The Identification of Slope Failure Using Cracked-Soil Approach and Groundwater Level (Case Study : Tator – Enrekang Road Section, KM 227+700)

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ABSTRACT

Slope failures in tropical regions are commonly associated with groundwater fluctuations, however, field observation indicated that subsurface cracking may play a more dominant role in certain cases. This study investigates slope stability along Kab. Tator – Enrekang road section at km 227+700 using numerical analysis to evaluate the effect of groundwater rise and subsurface cracking on slope failure mechanism. Slope stability analysis was performed using the Limit Equilibrium Method (LEM) with aid of Geo5 software under three conditions including: (1) the existing condition; (2) a fully saturated condition; and (3) a cracked soil approach condition. The results show that the existing slope condition yields a factor of safety (FS) of = 2.45 , while the fully saturated condition results in a reduced FS of 2.16, indicating that groundwater rise alone does not trigger failure. In contrast, the cracked soil scenario produces a significant reduction in stability, with an FS of 0.40, classifying the slope as unstable. These findings demonstrate that the surface cracking has a more pronounced impact on slope instability than groundwater level variation. Therefore, the landslide at KM 227+700 is primarily governed by the cracked soil mechanism, highlighting the importance of incorporating subsurface cracking into slope stability assessments.

Keywords: *Slope Stability, Cracked Soil, Groundwater Table, Factor of Safety, Limit Equilibrium Method*.

1. INTRODUCTION

South Sulawesi Province includes several regions that are classified as landslide-prone areas during the rainy season, including Enrekang, Tana Toraja, Palopo, North Luwu, East Luwu, Soppeng, Wajo, Sinjai, Jeneponto, Bantaeng and Gowa. Based on recorded landslide events, Enrekang ranks as the second most landslide-prone area in the province [1]. This study investigates a road section that experienced a landslide event in June 2025. The landslide occurred along the Bts. Kab. Tana Toraja – Enrekang road section, which is part of the provincial road network in South Sulawesi connecting several regencies to the provincial capital, Makassar. The total length of the studied road section is 43.42 Km [2], and the road is classified as a national road under the authority of the Balai Besar Pelaksanaan Jalan Nasional (BBPJN) of South Sulawesi. Several previous studies define a landslide as the downslope movement of soil and or rock masses under the influence of gravity. A slope itself may act as a potential slip surface when subjected to impermeable and saturated conditions. Climatic factors, combined with surface water erosion and groundwater activity, are recognized as primary contributors to slope deformation [3]. However, slope deformation occurring on rocky escarpments composed predominantly of stiff silty-clay underlain by hard strata-raises critical questions regarding the triggering mechanism of failure. The slope had remained stable for decades, of previous geotechnical investigations indicated that the calculated FS satisfied conventional stability criteria. Despite these conditions, failure was still observed in the field. [4]. Several studies have reported that reductions in slope stability are closely associated with groundwater table fluctuations, which increase pore water pressure and consequently reduce the factor of safety. Nevertheless, field evidence at the study location, characterized by stiff clay soil, indicates that slope failure occurred even when the calculated factor of safety (FS) remained above the conventional stability threshold, indicating an overestimation of slope stability [5][6]. This discrepancy between observed failure conditions and theoretical analysis suggest that conventional approach based solely on groundwater fluctuations theory is insufficient to represent the actual failure mechanism. The presence of surface cracks may need to be incorporated into the failure analysis, as such discontinuities can significantly reduce shear strength, as considered in this study. This research aims to address this gap by incorporating both groundwater level conditions and a cracked-soil approach in slope modeling, in order to provide a more realistic representation of slope behavior. Slope stability evaluation is based on FS, obtained through numerical modeling using the Limit Equilibrium Method (LEM) implemented in the Geo5 software.This study focuses on identifying the triggering mechanism of the landslide at km 227 + 700 the Tator – Enrekang road section through numerical modeling analysis.

