Interdisciplinary Social Studies
P-ISSN: 2808-0467 Volume 5
E-ISSN: 2808-5051 Number 1, December 2025

The Effect of Cracked Soil on Slope Stability on the Karo Regency Boundary Road – Panji STA 26+000, North Sumatra Province

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ABSTRACT

The landslide incident on the Karo Regency Boundary Road – Panji STA 26+000, North Sumatera Province, showed a decrease in slope stability, as indicated by a safety factor (SF) value of less than 1.00. This study aims to analyze the causes of slope instability influenced by the cracked soil phenomenon and heavy rain. The slope stability analysis was conducted using Geo5 software based on the limit equilibrium method with Bishop's simplified method. The simulation evaluated two scenarios: original soil conditions and cracked soil conditions with heavy rainfall infiltration. Geotechnical parameters were derived from Standard Penetration Test (SPT) data, while cracked soil parameters were determined based on residual shear strength correlations with the soil plasticity index. The simulation results using the Geo5 application under original soil conditions showed a safety factor (SF) value of 2.10, indicating that the slope was in a safe and stable condition. However, after incorporating the cracked soil parameters ($c = 0$ kN/m², $\phi = 19°$) and heavy rain intensity into the Geo5 application, the analysis results showed a drastic decrease in the safety factor (SF) value to 0.93, indicating that the slope was in an unsafe condition prone to landslide. The cracked soil phenomenon increased the infiltration path of rainwater, which then accelerated the rise in pore water pressure and weakened the soil's shear strength, causing the landslide.

Keywords:
cracked soil; safety factors; slope stability

INTRODUCTION

Slope is a piece of land or rock that has a certain incline and has the potential to experience landslides if it is in an unstable condition (Liu et al., 2025; Ma et al., 2025). Landslides often occur in the rainy season due to increased pore water pressure, which reduces the shear strength of the soil, causing damage to infrastructure, economic disruptions, and threats to public safety (Alok et al., 2024; Mochtar, 2017; Pham et al., 2024). Although conventional slope stability analysis suggests that a slope can be in a safe condition based on the parameters of the original soil, the reality is that many landslides occur on slopes that were previously declared stable based on soil investigations and traditional calculations (Nasional, 2017). This condition indicates that other factors affect slope stability, especially during heavy rains (Abdulnafaa et al., 2025; Pramana et al., 2022; Sebayang et al., 2022).

Recent studies have demonstrated that soil cracking significantly influences slope failure mechanisms. Research by Tang et al. (2018) showed that desiccation cracks can reduce slope stability by creating preferential flow paths for water infiltration. Similarly, Chang (2020) found that cracked soil mass exhibits substantially lower shear strength compared to intact soil due to the loss of apparent cohesion. Furthermore, Lakshmikantha et al. (2012) emphasized that crack networks in expansive soils can accelerate wetting front advancement, leading to rapid pore pressure buildup.

One of the important factors often overlooked in geotechnical analysis is the existence of cracked soil or soil that has experienced internal cracks. Based on the philosophy of "cracked soils" developed by Mochtar (2017), most soils on slopes have in fact experienced the formation of crack fields due to geological processes, weathering, changes in tension, or a history of soil movement in the past. This phenomenon has been extensively documented in tropical regions where wet-dry cycles cause repeated expansion and contraction of clayey soils (Fredlund et al., 2012). These cracks are not detected through standard investigations such as drill logs because they are very thin in size, only a few millimeters to centimeters (Dhanai et al., 2025). The detection limitation of conventional investigation methods has been acknowledged by several researchers, who suggest that geophysical methods or direct observation through test pits may be necessary to identify subsurface crack patterns (Dhanai et al., 2022; Xu et al., 2018).

The presence of cracks makes it easy for rainwater to enter the soil, and when rain intensity is high, the discharge of incoming water exceeds that which drains out, so the cracks become fully filled and cause an increase in pore water pressure (pore-water pressure buildup) (Harijan, 2022; Hoyos et al., 2025). Studies have shown that infiltration rates through cracked soil can be 10 to 100 times higher than through the intact soil matrix. This accelerated infiltration leads to rapid saturation of the crack planes and adjacent soil mass. The pressure of the water trapped inside these cracks significantly decreases the shear strength of the soil, making the crack plane behave like water-saturated sand (behaving like sand), and causes the slope to lose its stability suddenly (Huang et al., 2023; Lin et al., 2025; Sun et al., 2025). This behavior is consistent with the concept of residual shear strength, where pre-existing failure surfaces or crack planes exhibit significantly lower friction angles and near-zero cohesion (Hu et al., 2025).

