The Impact of Cracked Soil and Weathering on Slope Stability Against Landslides in Hilly Regions with Heavy Rainfall

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ABSTRACT

Landslides are frequent events occurring in hilly regions of Pacitan-Indonesia, specifically beneath High Voltage Air Line (SUTT) tower. These events occur during the rainy season, with a monthly and daily intensity of 1,000 mm and 300 mm, respectively. Therefore, this study aims to identify the causes of landslides in hilly regions with good soil conditions influenced by weathering and cracks. The field observations of geotechnical and geophysical were carried out including Electrical Resistivity Tomography (ERT) and Induced Polarization (IP). The results of geotechnical testing showed that soil conditions were generally stiff, while ERT and IP tests indicated a layer with weathering and cracks. Numerical modeling was also performed using limit equilibrium and finite element methods to simulate the impact of soil weathering and cracks. The results showed that the presence of cracks and weathering in soil at landslide location could significantly reduce slope stability, particularly during heavy rainfall. Additionally, the number of cracks and seepage parameter values in weathered soil influenced slope stability, potentially leading to landslides.

Keywords: Pacitan landslides, Cracked Soil, Soil Weathering, Numerical Modeling, ERT, Induced Plasmization

1. INTRODUCTION

Pacitan Regency is located at the southwestern edge of East Java, adjacent to several regencies, including Ponorogo, Wonogiri (Central Java), Trenggalek, and the Indian Ocean. This regency has a karst landscape that is part of Sewu Mountains with a low groundwater level (GWL), which contributes to the high occurrence of landslides, particularly in hilly regions such as Tulakan Village. The geological map from the Center for Geological Research and Development, published in 1999, shows significant diversity in Pacitan. Based on the map, landslide regions are characterized by Oligo Miocene Lava and Middle Miocene Sediments, comprising various rock types, including basaltic pillow lava, sandstone, mudstone, and rijang. According to landslides potential map from the Ministry of Energy and Mineral Resources Geological Agency, this regency has landslide potential classified as moderate to high. In early December 2017, Tulakan Village, Pacitan, East Java, experienced landslides which were triggered by heavy rainfall. These landslides caused a shift in the foundation of a high-voltage electricity tower located close to regions (Figure 1).

Figure 1. Landslide location under High Voltage Air Line (SUTT) electricity tower.

The electricity supply to various regions in East Java can be influenced when immediate measures are not taken to address the risk of future landslides. Although sparsely populated, Tulakan Village has a history of minor landslides that were previously not considered serious events. The recent landslides were more severe and occurred close to a major power source, showing the need for urgent action. To investigate the cause of these events, several field tests were performed, including Standard Penetration Test (SPT-N) and geophysical methods such as resistivity and induced polarization. Laboratory tests, such as volumetric-gravimetric assessments and unconfined tests, were also conducted to analyze soil parameters. Additionally, topographic measurements were taken at various locations to map slope contours, which would aid in both current and future slope stability evaluations.

Rainfall data from three nearby stations showed that Pacitan Regency experienced exceptionally high rainfall in November before landslides, with monthly and daily intensity exceeding 1000 mm and 300 mm, respectively. This significant rainfall was believed to be a primary factor contributing to landslides, along with weathered and cracked soil conditions. Therefore, soil testing was carried out at 4 locations and were in line with landslides location. SPT-N results showed that most soil conditions were characterized by hard layers with high SPT-N values. At shallow depths of approximately 10 meters, a hard cohesive soil layer was identified, while deeper layers consisted of non-cohesive and rocky materials. Based on categorization, soil at landslides location was grouped into four layers, consisting of silt loam, clay, hard silt loam, and rock.

Based on the description, this study aimed to investigate the mechanisms behind landslides that occurred in Tulakan, Pacitan-East Java. The analysis emphasized the impact of soil parameters, the presence of cracks and weathering, as well as variations in rainfall intensity on slope stability using cupled program Limit equilibrium and finete element. The integration of these two programs allowed simulation of the interactions between water, soil, and slopes, including the impact of changing rainfall intensity on seepage conditions and overall slope stability (GEO-SLOPE International Ltd, 2008). The results were expected to enhance understanding of landslides mechanisms in Tulakan and aid in developing more effective measures to prevent future occurrences.

