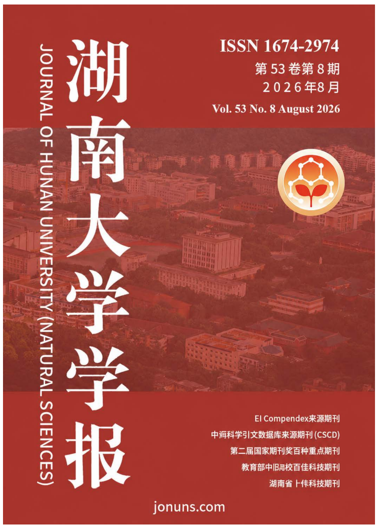

Journal of Hunan University

(Natural Sciences)

Vol. 53 No. 8

August 2026

Available online at

https://jonuns.com

Open Access Article https://doi.org/10.55463/issn.1674-2974.53.8.9

Slope Stability Analysis of Steep Tropical Volcanic Soil Slopes Stabilized by Moisture-Controlled Compaction

Semangat Marudut Tua Debataraja[1*], Agustinus Purna Irawan[2], Aazokhi Waruwu[3], Oei Fuk Jin[4]

[1,2] Doctoral study program in civil engineering, Faculty of Engineering, Tarumanagara University, Jakarta, Indonesia,
[3] Civil Engineering Study Program, Faculty of Science and Technology, Pelita Harapan University, Indonesia,
[4]Civil Engineering Doctoral Program, Tarumanagara University, Jakarta, Indonesia,

* Corresponding author: semangat.328222011@stu.untar.ac.id

Article History:

Received: July 12, 2026
Revised: August 26, 2026
Accepted: August 31, 2026
Published: September 10, 2026

Abstract: Landslides on steep slopes composed of tropical volcanic soils constitute a major geotechnical hazard because intensive weathering and variations in water content can substantially affect soil shear strength and slope stability. This study evaluated the effectiveness of moisture-controlled compaction in improving the stability of a steep roadside slope in Aek Godang Arbaan Village, Onanganjang District, Humbang Hasundutan Regency, North Sumatra, Indonesia. The engineering properties of the soil were determined through laboratory Proctor compaction and direct shear tests to obtain the optimum moisture content (OMC), maximum dry density, cohesion, and internal friction angle. Slope stability was assessed using the Fellenius and Bishop limit equilibrium methods and a three-dimensional finite element model developed in PLAXIS 3D using the φ–c reduction approach. Three moisture conditions were considered: 14.70% on the dry side of the OMC, an OMC of 19.25%, and 23.80% on the wet side. The Proctor test yielded an OMC of 19.25% and a maximum dry density of 1.614 g/cm³. At the OMC, the factors of safety calculated using the Fellenius, Bishop, and PLAXIS 3D methods were 1.51, 1.66, and 1.997, respectively. The Bishop method produced a slightly higher factor of safety under the dry-side condition of 14.70% (1.69) than at the OMC (1.66), whereas the Fellenius and PLAXIS 3D analyses exhibited different trends. Nevertheless, when maximum dry density and the combined results of the three stability analyses were considered, the OMC of 19.25%

was identified as the most favourable overall compaction condition. PLAXIS 3D provided additional insight into the stress distribution, deformation pattern, and progressive failure mechanism that could not be represented by the limit equilibrium methods. The large deformation values generated during the φ–c reduction analysis indicate numerical progression towards failure and should not be interpreted as predicted service-condition displacements. These findings demonstrate that controlling the water content during compaction at or near the OMC can enhance the stability of steep tropical volcanic soil slopes and provide a practical basis for slope stabilisation and landslide-risk mitigation.

Keywords: moisture-controlled compaction; slope stability; tropical volcanic soil; limit equilibrium method; finite element analysis.

含水率控制压实加固陡峭热带火山土边坡的稳定性分析

摘要： 由热带火山土构成的陡坡滑坡是一类重要的岩土工程问题，其形成与强烈风化作用及含水率变化密切相关，而这些因素会影响土体的抗剪强度和边坡稳定性。本研究评估了含水率控制压实技术对印度尼西亚北苏门答腊省洪邦哈顺杜坦县Onanganjang区Aek Godang Arbaan村一处公路陡边坡稳定性的改善效果。通过室内试验测定土体的工程性质，包括Proctor击实试验和直剪试验，以确定最优含水率（OMC）、最大干密度、黏聚力和内摩擦角。采用Fellenius法和Bishop法两种极限平衡方法以及基于PLAXIS 3D的三维有限元分析对边坡稳定性进行评价，其中有限元分析采用φ-c强度折减法。研究考察了三种含水状态：14.7%的干侧含水状态、19.25%的最优含水率状态以及23.8%的湿侧含水状态。Proctor击实试验结果表明，土体的最优含水率为19.25%，最大干密度为1.614 g/cm³。在最优含水率条件下，采用Fellenius法、Bishop法和PLAXIS 3D计算得到的安全系数分别为1.51、1.66和1.997。Bishop法在14.7%的干侧含水状态下得到的安全系数略高，为1.69，表明其变化趋势与Fellenius法和PLAXIS 3D的分析结果有所不同。尽管如此，综合考虑最大干密度和各类边坡稳定性分析结果，19.25%的最优含水率仍代表最佳的总体压实条件。与极限平衡法相比，PLAXIS 3D分析能够更为详细地反映边坡的应力和变形特征。φ-c强度折减分析中获得的较大变形值属于模拟破坏过程所产生的数值变形，不应直接解释为边坡在正常使用条件下的预期位移。研究结果表明，在压实施工过程中合理控制含水率能够提高陡峭热带火山土边坡的稳定性，并为边坡加固和滑坡灾害防治提供实践依据。

关键词： 压实；含水率；边坡稳定性；热带火山土；有限元分析

1. Introduction

Landslides remain one of the most frequent geotechnical hazards affecting transportation infrastructure in tropical regions. The susceptibility of slopes to failure is particularly high in areas dominated by volcanic soils, where intensive weathering processes, high rainfall infiltration, and fluctuations in soil moisture significantly influence soil mechanical behavior. Variations in moisture content affect matric suction, pore-water pressure, and soil shear strength, which ultimately control slope stability and the safety factor (SF) of natural and engineered slopes. In tropical environments, these processes are further intensified by prolonged rainfall and complex hydrological conditions, increasing the likelihood of slope instability [1].

North Sumatra Province is characterized by mountainous topography and extensive volcanic soil deposits that are highly susceptible to landslides. Along provincial road networks, slope failures frequently disrupt transportation activities, increase maintenance costs, and pose significant risks to public safety. The provincial road section in Aek Godang Arbaan Village, Onanganjang District, Humbang Hasundutan Regency, represents a critical transportation corridor where slope stability is essential for maintaining infrastructure functionality and ensuring road-user safety.

Among various stabilization techniques, soil compaction is considered one of the most practical and cost-effective methods for improving slope performance. Proper compaction increases soil density, reduces void ratios, and enhances shear strength characteristics. However, the effectiveness of compaction is highly dependent on moisture content. Variations in water content directly affect soil strength parameters and consequently influence slope stability and safety factor. Changes in soil mechanical parameters significantly affect slope stability and may alter failure mechanisms, emphasizing the importance of identifying the moisture condition that provides the most favorable combination of soil density and shear strength [2].

Slope stability can be evaluated using several analytical approaches. Conventional limit equilibrium methods, including the Fellenius and Bishop methods, remain widely used because of their simplicity and reliability in estimating the safety factor (SF) of slopes. Nevertheless, these methods have limitations in representing stress redistribution and deformation mechanisms within the soil mass. Finite element approaches provide a more detailed representation of stress and deformation behavior by accounting for the stress–strain relationship within the soil mass and the development of progressive failure mechanisms [3]. Similarly, finite element analysis offers a more comprehensive understanding of deep-seated landslide behavior compared with traditional limit equilibrium approaches [4].