The mechanism of rainfall-induced landslides in cracked soil has been investigated through both experimental and numerical approaches. Yao et al. (2021) conducted flume tests demonstrating that pre-existing cracks reduced the critical rainfall threshold for slope failure by approximately 40%. Meanwhile, numerical modeling by Sorbino & Nicotera (2013) revealed that crack infilling with water creates a perched water table effect, dramatically increasing pore pressures in shallow soil layers. Additionally, field monitoring studies have confirmed that slopes with extensive crack networks experience more frequent and rapid failure during intense rainfall events (Toll et al., 2011; Zhang et al., 2016).

This explains the many landslides that occur even though the results of soil analysis show a high safety factor. Therefore, a study that specifically evaluates the influence of cracked soil on slope stability is needed, especially in heavy rain conditions. This research focuses on the analysis of slope behavior by considering the internal cracks of the soil as well as changes in safety factor values that occur due to the influence of cracked soil, as examined in the case study. The results of the study are expected to provide a more accurate understanding of the mechanism of landslides and become the basis for improving slope stability analysis methods so that they are more in line with actual soil conditions in the field.

METHOD

This study uses a quantitative approach by utilizing secondary data obtained from related agencies and literature studies. Data collection is focused on the three main components required for numerical simulation on Geo5 software, namely geotechnical data, slope geometry data, and hydrological data.

Geotechnical Data Acquisition and Parameter Determination

Geotechnical data was obtained from the soil investigation report in the form of Standard Penetration Test (SPT) data at the nearest drilling point to the landslide site (STA 26+000). These N-SPT data were then correlated using an empirical approach to obtain the physical and mechanical parameters of the original soil, including soil content weight (γ), cohesion (c), and deep shear angle (ϕ). This parameter is used as a material input for the condition of the subsoil (intak soil).

For the cracked soil modeling, the parameters were modified based on the cracked soil philosophy (Mochtar, 2017) and residual shear strength theory. The key assumptions for cracked soil parameters include: (1) complete loss of cohesion (c = 0 kN/m²) due to the separation of soil particles along crack planes, which is consistent with residual strength conditions; (2) reduction of friction angle to residual values determined from the correlation between Plasticity Index (PI) and residual friction angle as proposed by Stark & Eid (1994); and (3) full saturation of crack planes during heavy rainfall, resulting in hydrostatic pressure within the cracks. The residual friction angle was obtained by plotting the soil's Plasticity Index (PI = 29.79%) onto the empirical correlation curve between PI and residual angle of shearing resistance (ϕ_r), yielding $\phi_r = 19°$. This approach has been validated by numerous researchers for clayey soils experiencing shear displacement along pre-existing failure surfaces or crack planes.

Slope Geometry Modeling

Slope geometry data is obtained from the document *Detailed Engineering Design* (DED) Karo Regency Boundary Road section – Panji. This data is in the form of a cross-section image on STA 26+000 which is used to model the stratigraphy of the soil layer and slope slope with precision in 2D modeling. The geometric model was constructed in Geo5 software by digitizing the cross-sectional profile, including slope angle, layer thicknesses, and groundwater table position. The slope configuration consists of multiple soil layers with distinct geotechnical properties, accurately representing the field stratigraphy. The cracked soil layer was modeled as a distinct zone in the upper 2-3 meters of the slope surface, where crack formation is most prevalent due to weathering and wet-dry cycles.

Hydrological Data and Rainfall Infiltration Modeling

Maximum daily rainfall data is collected from the nearest rainfall measuring station for the time period when the landslide occurred. This data serves to validate the assumption of extreme water infiltration that triggers the mechanism *cracked soil*, where the soil crack is assumed to be fully filled with rainwater, triggering an increase in pore-water pressure build-up. The rainfall intensity during the landslide event was compared with historical rainfall data to confirm that the event represented an extreme precipitation scenario. The infiltration analysis assumed that cracks act as preferential flow paths, allowing rapid water penetration to depth. The hydrostatic pressure within fully saturated cracks was calculated based on the water column height and applied as an external load in the Geo5 model. This approach is consistent with the methodology employed in rainfall-induced landslide studies.

