

Investigation of Rainwater Infiltration Effect on Cracked Soil Using Seepage Analysis

Putu Tantri K. Sari ^{1*}, Himatul Farichah ², Yudhi Lastiasih ¹, Indrasurya B. Mochtar ¹

¹ Civil Engineering Department, Sepuluh Nopember Institute of Technology, Surabaya 60111, Indonesia.

² Civil Engineering Department, Universitas Pembangunan Nasional Veteran Jawa Timur, Surabaya 60294, Indonesia.

Received 03 July 2025; Revised 19 March 2026; Accepted 03 April 2026; Published 01 May 2026

Abstract

This research is focused on examining the influence of crack position on slope stability, pore water pressure dynamics, and groundwater level rise induced by prolonged rainfall using seepage analysis. The adoption of a novel integrated method that coupled finite element (SEEP/W) and limit equilibrium (SLOPE/W) analyses led to the introduction of a systematic methodology for evaluating the effectiveness of horizontal drains specifically designed to suit pre-existing crack locations. The results showed that surface cracks in unsaturated soil triggered pore water pressure build-up and groundwater rise, forming localized saturated zones at crack tips after 40 days of continuous rainfall (6 hours/day). Horizontal drains significantly improved stability when positioned near cracks, increasing safety factors by approximately 13% and 6% for slope-surface and mid-slope cracks, respectively. However, it proved ineffective for drains located away from the slope edge. The main novelty centered on quantifying the location-dependent efficacy of drains, establishing a critical zone of influence for optimal drain placement. In addition, the conventional one-size-fits-all method adopted for drain installation was disputed. Field validation using Electrical Resistivity Tomography (ERT) showed that deeper rainwater infiltration realized through cracks during wet seasons supported numerical predictions. The results obtained were in line with the critical role of crack location in drain design. These also provided actionable, location-specific insights for landslide reduction on cracked slopes.

Keywords: Landslide; Rainfall Infiltration; Horizontal Drain; Cracked Soil; Transient Seepage; Slope Stability.

1. Introduction

Slope instability is the leading cause of landslides, which occur frequently, specifically during and shortly after rainfall. This instability is due to the significant impact of rainwater infiltration on soil stability factors such as pore water pressure and shear strength parameters. Additionally, the amount of water that infiltrates the soil depends on the intensity of rainfall and several related parameters, including hydraulic conductivity and porosity. Nam et al. [1] reported that hydraulic conductivity enabled water to steadily pass through the soil under transient conditions. Excess rainwater tends to generate surface runoff when the intensity of rainfall exceeds the soil's capacity to absorb water, as proven by the hydraulic conductivity. However, a large amount of rainwater infiltrates the ground if this parameter exceeds the rainfall intensity [2, 3]. This parameter varies significantly among different soil types, as well as impacting the rate and extent of infiltration. For example, cohesive soils have lower infiltration capacities than the non-cohesive. Clay also has a reduced ability to infiltrate rainwater compared to the sandy type. In this context, clay with hard consistency or rock-like texture exhibits limited infiltration capacity.

* Corresponding author: tantri@ce.its.ac.id

<https://doi.org/10.28991/CEJ-2026-012-05-011>



© 2026 by the authors. Licensee C.E.J, Tehran, Iran. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC-BY) license (<http://creativecommons.org/licenses/by/4.0/>).

Landslides triggered by rainfall frequently occur in hilly areas characterized by cohesive and stiff to hard soil or rock consistency [4, 5]. These areas are characterized by poor hydraulic conductivity, which leads to low water transmission rates. As a result, a significant amount of rainwater tends to be converted into surface runoff rather than infiltrating the ground, adversely affecting the slope. In certain conditions, such as the presence of a water channel, rainwater easily infiltrates the cohesive, stiff, and hard soil layers. This scenario triggers weathering by weakening the soil parameters at deeper elevations, leading to landslides after rainfall. Following the description above, the cracks on the slope surface cause rainwater to infiltrate cohesive, stiff, and hard soil layers. In addition, the shallow vertical cracks served as pathways for rainwater infiltration and potentially propagated deeper due to water pressure buildup [5]. Several research reports indicated that this opening changed soil parameters, leading to degradation of intact or fused soil, thereby causing variation in seepage and shear strength [5-9]. Cracks provided rapid pathways for rainwater to infiltrate the ground, resulting in soil saturation and degradation of parameters at greater depths. Despite this significance, few research had been conducted on how soil cracks affect slope stability, particularly concerning landslides.

Some research had addressed the influence of cracks and rainfall on slope stability. Cai et al. [10] reviewed a landslide case in China by integrating geological surveys, laboratory testing, and numerical simulation. The results showed that crack depth was the main controlling factor for failure pattern and mode of soil slope. The presence of cracks weakened the slope structure and facilitated softening by rainwater. Meanwhile, rainfall deepened the cracks, producing a damaging feedback cycle that triggered landslide disasters. The present research failed to address the impact of crack location on slope stability. Zhang et al. [11] adopted Finite Element Method (FEM) simulations using OptumG2 software, found crack depth, water filling level, and slope inclination were interacting parameters that significantly influenced slope stability sensitivity. Subsequently, Zhang et al. [12] developed an upper-bound kinematic analysis method, used to evaluate the stability of unsaturated, non-uniform, cracked soil slopes, by considering two variations, namely open and formation cracks. The results indicated that the factor of safety was greatly influenced by soil properties, slope geometry, crack type, unsaturated flow conditions, and variations in soil strength with depth. This research focused mainly on crack types without examining the impact of the location and position on the slope.

Several research projects had evaluated the connection between moisture content and soil cracks. Some reported an increase in soil moisture content, enhanced infiltration capacity, alterations in matric suction, and increased saturation levels [13-15]. According to Xing et al. [16], the infiltration rate increased alongside the number of cracks until it reached a saturation point (approximately 50 cracks in a sample), beyond which the rate of increase gradually declines. Larger crack apertures improved the initial infiltration rate, diminishing after the cracks close. A reduction in aperture from 10 mm to 1 mm decreased the infiltration rate by 31.2%. This also showed the occurrence of an internal catchment phenomenon, where water was trapped within the cracks before being absorbed by the soil matrix. Non-uniform crack closure at various depths led to uneven water distribution that affected the propagation of the wetting front. The condition caused the formation of localized water traps at specific depths with varying dimensions. An effective method was to stabilize the internal catchment or water trap at cracked locations by draining infiltrated water from the soil through the use of horizontal drains. Previous research focused on the positive impacts of using horizontal drains [17, 18], while a few examined the extent to which their presence influenced the effect of water traps caused by cracks with uncertain positions, including scattered distribution across the slope area.

