate soil type based on cone penetration test data, including Schmertmann (1978) and Douglas and Olsen (1981). However, Robertson's (1986) chart is widely adopted due to its ability to directly determine soil physical parameters. Initially, this chart included twelve soil types, but it was revised and streamlined to nine categories in 1990 (Figure 3) through normalization procedures (Robertson, 1991; Pranantya et al., 2018). This revised chart, often referred to as "Robertson's soil classification chart," remains a valuable tool for field identification of soil types using CPT data.

The soil type can be identified by referencing Figure 3 and locating the intersection of the cone penetration resistance (q_c) value and the friction ratio value. Table 1 provides a detailed explanation of these values and their corresponding soil types.

Several methods can be employed to analyze slope stability. This study employs the Limit Equilibrium Method (LEM) for slope stability calculations, specifically utilizing the Fellenius-Morgenstern approach. This method offers a straightforward yet effective approach, leveraging the slice method for analysis (Wardani et al., 2019). As a limit equilibrium method, it assumes that failure occurs along a circular surface within the slope (Utili and Crosta, 2015). The method determines the factor of safety (FS), defined as the ratio of the resisting forces to the driving forces on the slope

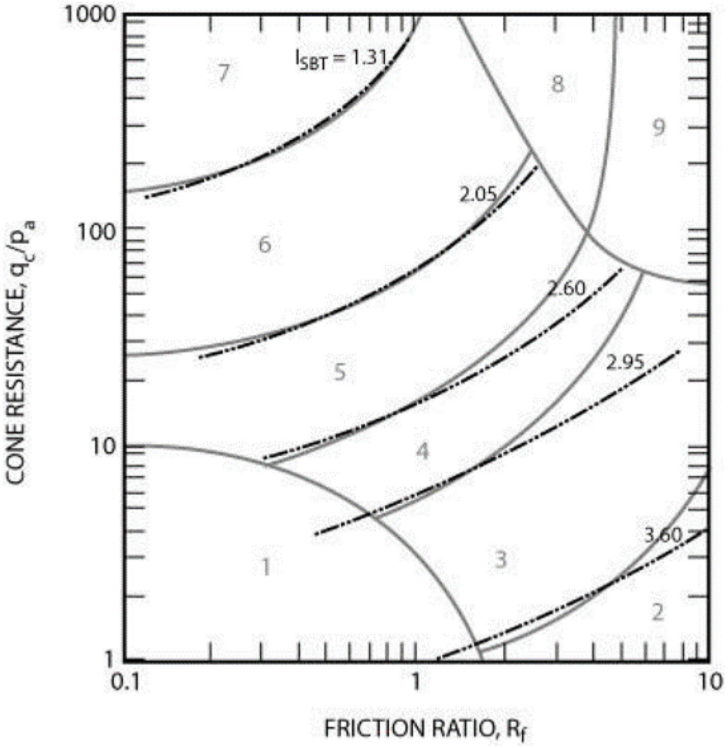

Figure 3. Soil classification chart based on CPT data (Robertson, 1990; Robertson, 2010)

Table 1. Soil type zones (Robertson, 1990; 2010)

Zone	Soil type
1	Sensitive fine-grained
2	Clay - organic soil
3	Clays: clay to silty clay
4	Silt mixtures: clayey silt & silty clay
5	Sand mixtures: silty sand to sandy silt
6	Sands: clean sands to silty sands
7	Dense sand to gravelly sand
8	Stiff sand to clayey sand*
9	Stiff fine-grained*

(Gasser et al., 2019). Figure 4 illustrates the key principles of this Fellenius-Morgenstern method.

In a slice equilibrium analysis, Hi and Vi represent the total horizontal and vertical components, respectively, of the resultant force Ei acting on the left side of a segment. Hi + 1, Vi + 1, and Ei + 1 denote the same forces acting on the right side of the segment. To achieve equilibrium, all these forces must be considered. This condition can be expressed by the following slope stability equation (Aryal, 2006; Patuti et al., 2019).

$$SF = \frac{Mr}{Md} = \frac{Rx\sum\left(c_i\,\Delta L_i + N_i\,\tan\varphi_i\right)}{Rx\sum W_i\,\sin\alpha_i} = \frac{\sum\left(c_i\,\Delta L_i + N_i\,\tan\varphi_i\right)}{\sum W_i\,\sin\alpha_i} \tag{1}$$

where: *SF* – factor of safety, *Mr* – overturning moment (kg m), *Md* – Resisting moment (kg m), R_x – Radius of sliding plane (m), c_i – cohesion along sliding plane (kg/m^2), ΔL – segment length (m), N_i – normal force (kg/m^2), φ_I – internal friction angle of soil (°), W_i – load on each segment (kg), α_i – angle between segment and sliding plane (°).