Numerical Analysis Using Geo5 Software

The slope stability analysis was performed using Geo5 software, which implements the limit equilibrium method (LEM) with various slice methods including Bishop's simplified method, Janbu's method, and Spencer's method. For this study, Bishop's simplified method was selected as it provides reliable results for circular failure surfaces and is widely accepted in geotechnical practice (Duncan, 1996). The analysis procedure involved: (1) creating the slope geometry model with accurate layer boundaries; (2) assigning material properties for intact soil conditions based on SPT correlations; (3) performing stability analysis to obtain the safety factor under original conditions; (4) modifying the surface layer parameters to represent cracked soil conditions; (5) applying hydrostatic pressure loads due to water-filled cracks; and (6) re-running the stability analysis to assess the cracked soil scenario. The factor of safety (FS) was calculated as the ratio of resisting forces to driving forces along the critical slip surface. Multiple potential failure surfaces were evaluated, and the minimum safety factor was reported.

Model Validation

The validity of the numerical model was assessed through several approaches: (1) comparison of predicted failure mode with observed field conditions; (2) verification that the critical slip surface in the cracked soil scenario matches the actual landslide scarp geometry; and (3) sensitivity analysis to evaluate the influence of parameter variations on safety factor results. The model's ability to reproduce the observed failure when cracked soil parameters are applied provides confidence in the adopted methodology.