Based on the description above, soil cracks influenced rainwater infiltration and potentially led to the formation of water traps, which affected slope stability. Horizontal drains were adopted as a reduction measure to decline the instability induced by these water traps caused by soil cracks. However, specific research that investigated the influence of crack position, area of water trap formation due to cracking, and placement of horizontal drains on slope stability were significantly excluded from the literature. The present research examined the effect of crack location on the slope connected to the position of water trap formation and its impact on the reduction of the safety factor. In this context, horizontal drains were modeled within the varying slope in crack locations. The method was used to assess the effectiveness of the drain placement in relation to the existing cracks and corresponding improvement in the safety factor realized. Additionally, rainwater infiltration in cracked soil through seepage analysis, alongside the implementation of reduction measures using horizontal drains, was also explored.

2. Theoretical Approach

The effect of rainwater seepage into the soil, including the potential to trigger slope instability, was critically reviewed. Furthermore, the result showed that it altered shear parameters and increased the groundwater level, affecting the safety margin of the slope. The extent of the seepage was determined by the transmission ability of the soil. According to Dourte et al. [19], heavy rainfall increased surface runoff and decreased groundwater recharge because of the low hydraulic conductivity of the soil. This scenario showed that the seepage coefficient or hydraulic conductivity played a crucial role. Zheng et al. [20] also found that extreme rainfall mainly contributed to groundwater as well as effectively replenished deep soil layers. He et al. [21] used ARC GIS to model how rainfall seepage impacts groundwater flow on slopes. The result showed that rainfall seepage altered the level of groundwater and flow on the slope, thereby affecting its stability. The formula proposed by Sangrey et al. [22] was used to calculate rainfall recharge, influenced by many factors and stated as follows:

$$R = P - Q_r - E \pm S_t - S_j - S \quad (1)$$

where, R = rainfall recharge, P = rainfall, Q_r = surface runoff, E = evaporation, S_j = rainfall interceptions, S_t = water storage, and S = bedrock seepage. The surface runoff was calculated using the following equation:

$$Q_r = P - I_r - S_j \tag{2}$$

where, I_r = seepage volume, meanwhile some of the parameters had a value of 0, such as E , S_t , and S . The evaporation (E), and water storage values (S_t) were equivalent to zero because of continuous rainfall, and seepage caused by lack of unsaturated water content, respectively. Bedrock seepage (S) was equivalent to zero in the impermeable clay layer; hence, by substituting the two equations above, the formula for rainfall recharge was simplified to $R = I_r$. The seepage volume depended on various factors, such as soil characteristics, layer thickness, rain intensity, slope, and duration of rainfall.

During the initial stages of rainfall, soil water content is low, and its permeability is high. However, when the permeability exceeds rain intensity, the rainwater tends to infiltrate the soil [21]. At this stage, the rate of seepage is equivalent to the intensity. The gradual rise in cumulative seepage volume raises the content of water in the unsaturated and seepage zones, but steadily decreases soil permeability. Finally, it declines lower than the rainfall intensity, causing water runoff to occur. In this situation, the seepage rate was equal to the saturated rate, with the accumulation of water/hydrops observed when the accumulated rainfall seepage reached the I_p value, which was determined using Mein & Larson formula [23]:

$$I_p = \frac{(\theta_s - \theta_0)S_f}{\frac{1}{K_s} - 1} = Z_p \cdot \Delta\theta \tag{3}$$

where, K_s = saturated permeability coefficient, I = rain intensity, θ_0 = initial water content volume, θ_s = saturated water content volume, S_f = suction in a wet front, Z_p = rainwater seepage depth at the time water was collected, and $\Delta\theta$ = deficit water content ($\theta_s - \theta_0$). Hydrops was detected between runoff and rainfall seepage, and its time formulated as follows:

$$t_p = I_p / I \tag{4}$$

Supposing the rain intensity surpassed the soil seepage capacity, the equation for calculating the rainfall rate was stated as follows, with t representing the duration:

$$I_R = I_p + K_s(t - t_p) + S_f \cdot \Delta\theta \cdot \ln\left(\frac{I + S_f \cdot \Delta\theta}{I_p + S_f \cdot \Delta\theta}\right) \tag{5}$$

Figure 1 shows the seepage process and changes in soil conditions through a schematic diagram of rainfall seepage on a slope. Furthermore, the three diagrams showed the initial state conditions, adopted rainfall seepage path from He et al. [21], and cracked soil, considered the main topic of discussion.

The depth of the wet front, denoted by Z_1 , is the ratio of seepage volume to deficit water content. However, storage time must be considered when analyzing the transformation of rainfall seepage into groundwater and its flow through the unsaturated zone. In cracked soil conditions, the depth of the wet front tends to be greater than without cracks, leading to differences in the unsaturated area. The existence of cracks intensifies water seepage and affects the humid zone. Sasekaran [24] reported that surface crack changes an existing seepage pattern by increasing soil water content in deeper layers during the wet season. Moreover, a deeper crack triggers the occurrence of saturated conditions in soil as well as rapidly increases the groundwater level. It also exhibited different shear and hydraulic parameters, which potentially led to a more rapid decrease in slope stability.

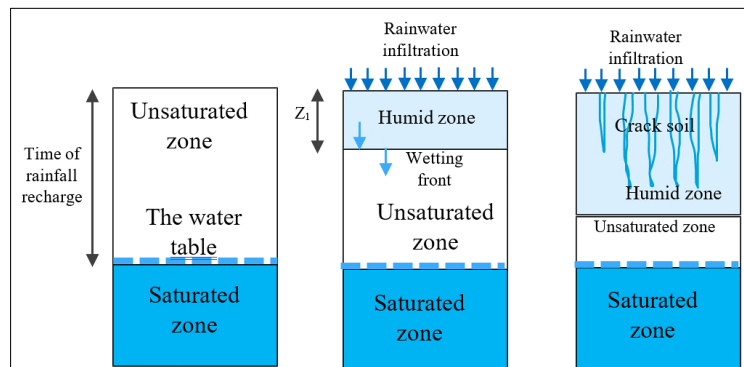


Figure 1. Slope rain schematic diagram. a) Initial state, b) Rainfall seepage path, c) Rainfall seepage path in cracked soil