Recent developments in geotechnical engineering have increasingly adopted three-dimensional numerical analyses to evaluate slope performance under complex loading and geological conditions. Three-dimensional finite element analysis can effectively compare alternative slope stabilization techniques and provide more detailed information regarding stress distribution and deformation patterns [5]. Furthermore, finite element modeling has been shown to be effective for assessing slope reinforcement strategies and evaluating the stability of landslide-prone areas under various geotechnical conditions [6].

Several recent studies have also compared limit equilibrium and finite element methods for slope stability assessment. Finite element analysis offers a more detailed representation of slope failure mechanisms than conventional limit equilibrium methods. Nevertheless, both approaches remain valuable and complementary tools for geotechnical engineering decision-making [7]. These findings suggest that integrating multiple analytical approaches can improve the reliability of slope stability evaluations by providing complementary information on the overall stability, stress distribution, and deformation behavior of slopes.

Despite extensive research on slope stability and numerical modeling, limited studies have investigated the influence of moisture-controlled compaction on steep slopes composed of tropical volcanic soils by integrating laboratory testing with both conventional limit equilibrium methods and three-dimensional finite element analysis. Moreover, comparative assessments involving Fellenius, Bishop, and PLAXIS 3D analyses under varying moisture content conditions remain scarce, particularly in volcanic soil environments in Indonesia. The comparison of these methods is important because different analytical approaches may produce different Safety Factor values and therefore provide different perspectives on the stability response of compacted slopes.

Therefore, this study aims to evaluate the effectiveness of compaction at different moisture content conditions in improving the stability of steep slopes located along the provincial road section in Aek Godang Arbaan Village, Onanganjang District, Humbang Hasundutan Regency, North Sumatra. The study considers three moisture conditions, namely 14.7%, 19.25%, and 23.8%, where 19.25% represents the experimentally determined optimum moisture content (OMC) associated with a maximum dry density (MDD) of 1.614 g/cm³. The 14.7% and 23.8% conditions are considered modified dry-side and wet-side moisture conditions, respectively.

The slope stability response is evaluated using the Fellenius and Bishop limit equilibrium methods and PLAXIS 3D numerical analysis based on the laboratory-derived soil parameters. The PLAXIS 3D analysis employs the φ-c reduction technique to determine the Safety Factor (SF) and to examine the associated deformation behavior under different moisture conditions. The results from the three analytical approaches are subsequently compared to determine the moisture condition that provides the most favorable overall slope stability performance.

The novelty of this study lies in the integration of laboratory compaction and direct shear testing with comparative slope stability analyses using the Fellenius, Bishop, and PLAXIS 3D methods for a tropical volcanic soil slope. By combining laboratory-derived soil properties with conventional limit equilibrium and three-dimensional finite element analyses, the study provides a comparative assessment of how moisture-controlled compaction influences slope stability and identifies the moisture condition associated with the most favorable overall stabilization performance.

2. Methods

This research was conducted through field investigations and laboratory testing to determine the optimum moisture content (OMC), maximum dry density (MDD), and soil shear strength parameters, including cohesion (c) and internal friction angle (φ). Slope stability analyses were subsequently performed using the Fellenius method, Bishop method, and the Finite Element Method (FEM) implemented in PLAXIS 3D software through the φ-c reduction technique. The integration of limit equilibrium methods and finite element analysis has been widely recognized as an effective approach for evaluating slope stability under complex geotechnical conditions [4], [7]. Modeling was carried out for three moisture conditions, namely 14.7%, 19.25%, and 23.8%, where 19.25% represents the experimentally determined OMC, while 14.7% and 23.8% represent modified dry-side and wet-side moisture conditions, respectively. The resulting safety factor (SF) values were compared to identify the moisture condition providing the most favorable overall stability performance for the steep tropical volcanic soil slope.

Figure 1. Research Location (2°8'8.655"N; 98°33'2.51"E)

Source: Research results (2026)

2.1. Laboratory Characterization and Compaction

To determine the engineering properties of the tropical volcanic soil, laboratory characterization and compaction tests were conducted in accordance with ASTM standards. Soil samples were collected from the study area and transported to the geotechnical laboratory for testing. Prior to testing, the samples were air-dried, pulverized, and passed through the appropriate sieve to ensure uniformity. Basic soil characterization included determination of natural water content, unit weight, and classification properties, while compaction characteristics were evaluated using the Standard Proctor Test following ASTM D698 procedures [8].

The compaction test was performed by preparing soil The compaction test was performed by preparing soil specimens at different moisture content levels ranging from approximately 10% to 30%. Each specimen was compacted into a standard cylindrical mold using controlled compaction energy. The resulting wet density values were converted into dry density values and plotted against moisture content to obtain the compaction curve. The relationship between moisture content and dry density plays a fundamental role in determining the optimum moisture content (OMC) and maximum dry density (MDD), which represent the most efficient compaction condition for a particular soil type [9].

Figure 2. Proctor compaction test equipment

Source: Developed by the authors (2026)

The improvement of slope stability in this study was achieved through controlled soil compaction, where moisture content was treated as the primary variable influencing soil density and mechanical behavior. Three moisture content conditions, namely 14.7%, 19.25%, and 23.8%, were selected to represent the modified dry-side condition, the optimum moisture condition, and the modified wet-side condition, respectively. These conditions were chosen to evaluate how changes in molding water content affect soil structure, particle arrangement, and the development of shear strength.

The optimum moisture content plays a critical role in reducing interparticle friction and facilitating particle rearrangement during compaction. At moisture contents lower than the optimum value, insufficient water prevents effective particle lubrication, resulting in higher void ratios and lower dry density. Conversely, at moisture contents exceeding the optimum level, excess water occupies pore spaces and may reduce effective stress and limit further densification [10].

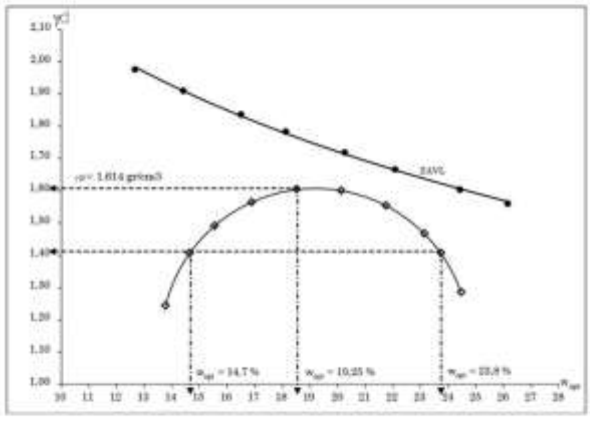

Figure 3. Relationship between water content (w) and dry density (gd)

Source: Research results (2026)

As shown in Figure 3, the compaction curve exhibits the characteristic Proctor behavior where dry density initially increases with increasing moisture content until reaching a maximum value and subsequently decreases beyond the optimum point. The maximum dry density obtained was $\gamma d = 1.614$ g/cm³ at a moisture content of 19.25%, indicating the experimentally determined optimum moisture condition. In comparison, the dry densities at 14.7% and 23.8% moisture contents were approximately 1.40 g/cm³.