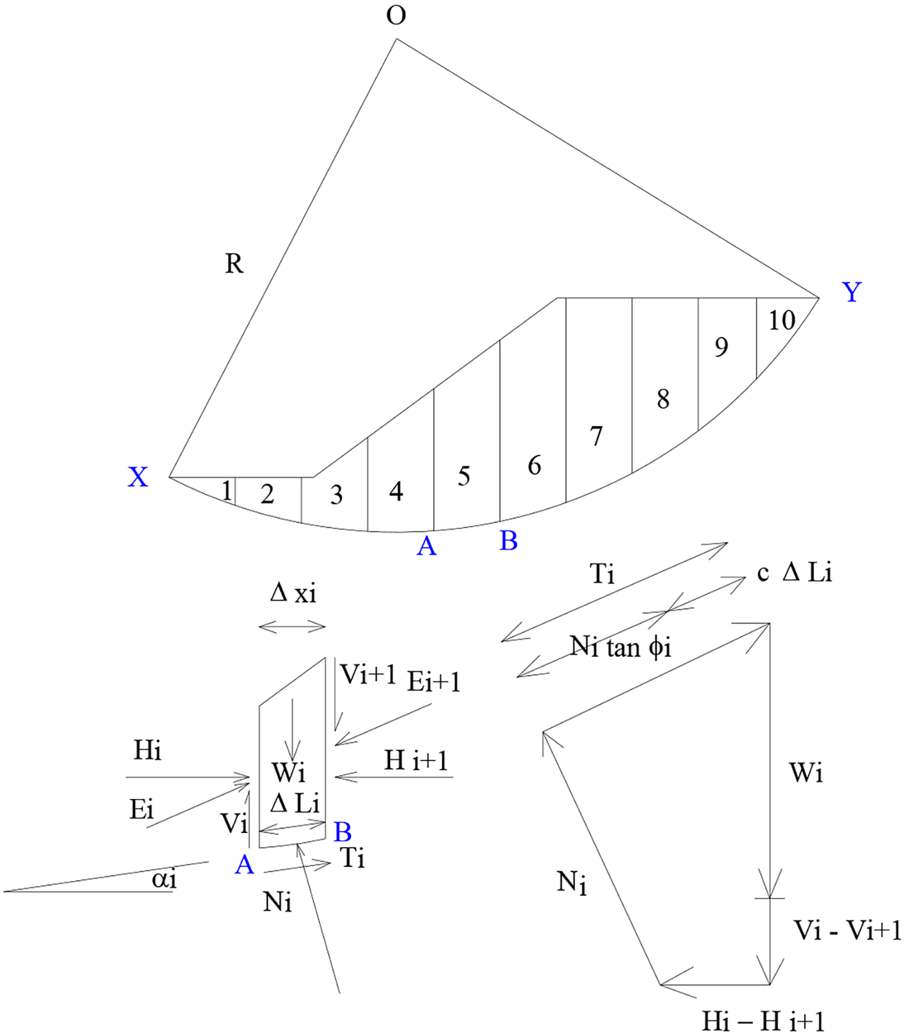

Figure 4. Illustration of the Fellenius method

Slope stability analysis in this study utilized the SLOPE/W software to model the slope and calculate the *FS*. According to Bowles (1989), a minimum *SF* of 1.25 is considered necessary for a slope to be classified as stable against landslides. The relationship between the *SF* value and the probability of landslide occurrence is further detailed in Table 2.

RESULT AND DISCUSSION

Soil investigation

Slope stability analysis or slope safety analysis requires soil investigation. In this study, a field investigation utilizing the cone penetration test was conducted at five locations. The results summarize the lowest soil strength in the near-surface layers and the depth of hard soil at each testing point (Table 3).