Regarding the investigations on rainwater seepage into the ground, Lumb [25] proposed a formula for calculating the depth of the wetting front, which was stated as follows:

$$h = \frac{K_s \cdot t}{n(S_f - S_i)} \tag{6}$$

where, h = depth of wetting front, K_s = saturated soil permeability, t = rainfall duration, n = porosity, S_f = final degree of saturation (100%), and S_i = initial degree of saturation. This formulation is unsuitable for the infiltration of rainwater

into the saturated soil. A simpler infiltration model, Green & Ampt [26] proposed a model based on Darcy's law. This model was later adopted by Pradel et al. [27] and represented by the following formula:

$$t_w = \frac{(\theta_s - \theta_w)}{K_s} \left[h - C_s \ln \left(\frac{C_s + h}{C_s} \right) \right] \quad (7)$$

where, h = wetting depth, θ_s = water content volume of saturated soil, θ_w = water content volume of in situ soil, K_s = saturated soil permeability, and C_s = wetting front suction or the negative pore water pressure just before the soil is saturated. It is crucial to understand the mechanism of water flow in soil, after gathering information about rainwater infiltration. Consequently, this research adopted several theories about water flow.

Following the description above, water flow occurred due to the gradient in the hydraulic head. Its total consisted of velocity (which can be disregarded), pressure, and elevation heads, as reported by the following equation:

$$h = \frac{U_w}{\gamma_w} + y \quad (8)$$

where, U_w = pore water pressure and y = elevation head above arbitrary datum. Darcy's law applied to characterize water movement through soil in both unsaturated and saturated states [28]. Moreover, the discharge per unit area (q) was determined by the coefficient of permeability (K_s) and total head gradient (i), calculated as follows:

$$q = K_w \cdot i \quad (9)$$

The seepage and water flow in the soil was estimated using partial differential equation, which considered heterogeneous, anisotropic, and saturated-unsaturated soil conditions. It was assumed that the total stress remained constant throughout the transient process. In addition, the 3D formula used for the calculation was stated as follows:

$$\frac{\delta}{\delta x} \left(k_{wx} \frac{\delta h}{\delta x} \right) + \frac{\delta}{\delta y} \left(k_{wy} \frac{\delta h}{\delta y} \right) + \frac{\delta}{\delta z} \left(k_{wz} \frac{\delta h}{\delta z} \right) = m_2^w \cdot \gamma_w \cdot \frac{\delta h}{\delta t} \quad (10)$$

where, k_{wx} , k_{wy} , and k_{wz} represented the permeability coefficients in the x , y , and z directions, respectively, and m_2^w denoted the slope of soil water characteristic curve, which describe water storage. This equation proved that two soil properties, namely permeability coefficient and water storage, played key role in solving the transient seepage problem associated with a saturated-unsaturated soil system [29, 30]. According to Lam et al. [31], the equation was stated as follows:

$$\frac{\delta}{\delta x} \left(k_x \frac{\delta h}{\delta x} \right) + \frac{\delta}{\delta y} \left(k_y \frac{\delta h}{\delta y} \right) + \frac{\delta}{\delta z} \left(k_z \frac{\delta h}{\delta z} \right) + q = \frac{\delta \theta_w}{\delta t} \quad (11)$$

where, q = external boundary flux and θ_w = volume water content (VWC). This equation was used to determine the fluid mass conservation in soil, which stated the sum of flow rate changes in x , y , and z directions including at the external boundary was equivalent to the water content change rate per unit time. Supposing the amount stress had remained constant and the phase of air is presumed to be continuous in the unsaturated soil, the change in VWC could be simplified as follows:

$$\delta \theta_w = m_w \cdot \delta u_w \quad (12)$$

where, u_w = pore water pressure and m_w = slope of soil water characteristic curve (SWCC). The equation for 2-D flows is stated as follows:

$$\frac{\delta}{\delta x} \left(k_x \frac{\delta h}{\delta x} \right) + \frac{\delta}{\delta y} \left(k_y \frac{\delta h}{\delta y} \right) + q = m_w \cdot \gamma_w \cdot \frac{\delta h}{\delta t} \quad (13)$$

This research was conducted using the 2-D formulation above, where the hydraulic conductivity parameter played a significant role. The process was observed in unsaturated soil conditions due to the existent close relationship with the matrix suction parameter. Several models were proposed to describe the relationship between matrix suction and relative hydraulic conductivity. A typical example was the van Genuchten model, which defined the function of hydraulic conductivity with respect to negative pressure head (matric suction) using curve-fitting parameters n also m , as follows:

$$k(h) = \frac{[1 - (ah)^{n-1} \{1 + (ah)^n\}^{-m}]^2}{[1 + (ah)^n]^{\frac{2m}{n}}} \quad (14)$$

where, $k(h)$ = calculated relative hydraulic conductivity, h = negative pressure head, and a, n, m = curve-fitting parameters. Additionally, a, n , and m were denoted to the air entry head for suction, distribution of soil pore size, and equal to $1 - 1/n$, respectively.

Apart from soil hydraulic parameters, shear factors were crucial in this analysis. In slope stability analyses, the shear strength of unsaturated soil accounts for the negative pore water pressures, or suction, within the matrix. This was according to the equation by Fredlund & Xing [32], which was stated as follows:

$$\tau = c' + (\sigma_n - u_w) \tan \phi' + (u_a - u_w) \tan \phi^b \quad (4)$$

where, τ is the unsaturated soil shear strength, c' denotes the effective cohesion, $(\sigma_n - u_w)$ represents the net normal stress, σ_n shows the total normal stress, u_a is the pore-air pressure, u_w imply pore-water pressure, ϕ' is the effective

angle of internal friction, $(u_a - u_w)$ denotes the matric suction, and ϕ^b represents the angle showing the rate at which shear strength increases in relation to matric suction.

The transient flow modeling was adopted to analyze how flow and pore pressure change over time. Additionally, the modeling of surface crack and its propagation into deeper layers was conducted through transient water flow modeling. This included adjusting the hydraulic and shear parameters on the crack plane. The modeling process in SEEP/W and SLOPE/W was performed in three stages, namely 1) considering time-dependent boundary conditions, 2) implementing time steps from a known initial condition, and 3) accounting for changes in boundary conditions and drainage that influence the volume of water content. Therefore, the flow in porous media was driven by the temporal changes in boundary conditions, the soil's capacity to store water, and variation in water content volume caused by boundary conditions or drainage.