The presence of the Zero Air Void Line (ZAVL) in Figure 3 serves as a theoretical reference representing complete saturation conditions. All compaction points remained below the ZAVL, confirming that full saturation was not achieved during testing. This observation is consistent with conventional compaction theory, which states that additional moisture beyond the optimum level no longer contributes to increased soil density [9]. Therefore, a moisture content of 19.25% was identified as the OMC associated with the maximum dry density of 1.614 g/cm³. To obtain the shear strength parameters required for slope stability analysis, direct shear tests were conducted on compacted specimens prepared at the three selected moisture conditions. The tests were performed under controlled loading conditions to determine the cohesion (c) and internal friction angle (φ) of the compacted soil. These parameters constitute the primary inputs for both limit equilibrium and finite element analyses.

2.2. Slope Stability Analysis Using Fellenius and Bishop Methods

The stability of the slope was initially evaluated using conventional limit equilibrium methods, namely the Fellenius Method and the Bishop Simplified Method. These methods were selected because they are widely accepted and extensively used in geotechnical engineering practice for assessing slope stability under circular failure mechanisms [11].

The analysis utilized the slope geometry observed in the field, which consisted of a slope inclination of approximately 55°. Soil shear strength parameters obtained from laboratory direct shear tests under the three compaction conditions were used as input variables. The safety factor (SF*)* was calculated for each condition to evaluate the effect of moisture-controlled compaction on slope stability.

The Fellenius Method, also referred to as the Ordinary Method of Slices, assumes a circular slip surface and calculates the safety factor (SF) by comparing the resisting forces generated by soil shear strength against the driving forces produced by the weight of the soil mass [12]. Although simple and practical, the method neglects interslice forces and therefore tends to provide relatively conservative safety factor values.

In contrast, the Bishop Simplified Method incorporates moment equilibrium and partially accounts for interslice forces, leading to safety factor estimates that may differ from those obtained using the Fellenius method [13]. Because of its balance between simplicity and accuracy, the Bishop Method is one of the most commonly adopted procedures in geotechnical design standards.

The results obtained from both methods were compared to identify the influence of compaction-induced changes in cohesion and friction angle on overall slope stability and to determine the moisture content condition that produced the most favorable safety factor (SF).

2.3. Numerical Integration and Material Calibration

To complement the limit equilibrium analysis, numerical modeling was carried out using PLAXIS 3D software. Experimental results obtained from laboratory testing were transformed into constitutive soil parameters suitable for finite element analysis. The numerical model was developed to represent the geometry and material conditions of the study slope based on the available field and laboratory data.

The Mohr–Coulomb constitutive model was adopted as the primary soil model because it requires a relatively small number of input parameters while still providing a practical representation of soil stress–strain behavior for slope stability analysis [14]. The required parameters included unsaturated unit weight (γ_{unsat}), saturated unit weight (γ_{sat}), cohesion (c), internal friction angle (φ), Young's modulus (E), and Poisson's ratio (ν). Additional parameters required by the adopted PLAXIS 3D material formulation, including λ and k*, were incorporated according to the corresponding model input requirements.* The unit weight values were derived from the available soil characterization and compaction data, while shear strength parameters were obtained from direct shear testing.

The principal PLAXIS 3D input parameters used in the numerical model are summarized in Table 1. The parameters are presented according to the soil layers used to construct the numerical model to facilitate transparency and reproducibility of the analysis.

Table 1. Principal Soil and Loading Parameters Used in the PLAXIS 3D Model

Layer	Soil type	γunsat (kN/m³)	γdry (kN/m³)	c (kN/m²)	φ (°)	E (kN/m²)	ν (-)	λ* (-)	k* (-)	Vehicle load (kPa)
1	Silt	16.29	14.13	12.75	11.96	10,000	0.30	0.619	0.206	12
2	Sandy	17.66	13.15	2.00	11.96	2,000	0.20	0.091	0.036	12

	clay									
3	Sandy clay	16.67	10.89	6.17	20.14	2,000	0.20	0.091	0.036	12
4	Sandstone	18.62	14.17	6.27	30.00	60,000	0.35	0.068	0.027	12

Source: Research results (2026)

Note: The values in Table 1 represent the material and loading parameters assigned to the respective layers in the PLAXIS 3D model. The moisture-condition-specific stability results for 14.7%, 19.25%, and 23.8% are presented separately in the Results and Discussion section.

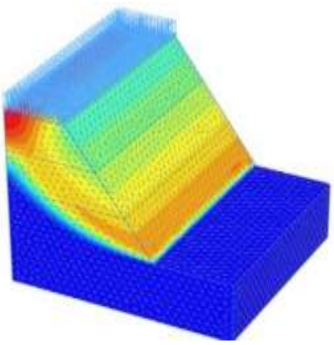

Figure 4. PLAXIS 3D numerical model
Source: Author's modeling using PLAXIS 3D (2026)

Material calibration was performed for each moisture content condition to incorporate the corresponding laboratory-derived soil properties into the numerical analysis. This process enabled comparison of the numerical stability response under the three selected moisture conditions.

2.4. Finite Element Slope Stability Analysis

The finite element analysis was conducted using staged construction procedures available in PLAXIS 3D. This approach allows the simulation of the sequential development of stresses and deformations within the soil mass. Slope stability was assessed using the Strength Reduction Method (SRM), commonly known as the φ-c reduction technique. In this method, the shear strength parameters, namely cohesion (c) and the tangent of the friction angle (tan φ), are progressively reduced until numerical failure occurs. The reduction factor corresponding to failure is interpreted as the safety factor (SF) of the slope [15].

The φ-c reduction procedure was applied to each of the three moisture conditions, namely 14.7%, 19.25%, and 23.8%. The resulting cumulative strength reduction factor (ΣMsf) at the onset of numerical failure was used as the Safety Factor (SF) for each model condition.

Compared with conventional limit equilibrium methods, the finite element approach provides additional information regarding stress redistribution, displacement patterns, strain localization, and potential failure mechanisms. However, the deformation values obtained from the φ-c reduction analysis represent the numerical response associated with progressive strength reduction toward failure and should not automatically be interpreted as expected service-condition slope displacements. Consequently, the integration of laboratory testing, limit equilibrium analysis, and finite element modeling provides complementary information for evaluating the effectiveness of moisture-controlled compaction in improving the stability of tropical volcanic soil slopes.

3. Result and Discussion

3.1. Slope Stability Analysis of Original Soil Using Fellenius, Bishop, and PLAXIS 3D Methods

The initial stability condition of the slope was evaluated using the Fellenius, Bishop, and PLAXIS 3D methods before any compaction treatment was applied. The analyzed slope represents the actual field condition with a height of 24 m, a slope angle of 55°, and a horizontal length of 17.04 m. The geometry used in the analysis is presented in Figure 5.

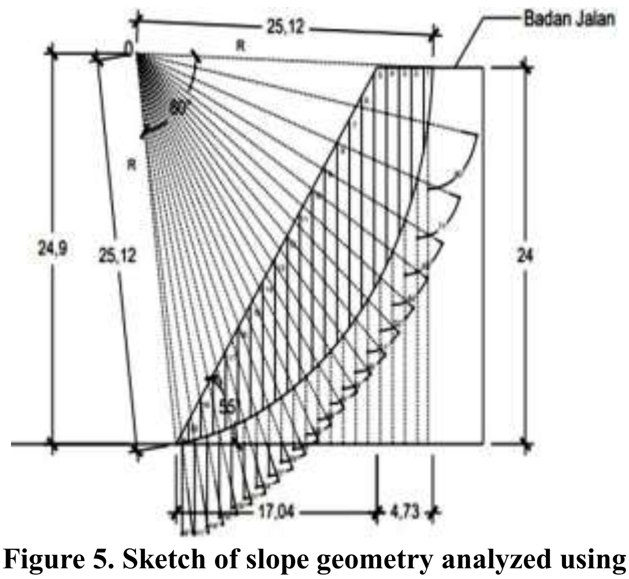

Figure 5. Sketch of slope geometry analyzed using the Fellenius method (55° slope angle)
Source: Developed by the authors (2026)

The analysis results indicate that the original slope was in an unstable condition. The Fellenius method produced a Safety Factor (SF) of 0.48, while the Bishop method yielded a slightly higher value of 0.54. Both values are substantially lower than the minimum SF generally considered acceptable for slope stability, indicating a high probability of slope failure under existing conditions [9], [11].