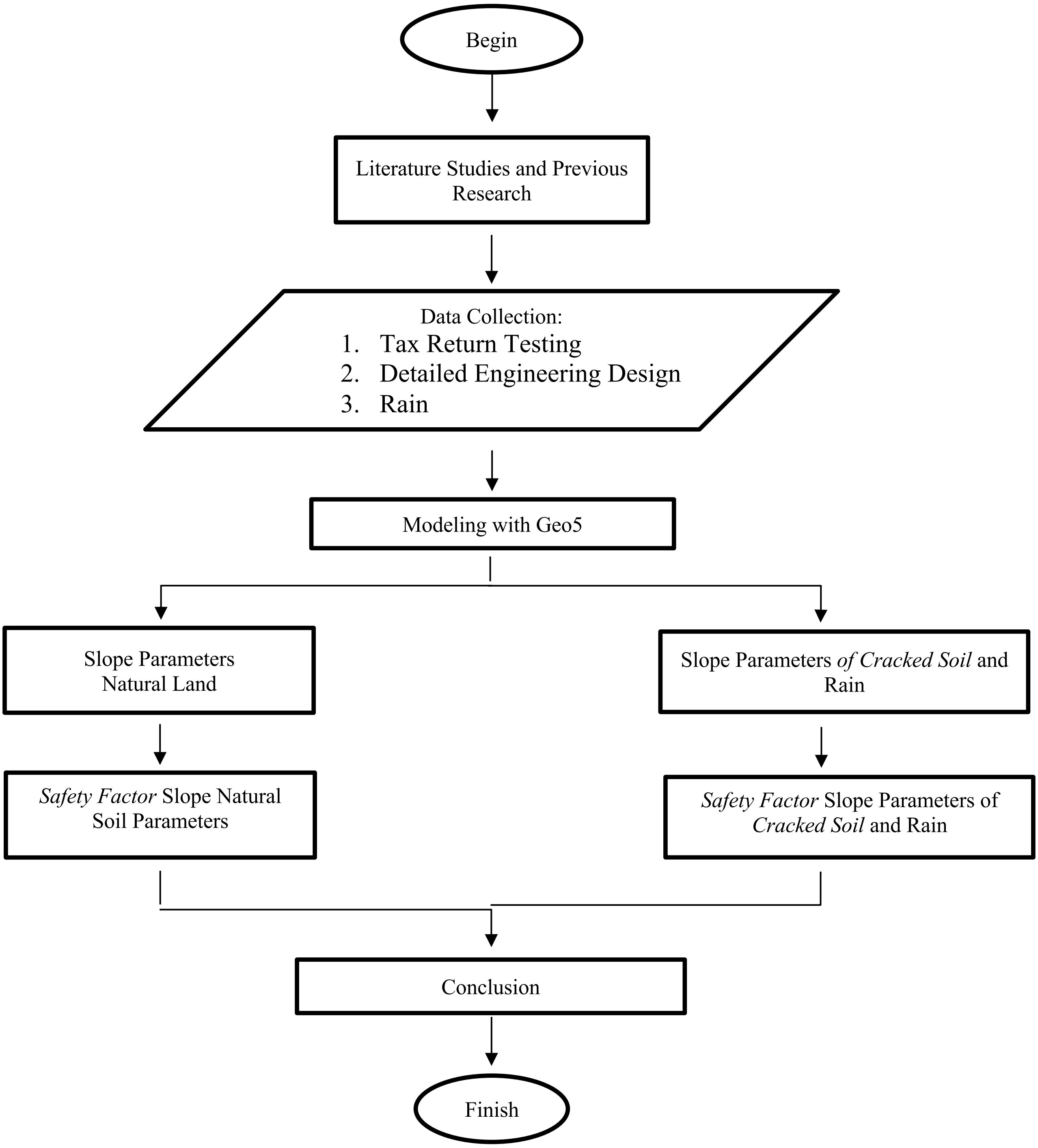

Figure 1. Data Collection Flowchart

RESULTS AND DISCUSSION

Slope stability analysis on native soil conditions was carried out by modeling slope geometry using native soil parameters based on field soil survey data. The analysis was performed using Geo5 auxiliary software based on the limit equilibrium method with the Bishop slice approach. Based on the results of the calculation, the value of the safety factor slope of 2.10. Referring to the SNI 8460:2017 standard concerning Geotechnical Design

Requirements, the SF value of > 1.50 is categorized as a stable and safe slope. This indicates that theoretically, with the existing geometry and load, the slope should have a holding force far beyond the drive force, so that it does not have the potential for landslides under normal conditions (without the influence of cracks).

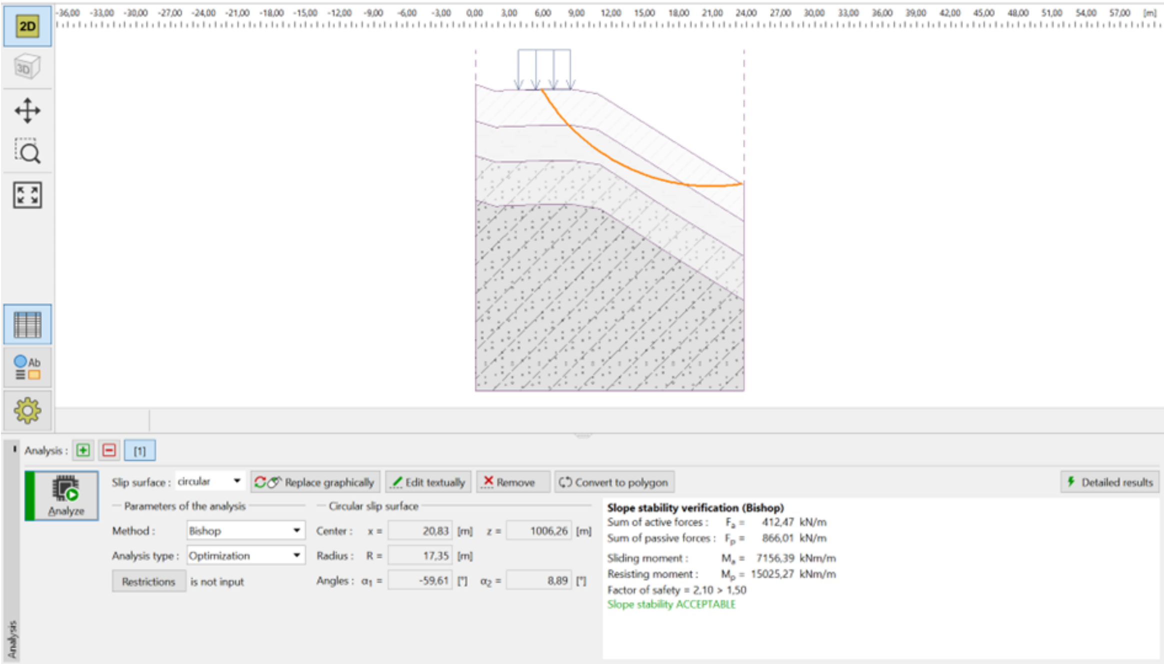

Figure 2. *The safety factor* of the slope of the original soil parameters using the Geo5 application is 2.10