2. STUDY METHODOLOGY

The numerical model of slope profile was constructed based on field conditions, including topography, subsurface layers, and hydrological factors at landslide site. The analysis applied various methods, focusing on seepage from rainfall and slope stability, using Finite Element Method (FEM) and Limit Equilibrium Method (LEM). To achieve a thorough understanding, this study used a numerical method with a 2-dimensional coupled program, namely SEEP/W and SLOPE/W. Specifically, SEEP/W analyzed seepage patterns and soil hydrological conditions, while SLOPE/W evaluated slope stability based on soil data and hydrological parameters obtained. In this study, two scenarios were analyzed, where the first considered surface cracks and weathered soil layers, and the second did not include any factor. In the sleep analysis using FEM, pore water pressure in soil was calculated. Subsequently, LEM was used to determine safety factors (SF) along the predicted landslide surface. The results showed the modeling of rainwater seepage in soil to explain how seepage could be integrated into slope stability assessments.

During the analysis, several factors were evaluated including variations in GWL, soil hydraulic conductivity, volumetric water content, and the safety factor of landslides mass in relation to seepage from rainfall. Boundary conditions were established based on previous studies, as shown in Figure 2 [1], [2], and [3], while the variations in GWL are presented in Figure 3. GWL variations, which influence slope stability due to rain, are derived from established previous study by [4] [5] [6]. By combining FEM and LEM methods, this study aimed to enhance understanding of landslides mechanisms influencing slopes and assess the effectiveness of different mitigation strategies to reduce potential risks.

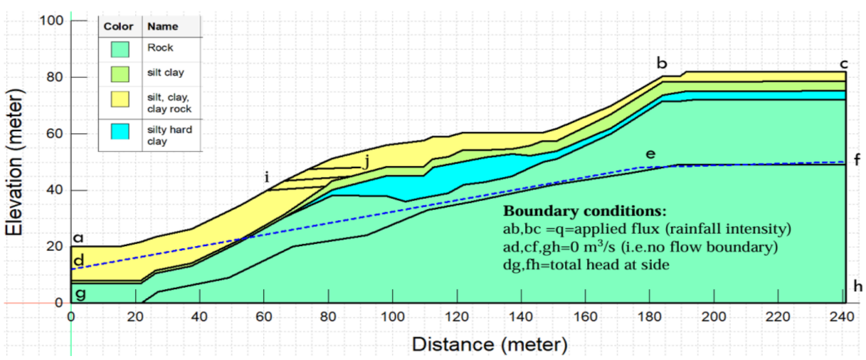

Figure 2. Boundary conditions used in numerical analysis

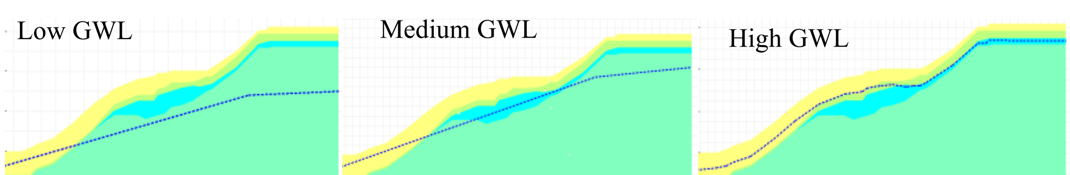

Figure 3. GWL variations

3. RESULT AND DISCUSSION

3.1. Analysis results based on field testing

Geotechnical testing, along with Electrical Resistivity Tomography (ERT) and Induced Polarization (IP) testing, were conducted in the field to obtain detailed information regarding soil conditions at landslides location. In this study, geotechnical data were collected through boring, N-SPT tests, and laboratory analysis of soil physical parameters. The results provided valuable information about various soil parameters crucial for slope stability analysis. The range of geotechnical parameters identified in each soil layer included Effective cohesion (c'): 0–90 kPa, Effective internal friction angle (φ'): 1–40°, Soil unit weight (γ): 17–19 kN/m³

Table 1 shows a comprehensive summary of soil data for each layer, indicating essential information such as soil type, cohesion value, friction angle, and other relevant parameters. Vertical crack parameters in soil and weathered layers are derived from references [7], [8] and [3]. These data are used for further analysis in slope modeling and stability evaluation, particularly regarding safety factor and the potential for future landslides. The geotechnical parameters serve as the foundation for numerical modeling and simulations using FEM and LEM to examine slope behavior and the impact of hydrological conditions on slope stability.