The difference between the Fellenius and Bishop methods is attributed to the assumptions adopted in each approach. The Fellenius method neglects interslice forces and therefore generally provides conservative *SF* values. In contrast, the Bishop method considers moment equilibrium and partially incorporates interslice force interaction, resulting in slightly higher and more realistic SF estimates [13]. Nevertheless, both methods consistently indicate that the original slope geometry does not possess sufficient shear resistance to withstand the driving forces generated by the steep slope inclination.

The results from the conventional limit equilibrium methods therefore provide an initial indication that the existing slope requires stabilization before further evaluation of the effectiveness of soil compaction is conducted.

3.2. Numerical Analysis of Original Slope Using PLAXIS 3D

To further investigate the mechanical response of the slope, a three-dimensional finite element analysis was conducted using PLAXIS 3D. The numerical model was developed using the Mohr–Coulomb constitutive model and calibrated based on laboratory-derived soil parameters, including unit weight, cohesion, and internal friction angle.

The simulation results revealed a maximum effective stress of 230.4 kN/m² occurring at element 561 (node 215), whereas the minimum effective stress reached −1889 kN/m² at element 512 (node 2483). The occurrence of negative effective stress should be interpreted carefully because it represents localized stress conditions within the numerical model and does not, by itself, constitute direct evidence of tensile cracking or failure. Nevertheless, the stress distribution provides an indication of significant stress redistribution within the slope mass, which is relevant to the assessment of potential instability [15], [16].

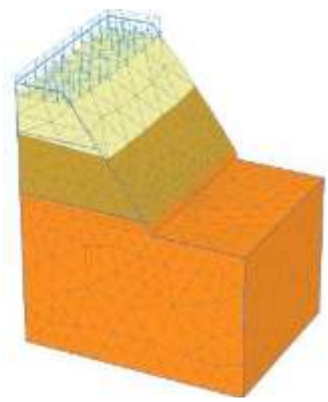

Figure 6. Deformed element mesh of the original slope

Source: Author’s modeling using PLAXIS 3D (2026)

The deformed mesh shown in Figure 6 illustrates the stress concentration and deformation pattern developed within the slope mass. Areas exhibiting high stress concentration are generally associated with potential zones of instability. Finite element analysis can provide additional information regarding stress redistribution and deformation patterns that cannot be directly obtained from conventional limit equilibrium methods [17].

The phi-c reduction analysis showed that the cumulative strength reduction factor (ΣMsf) increased gradually from 0.524 at Step 21 to 0.562 at Step 29. Simultaneously, the maximum principal stress increased from 644.225 kN/m² to 714.844 kN/m². This trend indicates progressive mobilization of soil shear strength as the reduction process proceeded toward failure conditions.

The highest ΣMsf value obtained in the analyzed stages was 0.562. This value was therefore adopted as the PLAXIS 3D Safety Factor (SF) for the original slope condition in the comparative analysis presented in Section 3.8. The SF below unity confirms that the original slope does not have sufficient shear resistance to maintain equilibrium under the analyzed loading and geometric conditions.

Table 2. Slope Safety Factor (SF) of Original Soil

Point	Step	Pmax (kN/m²)	ΣMsf (-)
31	29	714.484	**0.562**
30	28	715.447	0.551
29	27	715.981	0.544
28	26	716.112	0.541
27	25	716.140	0.539
26	24	716.127	0.537
25	23	715.747	0.532
24	22	717.716	0.527
23	21	644.225	0.524

Source: Research results (2026)

The results in Table 1 demonstrate that the original slope has a substantially lower SF than the compacted conditions evaluated subsequently. This provides a quantitative baseline for assessing the improvement achieved through moisture-controlled compaction.

3.3. Effect of Optimum Moisture Content on Slope Stability Using the Bishop Method

Slope stabilization was subsequently evaluated through soil compaction at moisture contents of 14.7%, 19.25%, and 23.8%. The shear strength parameters used in the analysis were obtained from direct shear tests performed on compacted specimens.

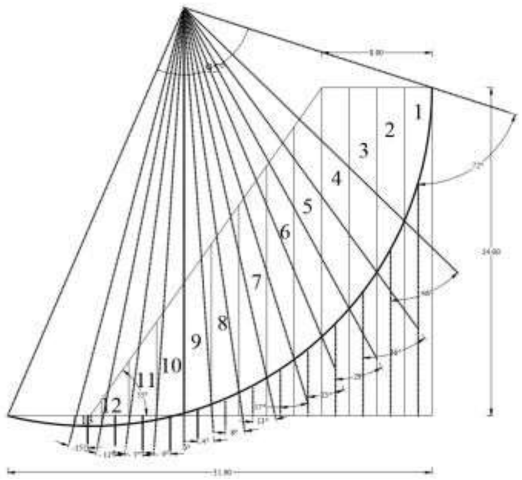

Figure 7. Original slope geometry with 55° inclination used in stability analysis

Source: Research results (2026)

Table 3. Safety Factor (SF) values obtained using the Bishop method

No.	Moisture Content (%)	SF
1	14.7	1.69
2	19.25	1.66
3	23.8	1.59

Source: Research results (2026)

The Bishop analysis demonstrated a substantial increase in slope stability following compaction treatment. Safety factors of 1.69, 1.66, and 1.59 were obtained for moisture contents of 14.7%, 19.25%, and 23.8%, respectively. The results indicate that all compacted conditions satisfy the commonly accepted stability criterion (SF > 1.25), suggesting that compaction significantly improved slope performance.

The highest safety factor was observed at a moisture content of 14.7%, indicating that the dry-side condition produced the highest SF according to the Bishop analysis. However, this result differs from the compaction test, in which the OMC was determined to be 19.25%. Therefore, the moisture content that produces the highest SF in a slope stability analysis should not automatically be interpreted as the OMC for compaction.

The gradual decrease in SF with increasing moisture content may be associated with changes in soil structure and effective stress. As moisture content increases toward and beyond OMC, the influence of water on particle rearrangement, pore occupancy, and shear resistance becomes increasingly important [10], [18], [19].

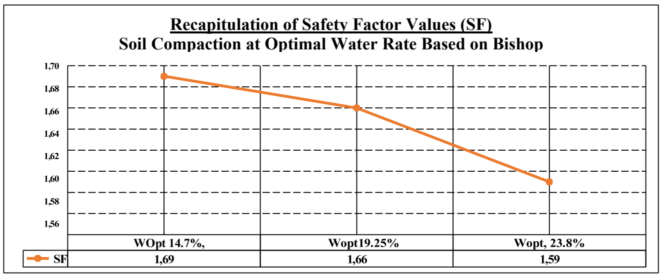

Figure 8. Relationship between optimum moisture content and safety factor based on the Bishop method

Source: Research results (2026)

The Bishop results therefore indicate that the relationship between moisture content and slope stability is not necessarily identical to the relationship between moisture content and maximum dry density. Although 14.7% produced the highest Bishop SF, 19.25% remains the experimentally determined OMC and provides the most favorable condition when the compaction characteristics and results from the other stability methods are considered together.

3.4. Effect of Optimum Moisture Content on Slope Stability Using the Fellenius Method

The Fellenius method produced Safety Factor values of 1.42, 1.51, and 1.43 for moisture contents of 14.7%, 19.25%, and 23.8%, respectively. Similar to the Bishop analysis, all compacted conditions resulted in stable slopes.