3. Research Methodology and Modelling

3.1. Research Methodology

The flowchart in Figure 2 started with a literature review, which focused on landslides during rainfall. The review specifically analyzed rainwater infiltration, cracks, and its reduction processes. These were realized using horizontal drains to manage rainwater that infiltrated through soil cracks. Meanwhile, modeling was carried out in two dimensions, namely, rainwater infiltration observed using real-time rainfall data acquired over 90 days and the homogeneous soil parameters used to simplify the observed impact on cracked soil. The result aimed to ascertain the influence of real-time rainfall observation duration on rainwater infiltration in cracked soil. The position of the cracks was also a determining factor in assessing the effectiveness of horizontal drains adopted as a reduction method. Additionally, field validation was conducted using ERT tests to observe changes in soil resistivity during rainy and dry seasons. The essence was to compare the results of the numerical modeling with actual field conditions.

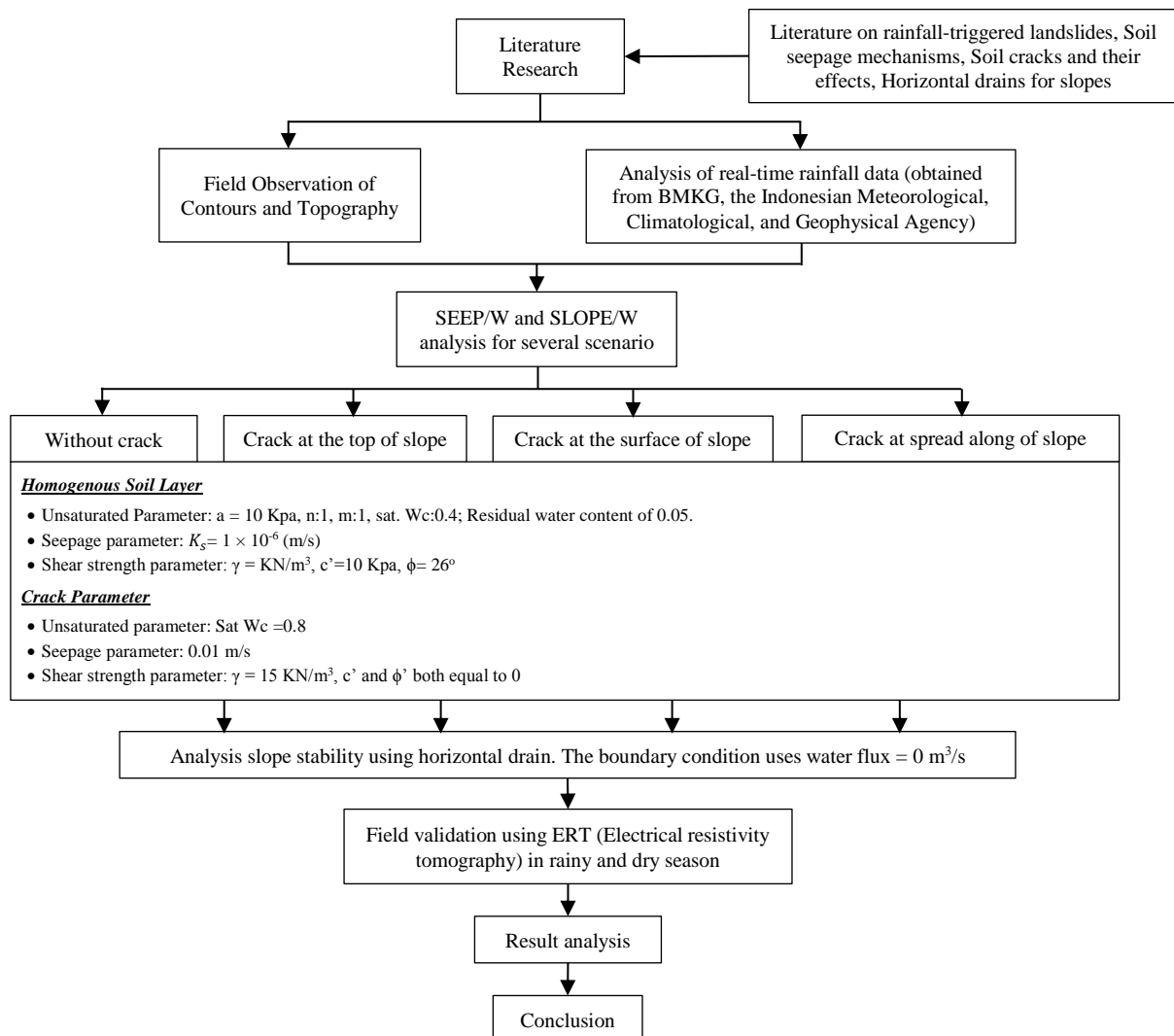


Figure 2. Flowchart of research methodology

3.2. Research Modelling

A uniform soil slope was modeled and exposed to rainfall for 90 consecutive days. However, to assess infiltration and change in groundwater levels, finite element analysis was performed employing SEEP/W. The slope stability was assessed through the method of limit equilibrium using SLOPE/W. Considering that the slope instability in the field was three-dimensional (3-D), this research was conducted using a two-dimensional (2-D) model because the safety factor was equivalent to 2-D and 3-D when the landslide's width-to-height ratio exceeded two [33]. The real-time rainfall data used was acquired from the Indonesian Meteorological and Geophysics Agency in the Malang area of East Java, within January to March 2020. Rainfall was assumed to occur uniformly for six hours daily, and its intensity for the entire 90 days is shown in Figure 3. Groundwater levels were found to be below the slope, as in Figure 4(a). The slope geometry adopted was based on a cut slope from the Gempol-Pandaan toll road in East Java, Indonesia. Meanwhile, three variations in crack position were incorporated into the slope model, with each extending to a depth of four meters. The cracks were located at the top of the slope, alongside, or distributed across the surface. Horizontal drains were incorporated at the toe and middle of the slope, as shown in Figure 4(b to d), to reduce the impact of these cracks on slope stability.