Based on the CPT test results in Table 3, the friction ratio values range between 2 and 3.3, indicating that the soil at the research location is classified as silt (Vos, 1982). The soil type can be identified by intersecting the cone resistance and friction ratio values (Figure 5).

Analyzing the intersection of cone resistance and friction ratio values in Figure 5 reveals that the majority of the soil falls within Zone 5, indicating a sand mixture that varies from silty sand to sandy silt. Once the soil type is determined, the unit weight of this sand mixture can be ascertained. This unit weight can be estimated based on research by Lunne et al. (1997), as shown in Table 4. Furthermore, Lindeburg (2001) presented unit weight values for various soil types, detailed in Table 5.

From the comparison of soil characteristics in Tables 4 and 5 above, it can be observed that the unit weight value of silty sand to sandy silt soil approaches the unit weight value of sand soil (dense and well graded). Therefore, the unit weight (γ) for silty sand to sandy silt soil with a value of 1.85 kN/m^3 can be further utilized to analyze the slope stability at the research location. For silty sand to sandy silt soils, the internal friction angle (φ) can be estimated based on Table 6, which presents the relationship between

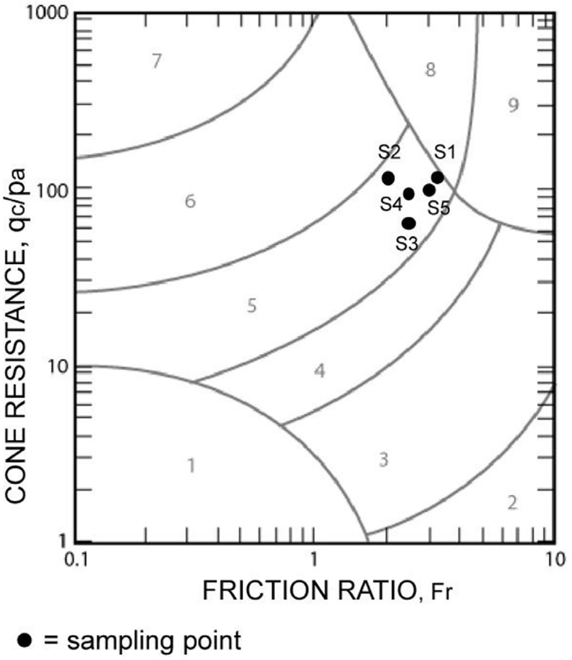

Figure 5. Graph of cone resistance and friction ratio values from the CPT test of each sampling point

Table 2. Landslide intensity classification based on factor of safety value (Bowles, 1989, as cited in Zakaria et al., 2018)

Factor of safety (FS)	Landslide intensity
FS < 1.07	Landslide occurs frequently (unstable slope)
1.07 < FS < 1.25	Landslide has occurred (critical slope)
FS > 1.25	Landslide rarely occurs (relatively stable slope)

Table 3. CPT test result of each research location

No	Point	Depth of hard soil (m)	The lowest cone resistance value (kg/cm^2)	Friction ratio
1	S1	1	134	3.3
2	S2	1	127	2
3	S3	1.8	64	2.5
4	S4	1.4	90.8	2.5
5	S5	1.2	101.7	3

Table 4. Approximate soil unit weight (Lunne et al., 1997)

Approximate unit weight of soil (γ) (kN/m^3)	Soil description
17.5	Sensitive fine grained
12.5	Organic material
17.5	Clay
18	Silty clay to clay
18	Clayey silt to silty clay
18	Sandy silt to clayey silt
18.5	Silty sand to sandy silt
19	Sand to silty sand
19.5	Sand
2	Gravelly sand to sand
20.5	Very stiff fine grained
19	Sand to clayey sand

Table 5. Common soil properties according to the civil engineering reference manual for the PE Exam (Lindeburg, 2001)

Soil type	γ (kN/m^3)
Sand, loose and uniform	14.13
Sand, dense and uniform	17.11
Sand, loose and well graded	15.54
Sand, dense and well graded	18.21
Glacial clay, soft	11.93
Glacial clay, stiff	16.64

internal friction angel (φ) and soil type (Carter and Bentley, 1991).