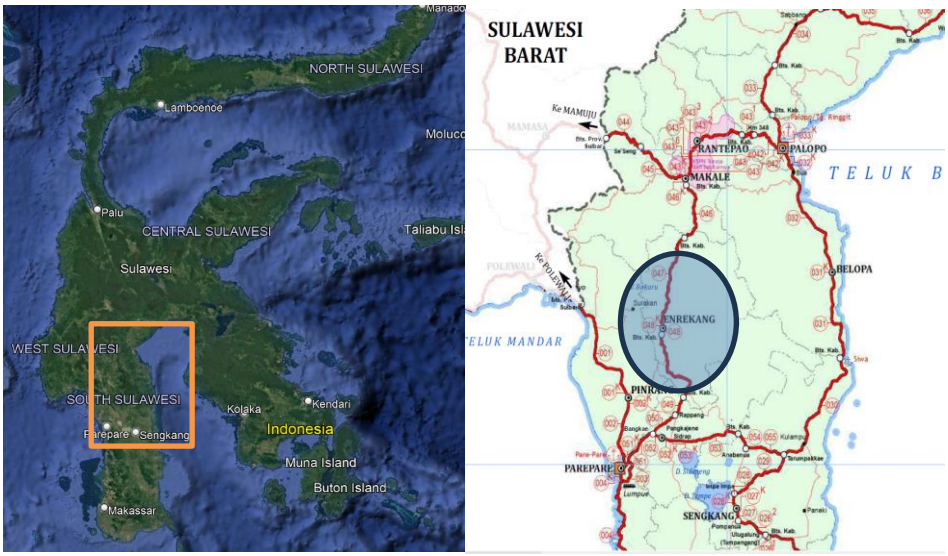

Figure 1. Research location

2. LITERATURE REVIEW

Slope stability analysis is conducted to evaluate the safety of slope, including both natural slopes and man-made embankment slopes. The stability of a slope influenced by several factors, including soil shear strength parameters, slope geometry, pore-water pressure conditions, and a external loads acting on slope surface [3] [7]. Furthermore, the factor of safety (FS) represents the stability condition of a slope. Slope failure occurs when the acting shear stress exceeds the available shear strength of the soil. Numerically, slope stability can be classified as follows FS>1 indicates a stable or safe slope condition, whereas FS<1 indicates an unstable or unsafe slope condition [8]. An increase in the groundwater level, such that the slope is assumed to be fully saturated, results in an increase in pore-water pressure and influences the rate of soil mass movement. This condition is associated with an increase in soil water content, leading to higher degrees of saturation and a corresponding reductions in soil shear strength [9][7]

To capture the complex mechanisms that occur during slope stability analysis, the cracked-soil approach provides a refined analytical framework. The cracked-soil approach assumes that slopes which appear stable at the surface may already contain cracks. During rainfall events, infiltrating water through these cracks at relatively low velocities, transporting fine soil particles and leaving behind coarser soil fractions along the crack plane. Under heavy rainfall conditions, the cracked may become fully filled with water, generating elevated pore -water pressure and promoting deeper crack propagation, which significantly affects slope stability[4][10]. Conventional slope stability analysis generally assumes an intact soil condition and treats groundwater level fluctuation as the primary triggering factor of slope failure. However, in several cases involving stiff to hard clay slopes, cracking may develop prior to failure, significantly reducing soil cohesion and forming internal weakness planes. Stability evaluation based solely on groundwater fluctuation may therefore lead to an overestimation of FS, particularly in slopes that appear stable but contain hidden structural weakness [4] [11]. Slope stability analysis using the Limit Equilibrium Method (LEM) is based on comparing resisting forces with driving forces acting along a potential slip surface. A Slope is considered stable when the resisting forces exceed the driving forces[10] In this study, the Geo5 software is employed to evaluate the global factor of safety of the slope under various analysis conditions.

3. RESEARCH METHODOLOGY

The study employed secondary data consisting of soil parameters obtained from laboratory testing conducted by the National Road Implementation Center (Balai Pelaksanaan Jalan Nasional, BPJN) of South Sulawesi. This research investigates the mechanism of slope failure at KM 227+700 through numerical modeling incorporating groundwater level variation and a cracked soil approach. Slope stability was evaluated using the Limit Equilibrium Method (LEM) implemented in Geo5 software to determine FS as a quantitative indicator of the governing failure mechanism. Groundwater conditions were simulated by elevating the groundwater level to the slope surface (GWL = 0.00 m), representing fully saturated conditions induced by intense rainfall. This scenario was adopted to assess the influence of increased pore water pressure on shear strength reduction and its effect on the computed FS. The cracked soil condition was modeled by assigning zero cohesion ($c = 0$) [4] to the upper soil layer to a depth of 3.00 m, representing shear strength degradation associated with tensile cracking in stiff clay. The assumed crack depth was supported by subsurface investigation data, where the 0 – 3.00 m layer exhibited relatively lower NSPT values compared to the underlying strata. Lower NSPT values indicate reduced soil density and lower shear resistance, suggesting