Table 1. Soil parameters

Layer	Soil type	γ_{soil}(kN/m^3)	ϕ'	C_u (kPa)	K_{sat} (m/s)	n
1	Silty clay with rock	17	1	50	2.34 x 10^{-8}	0.53
2	Silty clay	17	1	70	2.3 x 10^{-8}	0.53
3	Silty stiff clay	17.3	1	90	2.13 x 10^{-8}	0.53
4	Rock	19	40	0	2.3 x 10^{-8}	0.33
	Vertical crack	15	0	0	0.01	0.53
	Weathered layer	15	17.5	5.4	0.001	0.43

The results of ERT and IP testing in Figure 4 show regions with low resistivity values, which are suggested as weathered soil layers by previous studies [9] [10], [11]. The induced polarization results show regions with a high tendency to contain cracked soil that may contribute to landslides [12]. These cracks can alter soil shear parameters, leading to decreased slope stability and potentially resulting in landslides [13], [14] [15]. The presence of soil cracks, combined with high rainfall intensity and elevated soil seepage parameters, further reduces safety factor of slope [16] [17][18].

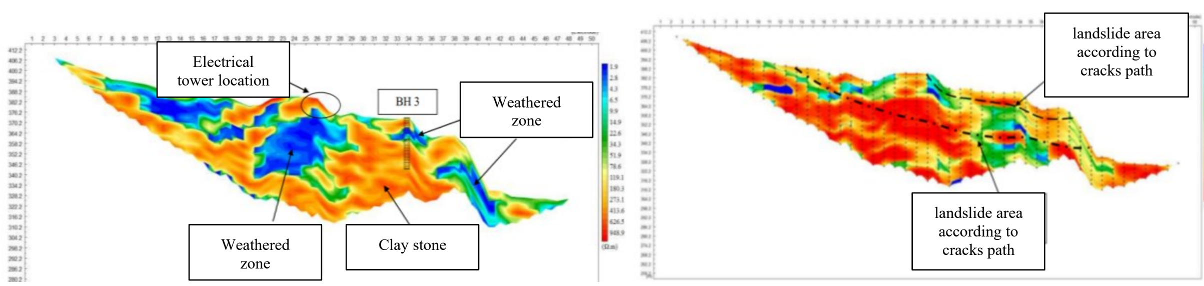

Figure 4. Results of resistivity and induced polarization tests.

3.2. Results of numerical modeling analysis

Analysis using the combined SEEP/W and SLOPE/W programs was performed to evaluate how rainwater seepage influences safety factor and slope stability. This study examined three distinct slope conditions, namely Existing Soil (ES), which reflected natural slopes without cracks or weathering, Vertical Cracks (VC), where cracks allowed deeper water penetration, and Vertical Cracks with Weathering Layers (VCWL) containing both cracks and weathered soil. Figure 5 shows these three slope conditions, while Figure 6 presents the results of slope stability analysis for each scenario, as described below:

- The impact of GWL: Higher GWL corresponded to lower safety factor values, showing that water presence negatively impacted the stability of slope.
- The impact of Rainfall: Prolonged rainfall reduced slope safety factors due to high water seepage and soil saturation.
- The impact of Cracks: The existence of surface cracks generally led to a reduced safety factor, which facilitated quicker rainwater infiltration into soil, thereby raising pore water pressure and diminishing stability.
- The impact of Weathering: Slopes with weathered soil layers showed a higher safety factor compared to those with only cracks. However, this observation was influenced by the parameters of weathered soil layer, which were not fully in line with field conditions.