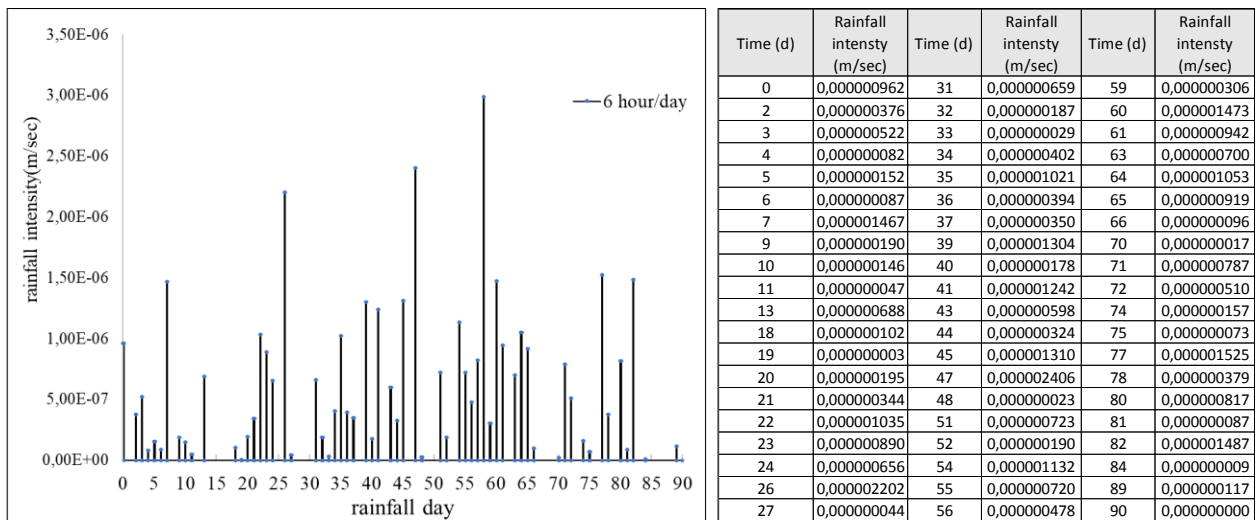
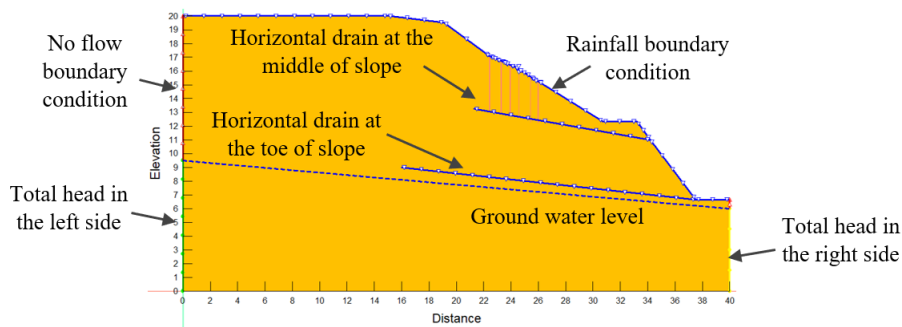
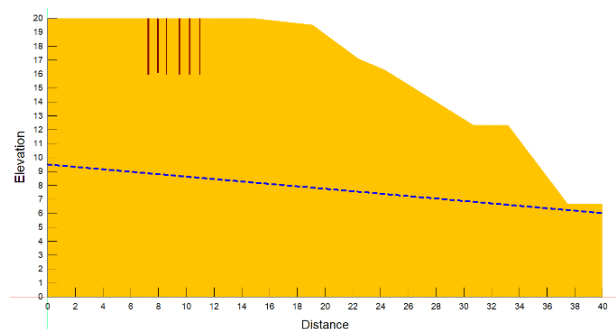


Figure 3. Real-time rain intensity for 90 days



(a)



(b) Crack at the top of slope

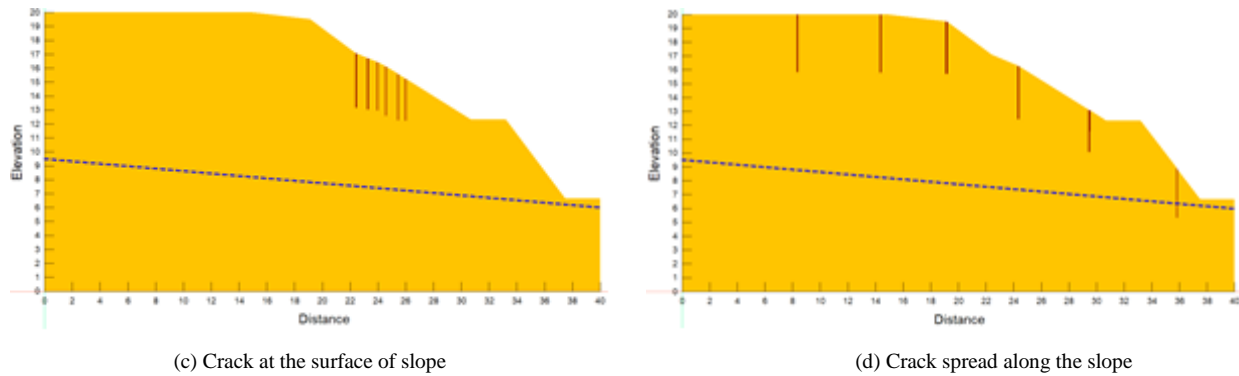


Figure 4. (a) The positions of the horizontal drain and the applied boundary condition; Variations in crack position on the slope: (b) Crack at the top, (c) Crack on the slope, (d) Crack spread along the slope

The modeling of crack parameters was motivated by the previous results. The crack was modeled as a thin vertical layer in respect to different parameters from other soil layers. Several existing theories reported that weak layers in soil existed as cracks initiated from the surface. Prior research conducted by Alessander et al. [4], Gofar et al. [9], Wang et al. [34], Zhang et al. [35], and Suryo [36] reported the presence of major cracks from the vine surface into and around the weak zone. According to Alessander et al. [4] and Gofar et al. [9], it allowed rainwater to directly infiltrate the slope soil. A high hydraulic conductivity parameter of thin materials (under 10 cm) was used in crack modeling to enable infiltration to a deeper depth. The model designed by Suryo [36] showed the weak layer was a saturated soil surface that was affected by direct rainwater seepage along deep cracks. This research only modeled the main crack to observe the propagation and formation of a weak zone, as performed initially.