Analysis of slope stability due to influence cracked soil and rain is carried out by simulating critical conditions where heavy rain occurs that triggers the phenomenon cracked soil on the soil surface layer (Layer 1). In this scenario, the soil shear strength parameter is modified to represent the behavior of the soil on the water-filled crack plane, with the following conditions:

- Cohesion (c): Reduced to 0 kN/m^2. This assumption is based on the characteristics of soil cracks that lose adhesion between grains when separated and saturated with water.
- Deep Shear Angle (ϕ): Lowered to 19°. The determination of this value is based on the empirical correlation between the soil Plasticity Index (IP) and the residual angle of shearing resistance (ϕ). With a soil IP value of 29.79%, the residual shear angle value of 19°

After parameter c = 0 kN/m^2 and ϕ = 19o and hydrostatic loads due to rain were applied to the Geo5 model, the results of the analysis showed a drastic decrease in slope stability. Value safety factor (sf) plummeted from 2.10 to 0.93.

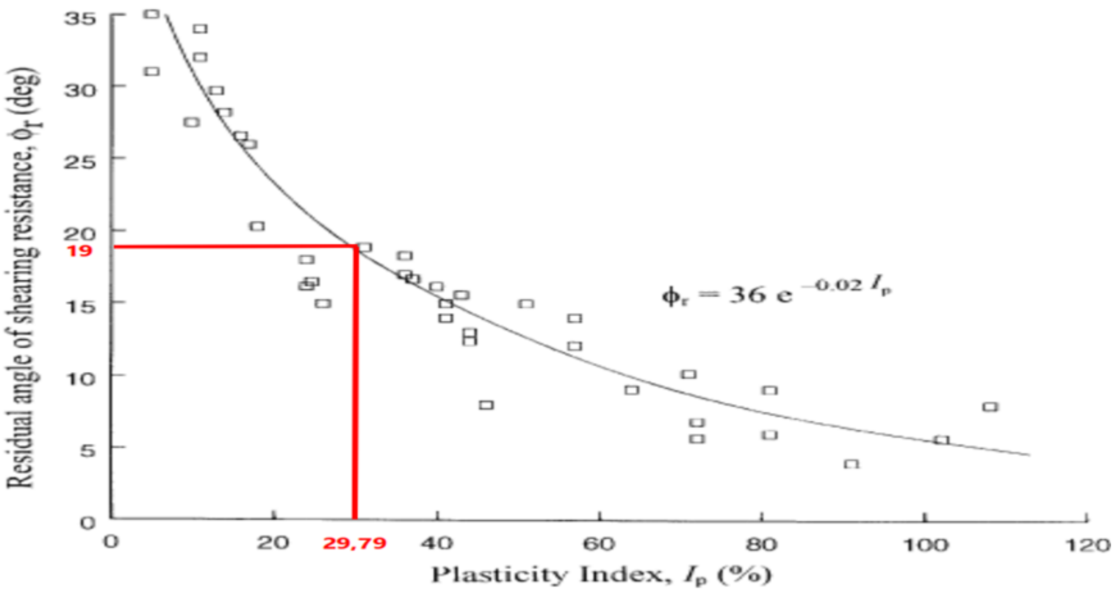

Figure 3. The relationship between the angle of deep shear (ϕ) and the plasticity of the soil

The determination of this parameter assumes that the soil in the crack plane loses the tensile force between the grains and behaves like sand (behaving like sand), with the following details:

1. Cohesion (c): The cohesion value of the cracked soil layer is determined at 0 kN/m2
2. Deep Shear Angle (ϕ): The value of the deep shear angle is determined using an empirical correlation approach based on soil plasticity characteristics. Referring to the relationship curve between the residual angle of shearing resistance (ϕ) and the Plasticity Index (Ip), the value of ϕ is determined based on the original soil data. It is known that the soil at the study location has a Plasticity Index (Ip) value of 29.79%. By plotting the value of Ip into a correlation graph, a deep shear angle value (ϕ) of 19° is obtained (Sun et al., 2025).