From the 4 results, it was obtained that ground water level, rainfall intensity, cracks and weathering in the soil can affect the stability of the embankment and cause landslides. The result can be seen on Figure 5 and Figure 6. The results of this numerical analysis showed that soil cracks were mainly contributing to a reduction in slope safety factor. These cracks facilitated the infiltration of rainwater, allowing seepage through and the development of water traps in the subsurface layer that accelerated weathering process of soil. Prolonged occurrence of this phenomenon could lead to a decrease in slope safety factor, causing landslides. Other results are, heavy rainfall on the 26th day of observation, with an intensity of 300 mm/day, reduced safety factor from SF = 1.2 to SF = 1.1 As the number of cracks on soil surface increases, safety factor value decreases, as shown in Figure 7.

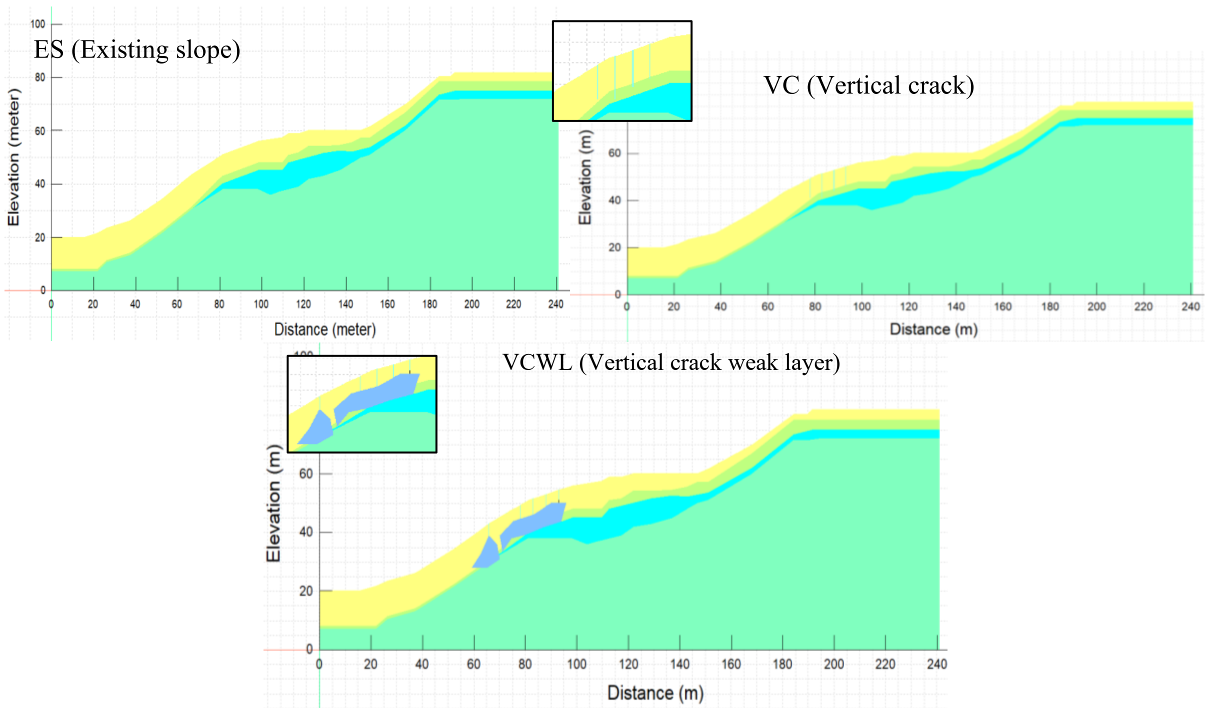

Figure 5. The three slope conditions.