The infiltration of rainwater into cracks weakened the subsurface layer, altering soil parameters, as reported in previous research. For example, Zhang et al. [35] reported that increasing the water content from 13.5% to 30% led to a reduction of approximately 80% in the shear strength. This result was consistent with the analyses conducted by Gofar et al. [9], Wang & Li [34], and Sari et al. [37]. In addition, Gofar et al. [9] and Wang & Li [34] stated that the shear strength of fractured materials had a zero value, showing weak interaction or bonding of soil particles. Another parameter that differed from the existing ones was the hydraulic conductivity (K) value, of the crack, assumed to be 10 cm/sec. Based on this perspective, the crack was modeled as a porous material similar to gravel. Wang & Li [34] expanded the characterization of cracking parameters in unsaturated conditions by evaluating SWCC graphs, including the hydraulic conductivity of soil with random apertures.

The parameters input for SEEP/W analysis were derived from previously established values, with the homogeneous slope modeled using the Unsaturated Soil Model. This also included the incorporation of parameters based on the Fredlund-Xing function. The parameters were set at $a:10$ Kpa, $n:1$, $m:1$, and $sat.Wc:0.4$. Hydraulic conductivity parameters were determined using Van Genuchten model, with a saturated horizontal (K_x) parameter and residual water content of 1×10^{-6} m/sec and 0.05, respectively. The analysis was conducted within a suction range of 0.01 Kpa -10000 Kpa, and the evaluation of slope stability performed employing SLOPE/W, where both the soil and its cracks were modeled using Mohr-Coulomb method. The soil parameters included a unit weight (γ), cohesion (c'), and friction angle (ϕ) of 20 KN/m³, 10 Kpa, and 26°. Suryo [36], reported that the parameters for soil crack were set at a unit weight (γ) of 15 KN/m³, including c' and ϕ' both equal to 0. The hydraulic conductivity for soil crack was determined using Van Genuchten modeling, with a saturated $K_x=0.01$ m/s and residual water content of 0.08. The saturated water content for crack modeling was set at 0.8, representing the material comparable to sand. This modeling method and parameter configuration were also adopted by Sari et al. [37] to examine how varying rain intensities affect slope stability. In addition, the recapitulation of the parameters used in this research is shown in Table 1.

Table 1. Soil parameters used in the analysis

Description	Unsaturated Parameters	Ksat (m/s)	Shear Strength Parameter
Homogenous soil layer	$a = 10$ Kpa, $n:1$, $m:1$, $sat.Wc:0.4$ Residual water content of 0.05	1×10^{-6}	$\gamma = \text{KN/m}^3$, $c'=10$ Kpa, $\phi= 26^\circ$
Crack	Sat Wc = 0.8	0.01	$\gamma = 15 \text{ KN/m}^3$, c' and ϕ' both equal to 0
Horizontal drain	The boundary condition uses water flux = 0 m ³ /s		

Boundary conditions were considered in respect to the slope by using the applied flux (q) to stimulate rainfall intensity over the entire soil surface. A no-flow boundary condition was imposed on the right and left sides of the slope above the groundwater level, with a constant type of $0 \text{ m}^3/\text{second}$. The total head on the left and right sides were constant at 9.5 meters and 6 meters, respectively. For horizontal drains, the boundary condition used water flux = $0 \text{ m}^3/\text{sec}$, and this was in line with several research studies [38-41].

4. Results and Discussion

4.1. Effect of Crack Position on Changes in Porewater Pressure and Level of Groundwater

The modeling outcomes from the SEEP/W and SLOPE/W program modeling showed that surface cracks affected matrix suction and pore water pressure. In particular, cracked soil exhibited a more rapid increase in matrix suction than uncracked, as in Figure 5. During the 90 days of rainfall, groundwater level fluctuations only occurred after the 40th day. The cracks altered soil saturation conditions, causing a saturated layer to appear at the end of a sloping crack on the 40th day of rainfall. This phenomenon occurred on the 60th day, supposing there was a crack on the upper side. Furthermore, the intensity and duration of rainfall affected the increase in the saturated zone of soil due to cracking.