Unlike the Bishop method, the Fellenius method identified 19.25% as the condition producing the highest SF. This result corresponds closely with the compaction test results, where the maximum dry density was achieved at an OMC of 19.25%.

Table 3. Safety Factor (SF) values obtained using the Fellenius method

No.	Moisture Content (%)	SF
1	14.7	1.42
2	19.25	1.51
3	23.8	1.43

Source: Research results (2026)

The increase in SF at 19.25% moisture content can be explained by improved particle rearrangement during compaction. At the OMC, water acts as a lubricant that facilitates particle movement and densification while minimizing air voids. Consequently, the soil develops improved interparticle contact and shear resistance [9], [20].

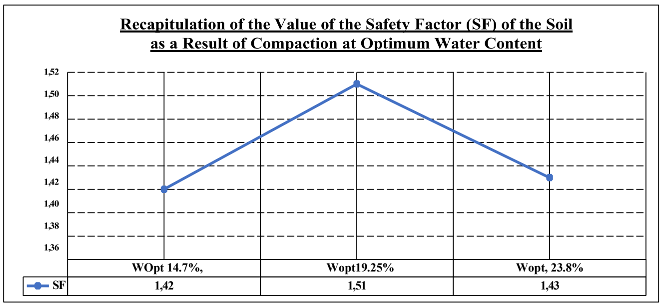

Figure 9. Relationship between optimum moisture content and safety factor based on the Fellenius method

Source: Research results (2026)

These findings suggest that moisture content is a critical parameter controlling the balance between soil density and shear strength. The Fellenius results are particularly consistent with the Proctor test because both identify 19.25% as the most favorable moisture condition.

The difference between the Bishop and Fellenius results also demonstrates that the selected analytical method influences the calculated SF. Nevertheless, both methods indicate that all three compacted conditions provide considerably greater stability than the original slope condition.

3.5. Introduction to PLAXIS 3D Stability Analysis

To complement the limit equilibrium analyses, slope stability was further evaluated using PLAXIS 3D. Finite element analysis offers several advantages over traditional methods because it considers stress redistribution, deformation behavior, and progressive failure mechanisms throughout the soil mass [14]. The numerical simulations incorporated geotechnical parameters obtained from laboratory testing under moisture contents of 14.7%, 19.25%, and 23.8%. The PLAXIS 3D input parameters were assigned for each soil layer based on the laboratory characterization and adopted material model. The model included unit weight, cohesion, internal friction angle, Young's modulus, and Poisson's ratio, while the additional model parameters λ and k* were assigned according to the adopted material model and input data.*

Compared with conventional limit equilibrium approaches, finite element analysis provides a more comprehensive understanding of slope behavior because it simultaneously captures stress concentration, displacement development, and strain localization processes [15], [21].

The PLAXIS 3D results were subsequently analyzed through deformation patterns, effective stress distributions, and Safety Factors obtained from the phi-c reduction method to determine the most effective moisture content condition for slope stabilization.

The input parameters used for the PLAXIS 3D model are summarized in Table 4.

Table 4. Soil Input Parameters Used in PLAXIS 3D

Layer	Soil Type	γUnsat (kN/m³)	γdry (kN/m³)	c (kN/m²)	φ (°)	E (kN/m²)	ν	λ*	k*	Vehicle Load (kPa)
1	Silt	16.29	14.13	12.75	11.96	10,000	0.30	0.619	0.206	12
2	Sandy Clay	17.66	13.15	2.00	11.96	2,000	0.20	0.091	0.036	12
3	Sandy Clay	16.67	10.89	6.17	20.14	2,000	0.20	0.091	0.036	12
4	Sandstone	18.62	14.17	6.27	30.00	60,000	0.35	0.068	0.027	12

Source: Research results (2026)

The use of these parameters enables the numerical model to represent the stratification and mechanical characteristics of the analyzed slope. The vehicle load of 12 kPa was applied consistently in the model to represent the imposed surface loading condition.

3.6. Slope Stability Analysis Using PLAXIS 3D Under Different Optimum Moisture Content Conditions

To further assess slope stability under different compaction conditions, numerical analysis was performed using PLAXIS 3D with the phi-c reduction method. The analysis was conducted at moisture contents of 14.7%, 19.25%, and 23.8% to evaluate deformation behavior and Safety Factor variations of the slope.

3.6.1. Safety Factor Analysis at Optimum Moisture Content of 14.7%

Deformed Mesh Analysis

The compacted soil condition at a moisture content of 14.7% was evaluated using PLAXIS 3D to investigate the deformation response and stability performance of the slope. The deformed mesh visualization, presented in Figure 10, was generated using a magnification factor of 0.5 to clearly illustrate displacement patterns occurring within the slope body.

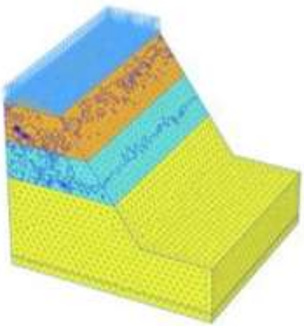

Figure 9. Deformed mesh at optimum moisture content of 14.7%
Source: Author’s modeling using PLAXIS 3D (2026)

The simulation results indicate that deformation is concentrated primarily in the upper and middle sections of the slope, reflecting the zones where gravitational driving forces are dominant. The maximum deformation was recorded at approximately 5.925 m within the critical zone. Although the magnitude of deformation is considerable in the numerical visualization, the deformed mesh does not by itself indicate complete slope collapse. The distribution of deformation should therefore be interpreted together with the calculated SF and failure mechanism.

The observed deformation behavior is strongly influenced by the interaction between slope geometry, self-weight loading, and the increase in soil density resulting from compaction. Finite element analyses indicate that deformation tends to concentrate in zones experiencing stress redistribution before slope failure, reflecting the progressive nature of the failure process [15]. Therefore, deformation contours provide valuable information regarding the potential location of future instability.

Safety Factor Analysis

The Safety Factor obtained from the phi-c reduction analysis reached SF = 1.83, indicating a stable slope condition according to the adopted stability criterion (SF > 1.25) [11].

Table 5. Safety factor results at optimum moisture content of 14.7%

Point	Step	Step [-]	ΣMsf [-]
96	94	94.000	1.827
97	95	95.000	1.828
98	96	96.000	1.828
99	97	97.000	1.828
100	98	98.000	1.829
101	99	99.000	1.829
102	100	100.000	1.829
103	101	101.000	1.830
104	102	102.000	1.830
105	103	103.000	**1.830**

Source: Research results (2026)

The improvement in SF compared with the original slope condition demonstrates the effectiveness of compaction in increasing soil shear resistance. The increase in density reduces void ratio and enhances particle interlocking, thereby increasing the soil's resistance to shear deformation [19].

Although 14.7% produced a higher Bishop SF than the other moisture conditions, the PLAXIS 3D analysis indicates that its SF of 1.83 is lower than the value obtained at 19.25%.

3.6.2. Safety Factor Analysis at Optimum Moisture Content of 19.25%

Deformed Mesh Analysis

The deformation pattern obtained at a moisture content of 19.25% is shown in Figure 11. The finite element simulation employed a deformation magnification factor of 0.1 to capture displacement distribution throughout the slope body.

Figure 11. Deformed mesh at optimum moisture content of 19.25%
Source: Author’s modeling using PLAXIS 3D (2026)

The numerical results indicate a maximum deformation of approximately 16.36 m occurring within the critical zone of the slope. The relatively large numerical displacement should be interpreted in conjunction with the deformation scale and the strength-reduction analysis rather than being considered as direct evidence of field-scale displacement. The deformation pattern remains distributed rather than localized into a distinct failure mechanism within the analyzed stability condition. This indicates that the soil mass is still capable of mobilizing substantial shear resistance before reaching collapse conditions.