higher susceptibility to deformation and crack development. Conversely, higher NSPT values at depths greater than 3.00 m reflect denser soil with greater mechanical competence and shear strength [12][3].

4. RESULT AND DISCUSSION

Slope condition modeling was carried out using three different scenarios to evaluate the influence of groundwater conditions and soil cracking on slope stability.

- The first scenario represents the existing condition of the slope, using the original soil parameters obtained from laboratory test result and groundwater table position based on borehole investigation data. In this condition, the groundwater table (GWT) is located at a depth of -2.00 meter below the ground surface, as presented in Figure 2.
- The second scenario represents the slope condition during periods of high rainfall intensity. In this scenario, the groundwater table is assumed to raise the ground surface level (GWT = 0.00 m), and the slope is considered to be in a fully saturated condition while maintaining the original soil parameter and presented in Figure 3.
- The third scenario represents the cracked-soil condition, in which crack act as preferential pathways for water flow. Thus, condition is modeled by assuming cohesion $(c) = 0$ and internal friction angle $(\varphi) \neq 0$ for the soil in layer one at depths ranging from 0.00 to 3.00 mete, regardless of the initial soil condition (see Figure 4). Under this assumption, the soil shear strength behavior is governed primarily by friction, and the soil is assumed to exhibit sand-like behavior.

The parameter used during analysis is presented in Table 1. Furthermore, the factor of safety (FS) value for each slope condition variation are summarized in Table 2. The difference in FS values among the modeling scenarios indicates that groundwater level rise alone is insufficient to explain the observed slope failure at the study site. The slope condition remains stable under both the existing and fully saturated scenarios, as reflected by safety factor value exceeding the stability threshold. A significant reduction in stability occurs only in the cracked soil model. The finding suggests that subsurface cracking plays a dominant role in controlling the slope failure mechanism. The result indicates that slope stability analyses that do not consider soil cracking may produce stability estimates that differ from actual field conditions.

Table 1. Soil parameter used during analysis using Geo5 software

Layer	Soil type	γ (kN/m³)	γ_{sat} ((kN/m³)	φ_{ef} (°)	c_{ef} (kPa)	c_u(kPa)
1	Clay (very stiff)	20.03	22.03	27	38.70	-
2	Clay (very stiff)	20.03	22.03	27	38.70	
3	Claystone (hard)	20.03	-	-	-	200
4	Claystone (hard)	20.03	-	-	-	200
5	Clay (very stiff) with cracked soil approach	20.03	22.03	27	0	-