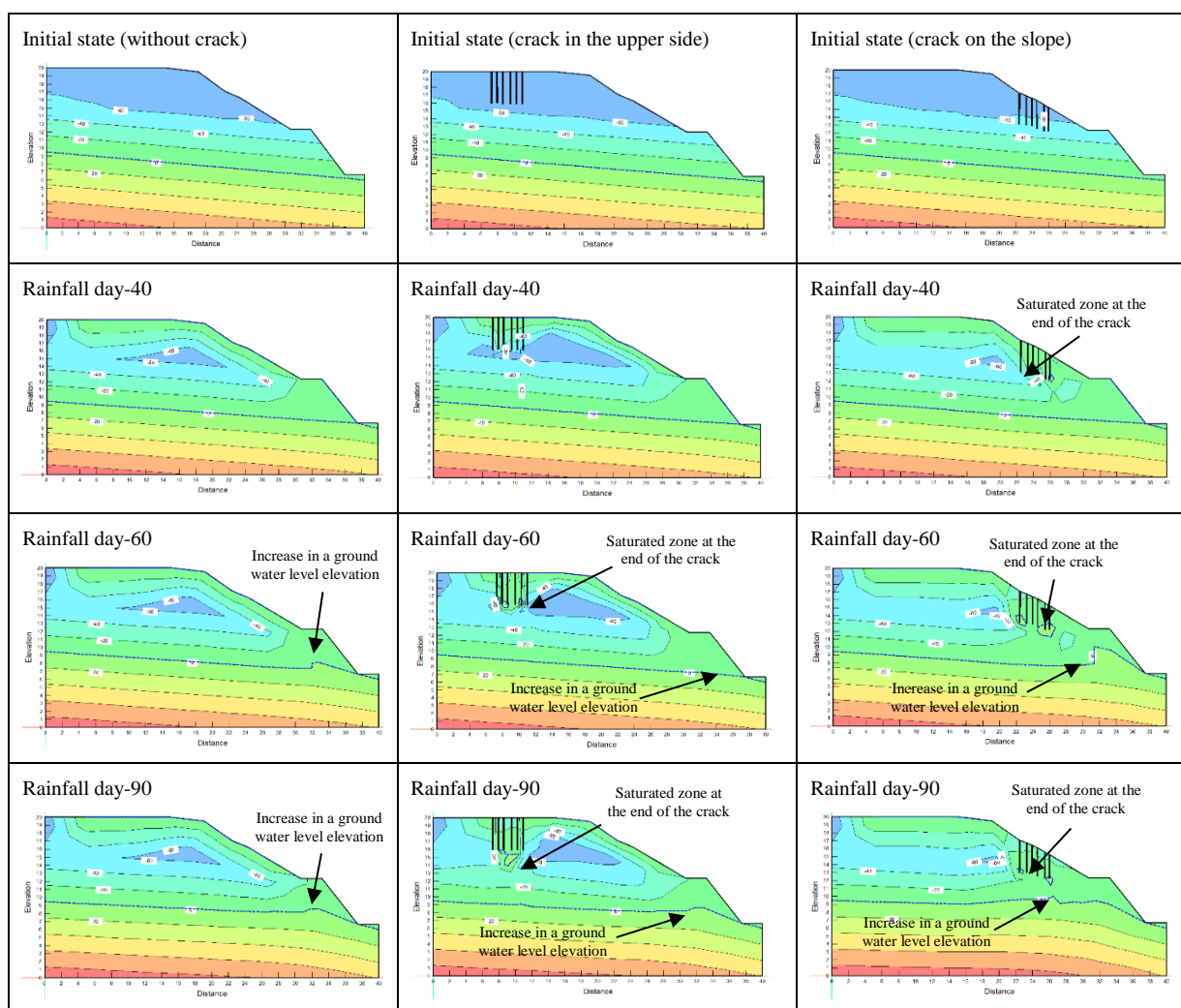


Figure 3. Pore water pressure and groundwater level changes observed on days 40, 60, and 90 under the following conditions, namely 1) without crack, 2) with crack on the upper side, and 3) with crack on the slope side

Crack location had a significant effect on the increase in groundwater level in response to rainfall. When it is situated close to the level of groundwater, the rise in the water level is intensified. The phenomenon was also observed with fewer cracks in soil, distributed in different positions as in Figure 6. Under these circumstances, the groundwater level rapidly increased at the toe of the slope on the 60th day of rain, where the zone of water saturation existed earlier due to the crack located near the water level.

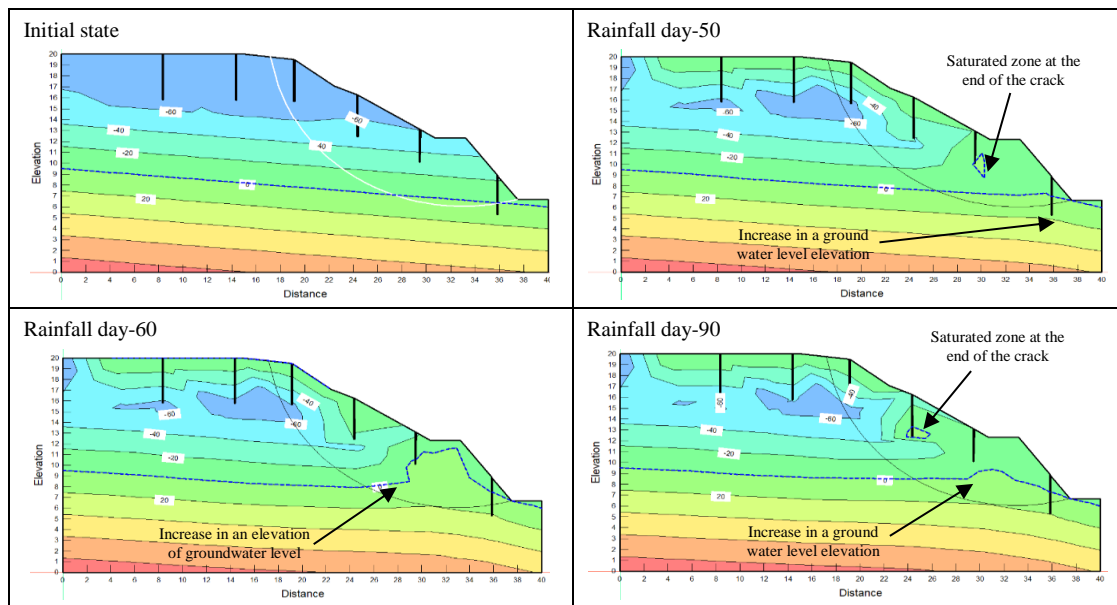


Figure 4. Changes in pore water pressure and groundwater level in cracked conditions with spread locations

Based on these results, surface cracks, which served as infiltration pathways for rainwater, intensified the seeping process into the deeper layers of the soil. This scenario is consistent with numerous landslide occurrences in the field at rock hill sites that had not experienced collapses. The process of water movement in the soil is typically slow, and laminar, implying it takes time for rainwater to soak into the soil, saturate the layer, resulting in unstable slope. The results of the analysis revealed that rainwater affected the pore water pressure in the unsaturated soil, for over 40 days causing a saturated condition. Sufficient time is required for water to increase soil saturation zone, leading to the loss of slope stability before sliding. In this context, the sliding of a hill that had not collapsed in a long time was considered a lasting effect of rainwater seepage in the ground, specifically with the initial occurrence of a surface crack. The saturated zone caused by the crack tended to spread, with the dimensions continuously increasing, thereby causing a weak layer to form around the main crack. This condition was similar to a weak layer reported by many research and proven through a field-scale geophysical test and numerical modeling [2, 4, 8, 9, 38, 42].

The results were consistent with laboratory and numerical research which mainly investigated preferential flow in cracked soil. Xing et al. [16], and Liu & She [43], explored the influence of surface cracks on the wetted region in soil, using laboratory and numerical models to examine preferential flow. The results of the laboratory test conducted by Liu & She [43] showed that water infiltrated through a modeled crack 15 cm deep, started the filling process from the tip within the first minute. Wetting in the crack area continued throughout the 180-minute observation period, eventually forming a saturated zone, as represented in the simulation model in the Figure 7. Preliminary research reported that these laboratory results were aligned with the outcomes of numerical modeling [16]. Furthermore, the numerical simulations in previous analyses clearly showed the formation of a saturated water trap zone initiating from the crack tip. This resulted from water applied under specific pressure, and a similar water trap formation was observed in the present research.