The moisture content of 19.25% corresponds closely to the experimentally determined optimum moisture content (OMC) obtained from the Proctor compaction test, where the maximum dry density was achieved. At this condition, water acts as a lubricant that facilitates particle rearrangement during compaction, resulting in a denser soil structure and stronger interparticle contact [9].

Safety Factor Analysis

The phi-c reduction analysis revealed that the cumulative strength reduction factor (ΣMsf) gradually increased until the final analyzed stage. The final Safety Factor obtained from the simulation reached SF = 1.997.

Table 6. Safety factor results at optimum moisture content of 19.25%

Point	Step	Step [-]	ΣMsf [-]
95	93	93.000	1.995
96	94	94.000	1.995
97	95	95.000	1.995
98	96	96.000	1.996
99	97	97.000	1.996
100	98	98.000	1.996
101	99	99.000	1.996
102	100	100.000	1.997
103	101	101.000	1.997
104	102	102.000	**1.997**

Source: Research results (2026)

This value represents the highest Safety Factor obtained in the entire study. The result clearly demonstrates that compaction at the OMC of 19.25% provides the most effective improvement in slope stability according to the PLAXIS 3D analysis. The increase in SF can be attributed to the attainment of maximum dry density and optimum particle arrangement. Under these conditions, the soil exhibits higher shear resistance due to improved frictional resistance and stronger interparticle contact. The OMC generally represents the condition at which the most favorable balance between soil density and strength characteristics is achieved [20], [21].

The SF of 1.997 obtained from PLAXIS 3D is also higher than those obtained at 14.7% and 23.8%, confirming that 19.25% is the most favorable moisture condition among the three numerical scenarios.

3.6.3. Safety Factor Analysis at Optimum Moisture Content of 23.8%

Deformed Mesh Analysis

he deformation pattern for the compacted soil at a moisture content of 23.8% is illustrated in Figure 12.

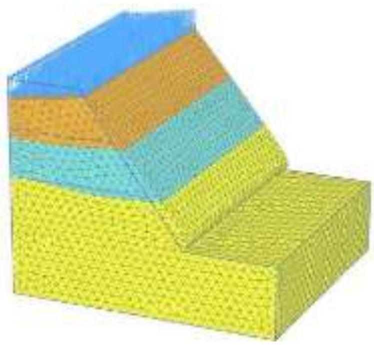

Figure 12. Deformed mesh at optimum moisture content of 23.8%

Source: Author's modeling using PLAXIS 3D (2026)

The simulation results show a maximum deformation of approximately 6.206 m concentrated within the slope body. The displacement contours indicate downward movement from the crest toward the toe of the slope, representing the typical mechanism associated with rotational slope movement.

Although the calculated SF indicates that the slope remains stable according to the adopted criterion, the lower SF compared with the 14.7% and 19.25% conditions indicates reduced stability performance under the wet-side condition. Excess moisture occupies pore spaces and reduces effective stress, thereby limiting the contribution of frictional resistance to slope stability [10].

Safety Factor Analysis

The phi-c reduction procedure reached failure at Step 103, producing a final safety factor of SF = 1.349.

Table 7. Safety factor results at optimum moisture content of 23.8%

Point	Step	Step [-]	ΣMsf [-]
96	94	94.000	1.346
97	95	95.000	1.346
98	96	96.000	1.347
99	97	97.000	1.347
100	98	98.000	1.347
101	99	99.000	1.348
102	100	100.000	1.348
103	101	101.000	1.348
104	102	102.000	1.349
105	103	103.000	**1.349**

Source: Research results (2026)

Although the resulting Safety Factor remains above the adopted minimum stability requirement, it is considerably lower than the values obtained at 14.7% and 19.25%. This reduction confirms that the wet-side moisture condition resulted in lower slope stability than the other two conditions.

When water content exceeds the optimum level, additional water occupies pore spaces and may increase pore-water pressure and reduce effective stress. Consequently, soil shear strength can decrease and the Safety Factor may be reduced [10]. This phenomenon explains the decline in stability observed under the wet-side compaction condition.

3.7. Comparison of Safety Factors Obtained from PLAXIS 3D

The comparison of Safety Factors obtained from PLAXIS 3D simulations under different moisture content conditions is presented in Table 8 and Figure 13.

Table 8. Recapitulation of safety factor values obtained using PLAXIS 3D

No.	Moisture Content (%)	SF
1	14.7	1.83
2	19.25 (OMC)	1.997
3	23.8	1.349

Source: Research results (2026)

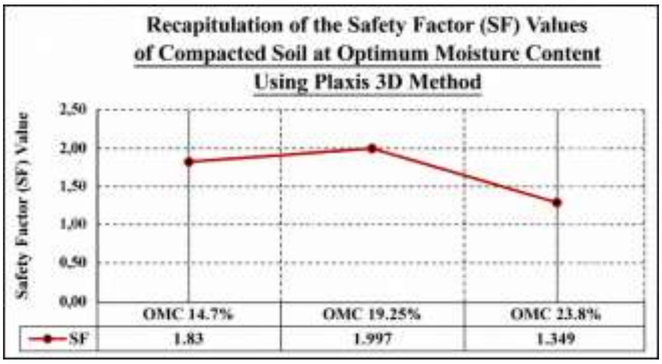

Figure 12. Relationship between optimum moisture content and safety factor obtained using PLAXIS 3D

Source: Research results (2026)

The results clearly indicate that moisture content has a substantial influence on slope stability. The Safety Factor increased from 1.83 at 14.7% moisture content to 1.997 at 19.25%, before decreasing significantly to 1.349 at 23.8%. This trend demonstrates the existence of an optimum moisture condition that maximizes slope stability under the PLAXIS 3D analysis.

The moisture content of 19.25% corresponds to the maximum dry density obtained from the Proctor compaction test and therefore represents the experimentally determined OMC and the most effective compaction condition in the numerical analysis. Soil strength and slope resistance are significantly improved when compaction is performed at or near the optimum moisture content, highlighting the importance of proper moisture control in geotechnical engineering applications [17], [19].

The PLAXIS 3D results provide stronger evidence for selecting 19.25% as the recommended moisture content because this condition simultaneously corresponds to the OMC obtained from the laboratory compaction test and produces the highest numerical SF of 1.997.

3.8. Comparative Analysis of Fellenius, Bishop, and PLAXIS 3D Methods

The comparison between the Fellenius, Bishop, and PLAXIS 3D methods is presented in Table 9 and Figure 14.

Table 8. Comparison of safety factor values obtained from different analytical methods

No.	Method and Condition	SF
1	Fellenius – Original soil, 55°	0.480
2	Bishop – Original soil, 55°	0.540
3	PLAXIS 3D – Original soil, 55°	0.562
5	Fellenius – 19.25% moisture content	1.510
6	Bishop – 19.25% moisture content	1.660
7	PLAXIS 3D – 19.25% moisture content	1.997

Source: Research results (2026)

The original slope condition produced Safety Factor values of 0.480, 0.540, and 0.562 using the Fellenius, Bishop, and PLAXIS 3D methods, respectively. All values were below unity, confirming that the original slope was unstable under the analyzed conditions.

Following compaction at the OMC of 19.25%, the Safety Factors increased substantially to 1.510, 1.660, and 1.997 for the Fellenius, Bishop, and PLAXIS 3D methods, respectively.

Compared with the original condition, the corresponding increases in SF were approximately 214.6% for the Fellenius method, 207.4% for the Bishop method, and 255.3% for PLAXIS 3D. These results demonstrate the substantial improvement in slope stability following compaction at the OMC.