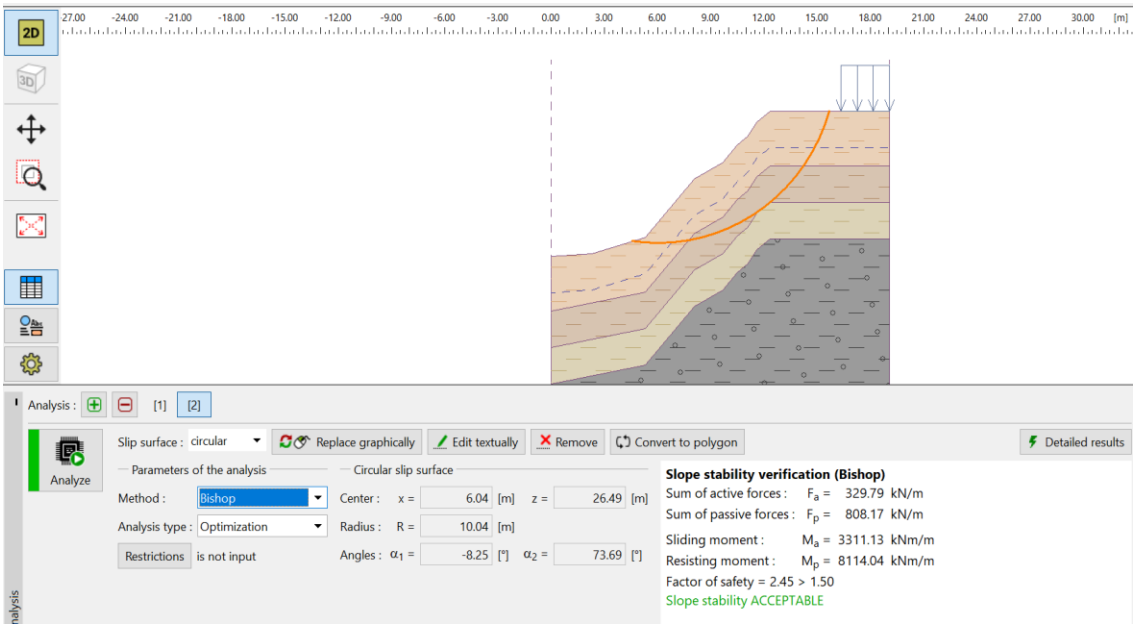

Figure 2. Result of slope analysis under existing condition

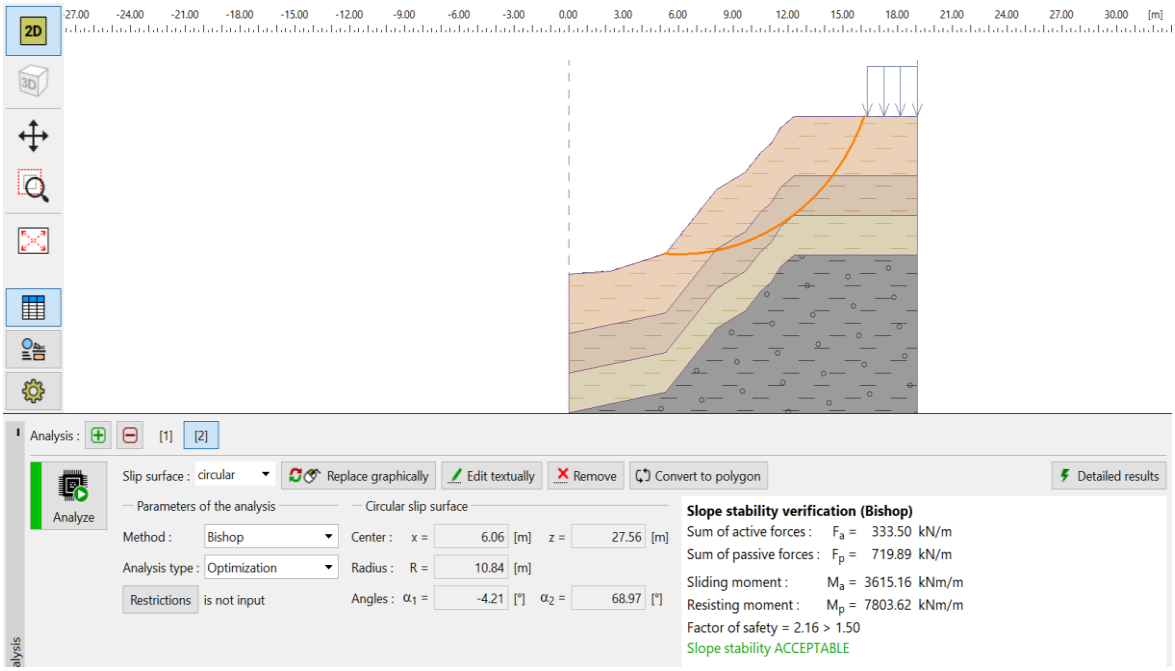

Figure 3. Results of slope analysis under fully saturated conditions (GWT = 0.00 m)