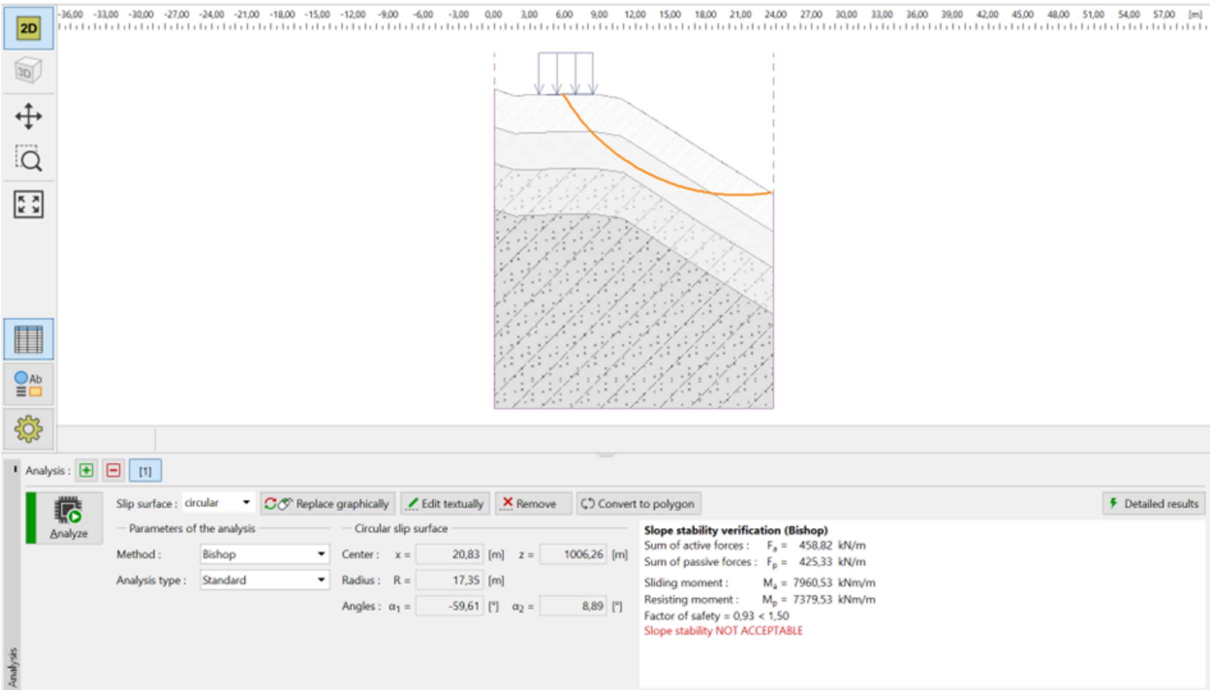

Figure 4. *Slope Safety Factor* Cracked *Soil* and Rain Parameters Using Geo5 Application Is 0.93

CONCLUSION

The analysis revealed that under original soil conditions, the slope exhibited a safety factor (SF) of 2.10, exceeding the SNI 8460:2017 safe threshold of 1.50 and confirming geometric and structural stability against landslides. However, incorporating cracked soil parameters in the surface layer—reducing cohesion to $c = 0$kN/m² and friction angle to $\phi = 19°$based on the plasticity index, alongside hydrostatic loads from heavy rain—dropped the SF sharply to 0.93, indicating critical instability and collapse. This confirms that landslides at the site stemmed not from inherent soil weakness, but from cracked soil infiltrated by extreme rainwater, which elevates pore-water pressure, eliminates cohesion, and induces sand-like behavior. For future research, integrating advanced geophysical imaging (e.g., ground-penetrating radar) with real-time rainfall monitoring could refine crack detection and predictive modeling for proactive slope reinforcement in tropical regions.

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