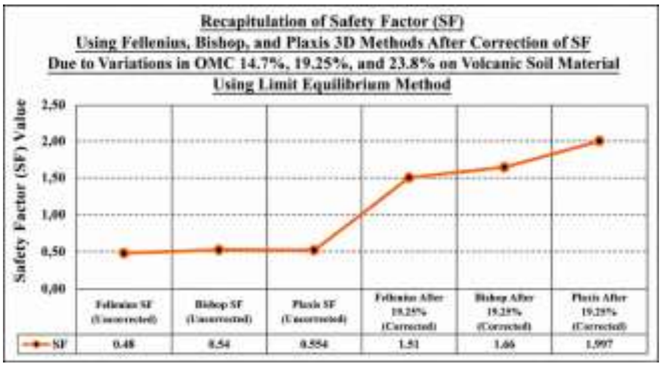

Figure 13. Comparison of safety factor values obtained using Fellenius, Bishop, and PLAXIS 3D methods

Source: Research results (2026)

The consistently higher Safety Factor produced by PLAXIS 3D can be attributed to the capability of finite element analysis to consider stress redistribution, progressive failure mechanisms, strain development, and the three-dimensional stress state within the soil mass. In contrast, the Fellenius and Bishop methods are based on limit equilibrium assumptions and primarily evaluate the balance between driving and resisting forces without explicitly modeling the complete deformation and stress redistribution process [14], [15].

The differences among the three methods should therefore not be interpreted as indicating that one method is universally superior to the others. Rather, they reflect differences in the theoretical assumptions and numerical formulations used to evaluate slope stability.

Overall, the results demonstrate that compaction significantly improves slope stability and that 19.25%, corresponding to the experimentally determined OMC, provides the most favorable overall condition when the Proctor compaction results, Fellenius analysis, and PLAXIS 3D results are considered together.

An important observation is that the Bishop method produced its highest SF at 14.7%, whereas the Fellenius and PLAXIS 3D analyses produced their highest SF at 19.25%. Therefore, the selection of 19.25% as the recommended compaction moisture content is based not solely on the highest value from one analytical method, but on the consistency between the laboratory-determined OMC and the results of the Fellenius and PLAXIS 3D analyses.

The PLAXIS 3D analysis further confirms the effectiveness of moisture-controlled compaction, with the SF increasing from 0.562 for the original slope to 1.997 at 19.25% moisture content. These findings indicate that controlling the moisture content during compaction is an important factor in improving the stability of steep slopes composed of the investigated soil.

4. Conclusion

Based on the results of laboratory tests, limit equilibrium analyses using the Fellenius and Bishop methods, and numerical modeling using PLAXIS 3D, it can be concluded that:

1) The compaction characteristics of tropical volcanic soils are greatly influenced by the optimum moisture content (OMC). The Proctor test showed that the maximum dry density ($\gamma d,max$) of 1.614 g/cm³ was obtained at an OMC of 19.25%. In comparison, the dry densities obtained at moisture contents of 14.7% and 23.8% were lower. Thus, 19.25% represents the experimentally determined optimum condition for achieving maximum dry density.

2) Moisture content variation influences the Safety Factor (SF) of the analyzed slope. Based on the Fellenius method, the SF values were 1.42, 1.51, and 1.43 at moisture contents of 14.7%, 19.25%, and 23.8%, respectively. Meanwhile, the Bishop method yielded SF values of 1.69, 1.66, and 1.59, respectively. All compacted conditions produced SF values above 1.25, indicating a substantial improvement in stability compared with the original slope condition.

3) Numerical analysis using PLAXIS 3D showed that the OMC of 19.25% produced the highest SF among the three moisture conditions. The SF increased from 1.83 at 14.7% moisture content to 1.997 at 19.25%, before decreasing to 1.349 at 23.8%. The maximum SF of 1.997 indicates that 19.25% is the most effective moisture condition for improving slope stability in the PLAXIS 3D analysis.

4) Compaction at the OMC substantially improved slope stability compared with the original soil condition. For the original 55° slope, the SF values were 0.48 using the Fellenius method, 0.54 using the Bishop method, and 0.562 using PLAXIS 3D, indicating an unstable condition. After compaction at 19.25% moisture content, the SF increased to 1.51, 1.66, and 1.997 for the Fellenius, Bishop, and PLAXIS 3D methods, respectively. These results demonstrate that moisture-controlled compaction can substantially increase the resistance of the slope against failure.

5) PLAXIS 3D provided additional information on slope behavior that could not be obtained directly from the limit equilibrium methods, particularly with respect to stress redistribution, deformation patterns, and the development of potential failure zones. The higher SF obtained from PLAXIS 3D should, however, be interpreted in relation to the different assumptions and formulations of each analytical method rather than as evidence that the method is universally superior.

6) Overall, controlling moisture content during compaction is an important factor in improving the stability of steep tropical volcanic soil slopes. The results indicate that an OMC of 19.25% provides the most favorable overall compaction condition, as it corresponds to the maximum dry density obtained from the Proctor test and produces the highest SF in the PLAXIS 3D and Fellenius analyses. Therefore, compaction at 19.25% moisture content can be considered an effective slope stabilization alternative for the analyzed road slope in Aek Godang Arbaan Village, Onanganjang District, Humbang Hasundutan Regency, North Sumatra.

Declarations

Author Contributions

Conceptualization, S.M.T.D. and A.P.I.; methodology, S.M.T.D.; software, S.M.T.D.; validation, S.M.T.D., A.P.I., A.W., and O.F.J.; formal analysis, S.M.T.D.; investigation, S.M.T.D.; resources, A.P.I.; data curation, S.M.T.D.; writing—original draft preparation, S.M.T.D.; writing—review and editing, A.P.I., A.W., and O.F.J.; visualization, S.M.T.D.; supervision, A.P.I. and O.F.J.; project administration, A.P.I.; funding acquisition, A.P.I. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

Data presented in this study are available on request from the corresponding author. The data are not publicly available due to institutional privacy restrictions.

Funding

This research was self-funded by the authors. No external funding was received for the conduct and publication of this study.

Acknowledgements
The authors would like to express their sincere gratitude to Tarumanegara University and Pelita Harapan University for the academic support provided during this research.

Institutional Review Board Statement
Not applicable.

Informed Consent Statement
Not applicable.

Conflicts of Interest
The authors declare no conflict of interest regarding the publication of this manuscript. All ethical considerations, including plagiarism, informed consent, data integrity, and publication ethics, have been fully observed.