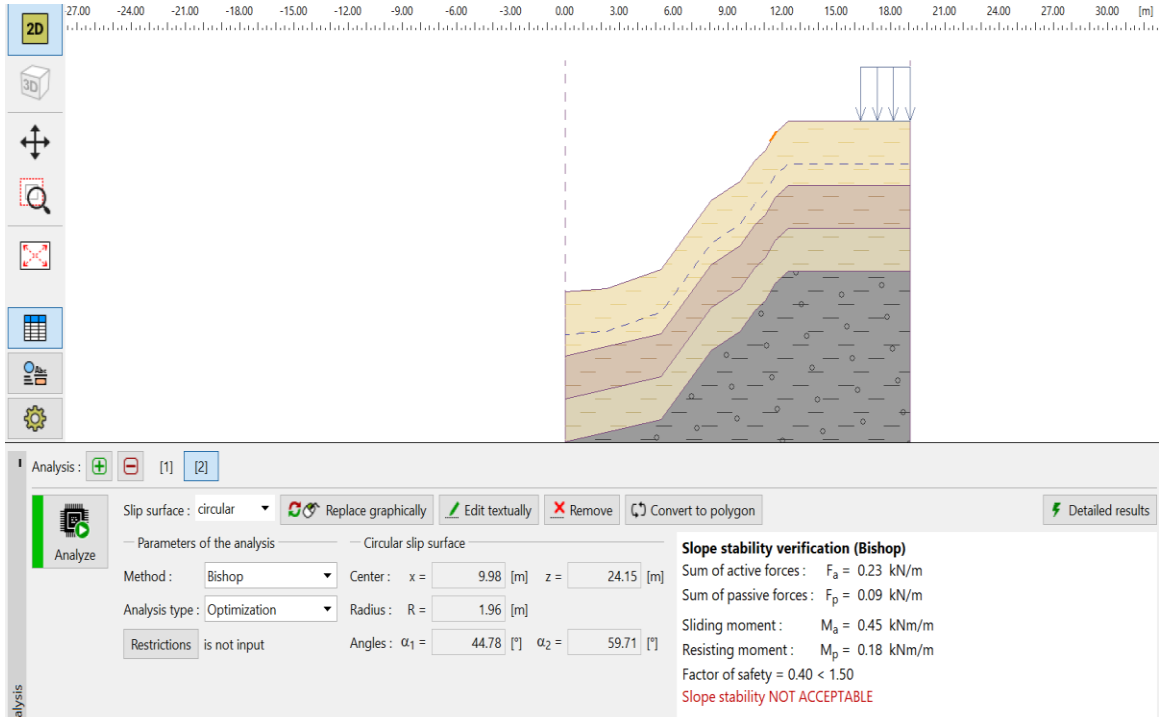

Figure 4. Results of slope analysis using the cracked soil approach

Table 2. *Factor of safety values for each modeling variation*

Condition Variation	FS	Conclusion
Existing condition	2.45	Safe
Fully saturated slope condition	2.16	Safe
Slope condition using the cracked soil approach	0.40	Unsafe

5. CONCLUSION

Slope stability was evaluated through a series of numerical modeling scenarios to determine the global FS under different controlling mechanisms. Under the existing slope condition, using the original soil parameters, the analysis produced of FS = 2.45, indicating stable slope condition. When the slope was assumed to be fully saturated, with the groundwater table rising to the ground surface (GWT = 0.00 m), the FS decreased to 2.16. Although groundwater rise reduced the overall stability, the slope remained stable and did not adequately represent the landslide condition observed in the field. A markedly different response was obtained when the cracked soil approach was introduced in this scenario, subsurface cracks-although not visually detectable-were assumed to develop within the upper soil layer and act as potential slip surfaces. The cohesion of the cracked zone was assumed cohesion (c) = 0. This modeling condition resulted in a substantial reduction in stability, with FS = 0.40, indicating an unstable slope condition. The comparative assessment demonstrated that groundwater rise alone is insufficient to trigger slope failure at the study site at the study site. In contrast, the presence of subsurface cracking leads to a pronounced degradation of shear strenght and a significant reduction in slope stability. These results indicate that the cracked soil mechanism exerts a far greater influence on slope instability than groundwater level variation. Consequently, slope failure at KM 227+700 is primarily controlled by surface cracking rather than by groundwater rise alone, which is consistent with established concepts of crack-induced slope failure reported in previous studies [8] [4] [13] [14]

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