Based on Table 6 above, the soil type at the research location is silty sand with a dense soil condition, so the minimum shear angle is 30°. According to the analysis results above, the soil type, unit weight, and soil shear angle can be summarized in Table 7. Table 7 illustrates that the sandy soil layer, specifically silty sand to sandy silt, is found at 1.8 depth. Soil layer in this depth is categorized as hard soil due to cone resistance values exceeding 250 kg/cm^2.

Table 6. Internal friction angle (*φ*) values for non-cohesive soils (Carter and Bentley, 1991)

Type of materials	Internal friction angel (φ)	
	Loose sand	Dense sand
Uniform sand, round grains	27°	34°
Well-graded sand, angular grains	33°	45°
Sandy gravels	35°	50°
Silty sand	27–33°	30–34°
Inorganic silt	27–30°	30–35°

Slope stability analysis

The first step in slope stability analysis is to determine the longitudinal cross-section of the slope at the research site. This slope cross-section is obtained from the existing contour map so that it can be used to analyse slope stability (Figure 6).

Based on the soil investigation data, the soil layer at the research location is not very deep, only up to a depth of 1.8 m. Therefore, there is two soil layers namely the sand mixture soil layer: silty sand to sandy silt in the first layer and the hard soil layer in the layer below or the second layer. So, the soil data that will be used as input to the model is as follows:

- soil layer 1,
- unit weight (γ) = 1.85 kg/cm^3,
- internal friction angle (φ) = 30°,
- soil type – silty sand to sandy silt (dense soil);
- soil layer 2,
- hard soil layer (bedrock).

Figure 6 above illustrates the slope inclinations examined for two slope models. The first condition considers a horizontal distance of 31.09 m from the slope edge (point 0,0) with a slope height of 12.60 m. The second condition examines a horizontal distance of 60.14 m from the slope edge (point 0,0) with a slope height of 19 m. The slope angles for the first and second models are V/H = 0.405 and V/H = 0.315, respectively. Based on the soil data and slope inclinations, a

Table 7. Summary of soil type, unit weight, and shear angle at the research location

No	Point	Depth of hard soil (m)	Unit weight (kg/cm^3)	Soil type	Internal friction angel (°)
1	S1	1	1.85	Sand mixtures: silty sand to sandy silt	30
2	S2	1	1.85	Sand mixtures: silty sand to sandy silt	30
3	S3	1.8	1.85	Sand mixtures: silty sand to sandy silt	30
4	S4	1.4	1.85	Sand mixtures: silty sand to sandy silt	30
5	S5	1.2	1.85	Sand mixtures: silty sand to sandy silt	30

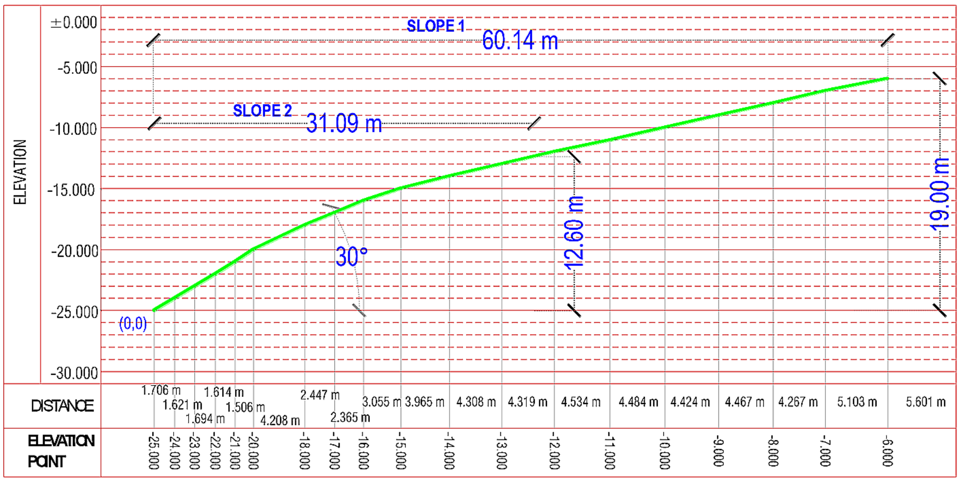

Figure 6. Longitudinal cross-section of slope (A–B) at the research location

model is constructed as shown in Figure 7 below. The entry and exit method were employed for the slip surface in the SLOPE/W model. According to both models, the results displayed in Figures 8 and 9 were obtained. The slope stability assessment was conducted under two conditions: within 0–31.09 m and a distance of 0–60.14 m from the edge of the slope (point 0,0). Figure 8 displays the collapse model for the 0–31.09 m distance, while Figure 9 presents the collapse model for the 0–60.14 m distance. After executing the model in SLOPE/W, the slope stability analysis for the first condition yields the following results:

1. Minimum SF – 1.229 at 0–31.09 m from the slope edge.
2. Slip surface – located 20 m from the slope edge with an approximate depth of 1 m.