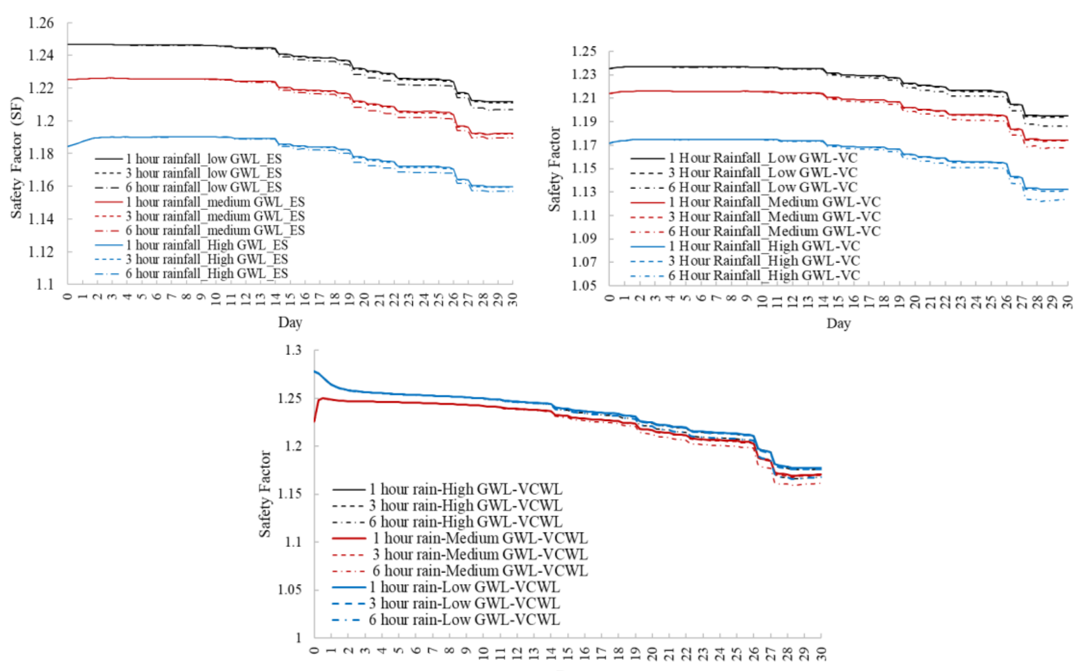

Figure 6. Results of slope stability analysis for each condition

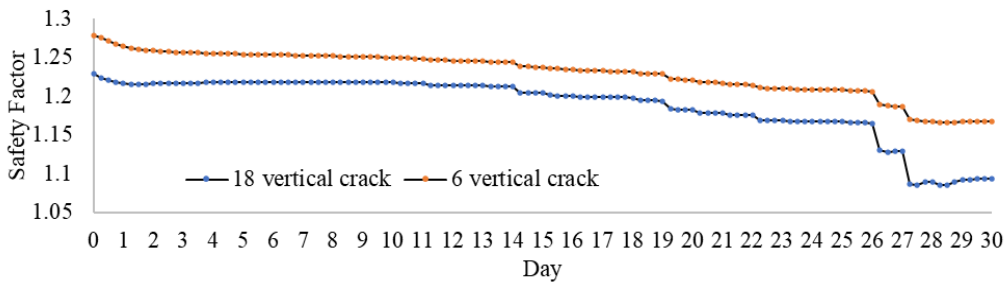

Figure 7. The slope safety factor decrease in 30 days rainfall with variations in the number of cracks.

The existence of soil cracks served as the main factor contributing to landslides in the study location, particularly as shown by geotechnical tests which indicated hard and rocky. Surface cracks served as pathways for water to infiltrate deeper layers, leading to soil weathering. The results of ERT and IP tests conducted at the location showed the extent of weathering and predicted the formation of new cracks.

4. CONCLUSION

In conclusion, this study showed that landslides occurred in hilly regions characterized by relatively good soil conditions. Geophysical tests, specifically ERT and IP, revealed the presence of cracked and weathered soil, although these conditions were not detected in the geotechnical field tests. Numerical analysis conducted with the combined SEEP/W and SLOPE/W programs showed that soil cracks significantly impacted slope stability during the rainy season. Furthermore, the safety factor decreased in the presence of surface cracks, showing that the more cracks present, the lower the safety factor. For instance, heavy rainfall on the 26th day of observation, with an intensity of 300 mm/day, reduced the safety factor from SF = 1.2 to SF = 1.1. The results from field observations and numerical analysis confirmed that cracks in soil facilitated rainwater infiltration into deeper layers, triggering weathering and decreasing slope safety. The number of cracks and seepage parameters in weathered soil further influenced slope stability, potentially leading to landslides. This study showed that landslides could occur in hilly regions with seemingly good soil conditions due to surface cracks and soil weathering. Therefore, integrating geophysical observations was recommended for identifying weathering and cracks on slopes to anticipate landslides, particularly during the rainy season

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