References

[1] S. Cuomo, A. Di Perna, and M. Martinelli, “Modelling the Spatio-Temporal Evolution of a Rainfall-Induced Retrogressive Landslide in an Unsaturated Slope,” Eng. Geol., vol. 292, p. 106263, 2021, doi: 10.1016/j.enggeo.2021.106263.
[2] Y. Zeng et al., “A Case Study on Soil Slope Landslide Failure and Parameter Analysis of Influencing Factors for Safety Factor Based on Strength Reduction Method and Orthogonal Experimental Design,” PLoS One, vol. 19, no. 5, p. e0303623, 2024, doi: 10.1371/journal.pone.0303623.
[3] T. Kadliček and D. Mašin, “Surface Layer Method for Analysis of Slope Stability Using Finite Elements,” Comput. Geotech., vol. 163, p. 105513, 2023, doi: 10.1016/j.compgeo.2023.105513.
[4] T. Mebrahtu, T. Heinze, S. Wohnlich, and M. Alber, “Slope Stability Analysis of Deep-Seated Landslides Using Limit Equilibrium and Finite Element Methods in Debre Sina Area, Ethiopia,” Bulletin of Engineering Geology and the Environment, vol. 81, p. 354, 2022, doi: 10.1007/s10064-022-02729-6.
[5] O. F. Usluogullari, A. Temugan, and E. S. Duman, “Comparison of Slope Stabilization Methods by Three-Dimensional Finite Element Analysis,” Natural Hazards, vol. 80, no. 2, pp. 1223–1245, 2016, doi: 10.1007/s11069-015-2013-3.
[6] B. Mehdi, A. H. Abderrahmane, and G. Ismahene, “Modeling, Reinforcement, and Assessment of the Landslide in Ben Djerrah (Guelma, Algeria) Using the Finite Element Method,” Studies in Engineering and Exact Sciences, vol. 5, no. 1, p. 20240013, 2024, doi: 10.38444/2395-7996.2024.0013.
[7] M. Misriani et al., “Influence of Slope Geometry Variations on Factor of Safety: Comparative Analysis of Limit Equilibrium and Finite Element Method,” in E3S Web of Conferences, 2025, p. 5001. doi: 10.1051/e3sconf/202553205001.
[8] ASTM International, “ASTM D698-21: Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort,” 2021.
[9] B. M. Das and K. Sobhan, Principles of Geotechnical Engineering, 9th ed. Cengage Learning, 2018.
[10] M. Budhu, Soil Mechanics and Foundations, 3rd ed. John Wiley and Sons, 2015.
[11] J. M. Duncan, S. G. Wright, and T. L. Brandon, Soil Strength and Slope Stability. John Wiley and Sons, 2014.
[12] W. Fellenius, “Calculation of the Stability of Earth Dams,” in Proceedings of the 2nd Congress on Large Dams, 1936, pp. 445–462.
[13] A. W. Bishop, “The Use of the Slip Circle in the Stability Analysis of Slopes,” Geotechnique, vol. 5, no. 1, pp. 7–17, 1955.
[14] R. B. J. Brinkgreve, S. Kumarswamy, W. M. Swolfs, F. Foria, D. Waterman, and A. Chesaru, “PLAXIS 3D Reference Manual,” 2023.
[15] D. V Griffiths and P. A. Lane, “Slope Stability Analysis by Finite Elements,” Geotechnique, vol. 49, no. 3, pp. 387–403, 1999.
[16] Y. M. Cheng, T. Lansivaara, and W. B. Wei, “Recent Advances in Slope Stability Assessment Using Numerical Methods,” 2022.
[17] X. Luo, D. Li, and J. Zhang, “Finite Element Evaluation of Stress Concentration and Failure Mechanisms in Steep Slopes,” Eng. Geol., vol. 293, p. 106305, 2021.
[18] D. G. Fredlund and H. Rahardjo, Soil Mechanics for Unsaturated Soils. John Wiley and Sons, 1993.
[19] Y. Zhang, H. Wang, X. Chen, and Z. Liu, “Effect of Moisture Content on Compaction Characteristics and Slope Stability of Volcanic Residual Soils,” Journal of Rock Mechanics and Geotechnical Engineering, vol. 15, no. 6, pp. 1543–1558, 2023.
[20] T. W. Lambe and R. V Whitman, Soil Mechanics. John Wiley and Sons, 1969.
[21] Y. M. Cheng, T. Lansivaara, and W. B. Wei, “Numerical Methods and Slope Stability Assessment: Recent Advances and Applications,” Comput. Geotech., vol. 146, p. 104700, 2022.

参考文献

[1] S. Cuomo, A. Di Perna, and M. Martinelli, “非饱和边坡中降雨诱发后退式滑坡时空演化建模,” *Engineering Geology*, vol. 292, p. 106263, 2021, doi: 10.1016/j.enggeo.2021.106263.
[2] Y. Zeng et al., “基于强度折减法和正交试验设计的土质边坡滑坡破坏案例及安全系数影响因素参数分析,” *PLoS One*, vol. 19, no. 5, p. e0303623, 2024, doi: 10.1371/journal.pone.0303623.

[3] T. Kadliček and D. Mašin, “采用有限元法分析边坡稳定性的表层法,” *Computers and Geotechnics*, vol. 163, p. 105513, 2023, doi: 10.1016/j.compgeo.2023.105513.
[4] T. Mebrahtu, T. Heinze, S. Wohnlich, and M. Alber, “采用极限平衡法和有限元法分析埃塞俄比亚Debre Sina地区深层滑坡的稳定性,” *Bulletin of Engineering Geology and the Environment*, vol. 81, p. 354, 2022, doi: 10.1007/s10064-022-02729-6.
[5] O. F. Usluogullari, A. Temugan, and E. S. Duman, “基于三维有限元分析的边坡加固方法比较,” *Natural Hazards*, vol. 80, no. 2, pp. 1223–1245, 2016, doi: 10.1007/s11069-015-2013-3.
[6] B. Mehdi, A. H. Abderrahmane, and G. Ismahene, “采用有限元法对阿尔及利亚盖尔马省Ben Djerrah滑坡进行建模、加固与评估,” *Studies in Engineering and Exact Sciences*, vol. 5, no. 1, p. 20240013, 2024, doi: 10.38444/2395-7996.2024.0013.
[7] M. Misriani et al., “边坡几何形态变化对安全系数的影响：极限平衡法与有限元法的比较分析,” in *E3S Web of Conferences*, 2025, p. 5001. doi: 10.1051/e3sconf/202553205001.
[8] ASTM International, “ASTM D698-21：采用标准击实功测定土壤实验室压实特性的标准试验方法,” 2021.
[9] B. M. Das and K. Sobhan, 《岩土工程原理》, 第9版. Cengage Learning, 2018.
[10] M. Budhu, 《土力学与地基基础》, 第3版. John Wiley and Sons, 2015.
[11] J. M. Duncan, S. G. Wright, and T. L. Brandon, 《土体强度与边坡稳定性》. John Wiley and Sons, 2014.
[12] W. Fellenius, “土坝稳定性计算,” in *Proceedings of the 2nd Congress on Large Dams*, 1936, pp. 445–462.
[13] A. W. Bishop, “滑动圆弧在边坡稳定性分析中的应用,” *Géotechnique*, vol. 5, no. 1, pp. 7–17, 1955.
[14] R. B. J. Brinkgreve, S. Kumarswamy, W. M. Swolfs, F. Foria, D. Waterman, and A. Chesaru, 《PLAXIS 3D参考手册》, 2023.
[15] D. V. Griffiths and P. A. Lane, “基于有限元法的边坡稳定性分析,” *Géotechnique*, vol. 49, no. 3, pp. 387–403, 1999.
[16] Y. M. Cheng, T. Lansivaara, and W. B. Wei, “采用数值方法进行边坡稳定性评估的最新进展,” 2022.
[17] X. Luo, D. Li, and J. Zhang, “陡坡应力集中与破坏机制的有限元评估,” *Engineering Geology*, vol. 293, p. 106305, 2021.
[18] D. G. Fredlund and H. Rahardjo, 《非饱和土力学》. John Wiley and Sons, 1993.
[19] Y. Zhang, H. Wang, X. Chen, and Z. Liu, “含水率对火山残积土压实特性及边坡稳定性的影响,” *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 15, no. 6, pp. 1543–1558, 2023.
[20] T. W. Lambe and R. V. Whitman, 《土力学》. John Wiley and Sons, 1969.
[21] Y. M. Cheng, T. Lansivaara, and W. B. Wei, “数值方法与边坡稳定性评估：最新进展及应用,” *Computers and Geotechnics*, vol. 146, p. 104700, 2022.

Manuscript Information
Word count: 9,091 words (excluding references).
Peer-Review Record

Fast-track status: Not fast-tracked.
First-round reviews received: 3 reports.
Revision cycles completed: 3 rounds.
Final version submitted: August 31, 2026