The safety factor obtained for the first model is comparable to the findings of a previous slope stability analysis by Shiferaw (2021). Shiferaw reported a safety factor of 1.241 for sandy soil with a slope height of 12 m. Considering the safety factor obtained in this study, the slope can be considered susceptible to landslides.

The results of executing the model in SLOPE/W for the second condition reveal the following:

1. Minimum safety factor – 1.427
2. Slip surface: located 31 m from the slope edge with a depth of 1.8 meters.

This safety factor is lower than that obtained for the first condition. It can be compared to the findings of Shiferaw (2021), who reported a safety factor (SF)

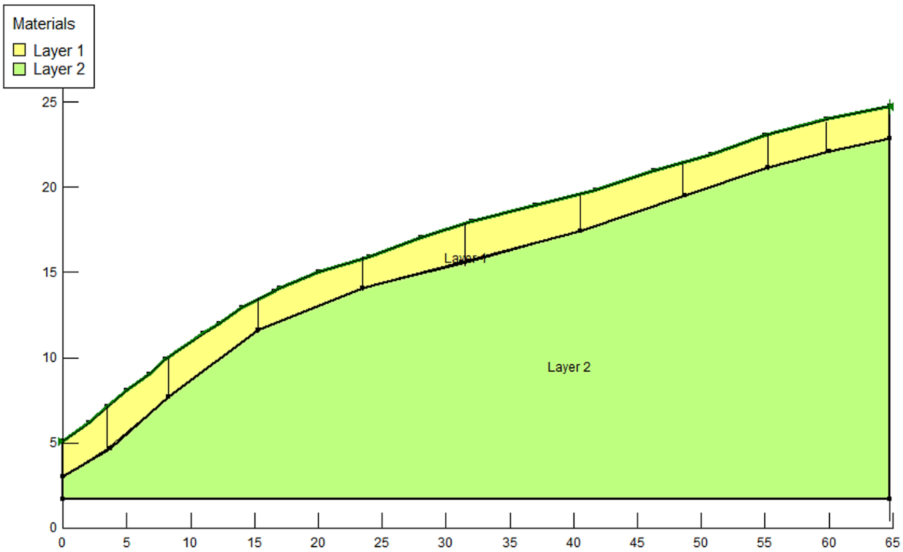

Figure 7. Slope model in SLOPE/W software

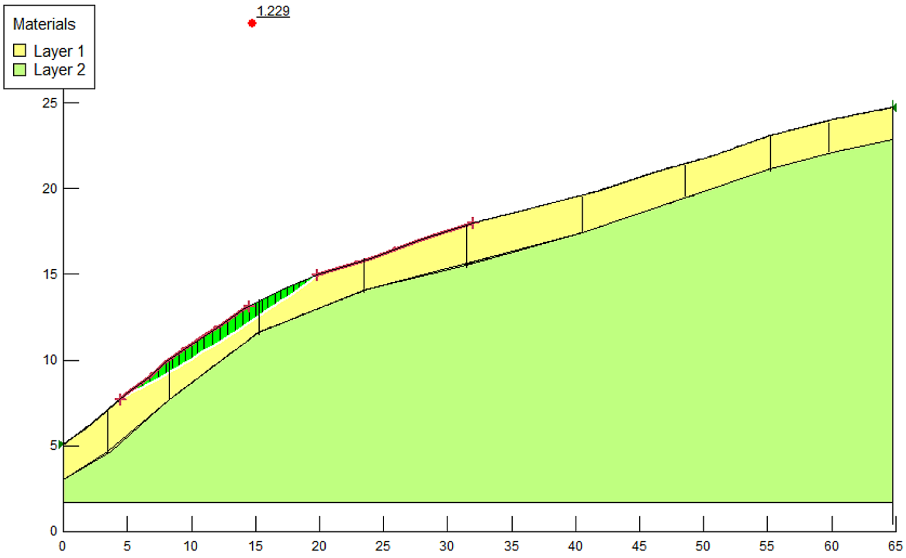

Figure 8. Results of running the model in SLOPE/W software at a location 0–31.09 m from the edge of the slope (0,0)

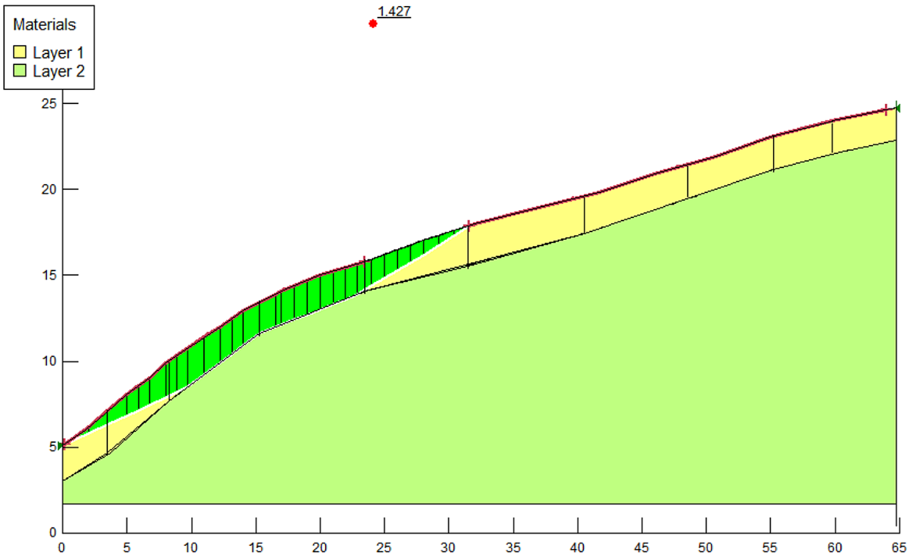

Figure 9. Results of running the model in SLOPE/W software at a location 0–60.14 m from the edge of the slope

of > 1.8047 for a slope angle (V/H) of 0.3429. The slope angle at the research site is 0.315. Although the safety factor obtained in this study is lower than that of Shiferaw (2021), the slope can still be considered relatively safe against landslides based on Bowles' (1997) criteria, which states that a safety factor greater than 1.25 is considered safe. The two models presented above demonstrate a strong relationship between soil type and slope angle with respect to slope stability. It can also be noted that CPT test results can be used to derive the soil parameters required for slope stability analysis, given that proper interpretation is performed using various methods.

CONCLUSIONS

Data collected through field soil testing using cone penetration test at the research site revealed the characteristics of the soil layer. The CPT testing indicated that the depth of hard soil at the research site is relatively shallow, with the deepest layer reaching approximately 1.8 m. Upon converting the CPT test results, the soil at the research location was identified as sandy silt with γ (unit weight) value of 18.5 kN/m³ and φ (internal friction angle) of 30°. This demonstrates the utility of the CPT test, a relatively simple and straightforward method, for field soil testing. Through proper conversion of the test values, relevant soil parameters can be obtained. However, accurate interpretation of the test data is crucial to avoid errors in subsequent analyses. Slope stability analysis of the research site using two models in SLOPE/W yielded the following safety factors: 1.229 for model 1 and 1.427 for model 2. The safety factor in model 1 is less than 1.25, indicating a susceptibility to landslides. Conversely, the safety factor in model 2 is greater than 1.25, suggesting that the slope is safe against landslides. To mitigate landslide risk during construction, it is recommended that buildings be positioned at least 20 m from the slope edge. Furthermore, for a shallow foundation, the foundation base should be situated at a depth of 1.8 m to ensure the stability of the building. To further enhance overall safety, the implementation of additional slope stabilization techniques should be prudently considered. These techniques could encompass retaining walls, drainage systems, or buttresses. While CPT testing has provided valuable preliminary insights, a more comprehensive geotechnical investigation is recommended for a more robust assessment, especially for critical infrastructure projects. This comprehensive investigation should include borings and laboratory testing to obtain a more detailed understanding of the soil properties and potential failure mechanisms.

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