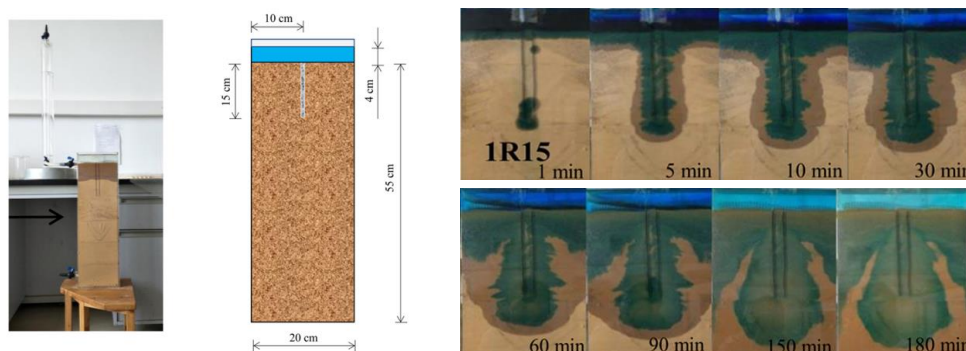


Figure 5. Experiment by Liu & She [16] for preferential water flow along crack in a soil surface

In the numerical model, the crack was modeled to a depth of 4 meters, and required a prolonged rainwater infiltration period of over 40 days to form a water trap at the crack tip. Slight variations in results were observed among surface, slope, and distributed cracks, caused mainly by differences in length. The formation of a water trap was detected after

40 days of rainfall for cracks situated on the slope face, a significantly shorter duration than the relatively 50 days required for those found at the crest. This rapid formation was caused by the inclination of the slope, which resulted in smaller crack dimensions compared to those on flat ground. The distributed cracks proximal to the groundwater level prompted an increase in the water table, which was pronounced at the slope toe.

Cai et al. [10] investigated the impact of crack depth as well as rainwater infiltration on slope stability. The major result was that the pressure of pore water in the superficial soil layer of a landslide mass was generally higher than in its deeper parts. However, as rear cracks deepened, rainwater readily infiltrated into the lower sections of the soil mass. This gradually reduced the pore water pressure difference between the superficial and deeper soil layers.

These results were consistent with the results of the present research, where deeper cracks allowed rainwater to penetrate more easily into the layers, thereby influencing the pore water pressure. The cited research also reported that the rainwater infiltration depth increased significantly at crack depths of 4.5 m and 6.0 m. This intensified the wedging action of water within the crack, leading to the softening of the soil on both of inner walls. Similarly, soil softening caused by rainwater seepage around the crack area was observed in zones where a water trap had formed.

The numerical results were validated by conducting field tests with the aim of evaluating the impact of rainwater seepage on subgrade soil conditions, particularly the moisture content. Changes in soil moisture were intricately connected to variations in saturation, forming the basis for comparing outcomes derived from numerical models. Meanwhile, the focus was directed towards the development of a saturated zone at the tip of a crack. The field testing was carried out in an area characterized by a rocky cutting slope in Pandaan, East Java, Indonesia, where landslides had previously occurred on three occasions in the surrounding vicinity, as shown in Figure 8. Geophysical methods, such as Electrical Resistivity Tomography (ERT) tests, were adopted during rainy and dry seasons. These were aimed at examining how rainfall and soil conditions affect fluctuations in water content. The correlation detected between soil resistivity and water content was aligned with the analysis conducted by Acosta et al. [44], Kazmi et al. [45], and Rostami & Ozouli [46].

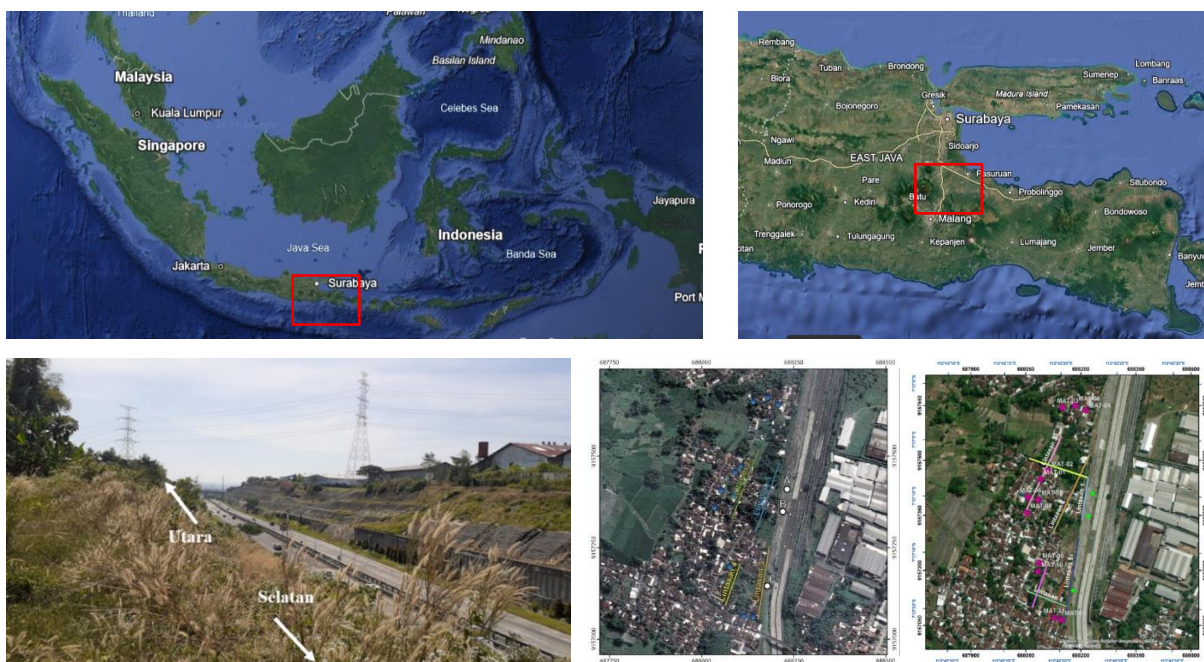


Figure 6. The landslide case research location where ERT testing was conducted during the rainy and dry seasons

During the dry season, ERTs were conducted in July 2022, followed by post-rainy season tests in early May 2023. Based on the analysis of meteorological data from pertinent agencies, rainfall was observed from September 2022 to April 2023. Intense rainfall persisted for three months from November 2022 to January 2023, followed by a continuation at a lower intensity until April 2023.

An examination of ERT results obtained from the field showed that there were changes in resistivity score during the dry and rainy seasons. Furthermore, in the rainy season, a subsurface region showed a reduction in resistivity compared to the dry season, as in Figure 9. The zones characterized by low resistivity values at specific depths exhibited expansion during the rainy period. Surface layers at shallower depths were subjected to minimal alteration, thereby maintaining relatively high resistivity values. The proposed hypothesis stated that rainwater infiltrated the deeper layers of the soil through a vertical surface crack, and this led to a zone of diminished resistivity, as in Figure 9. The surface cracks were believed to have occurred, though it was not properly detected, leading to several landslides at the location.

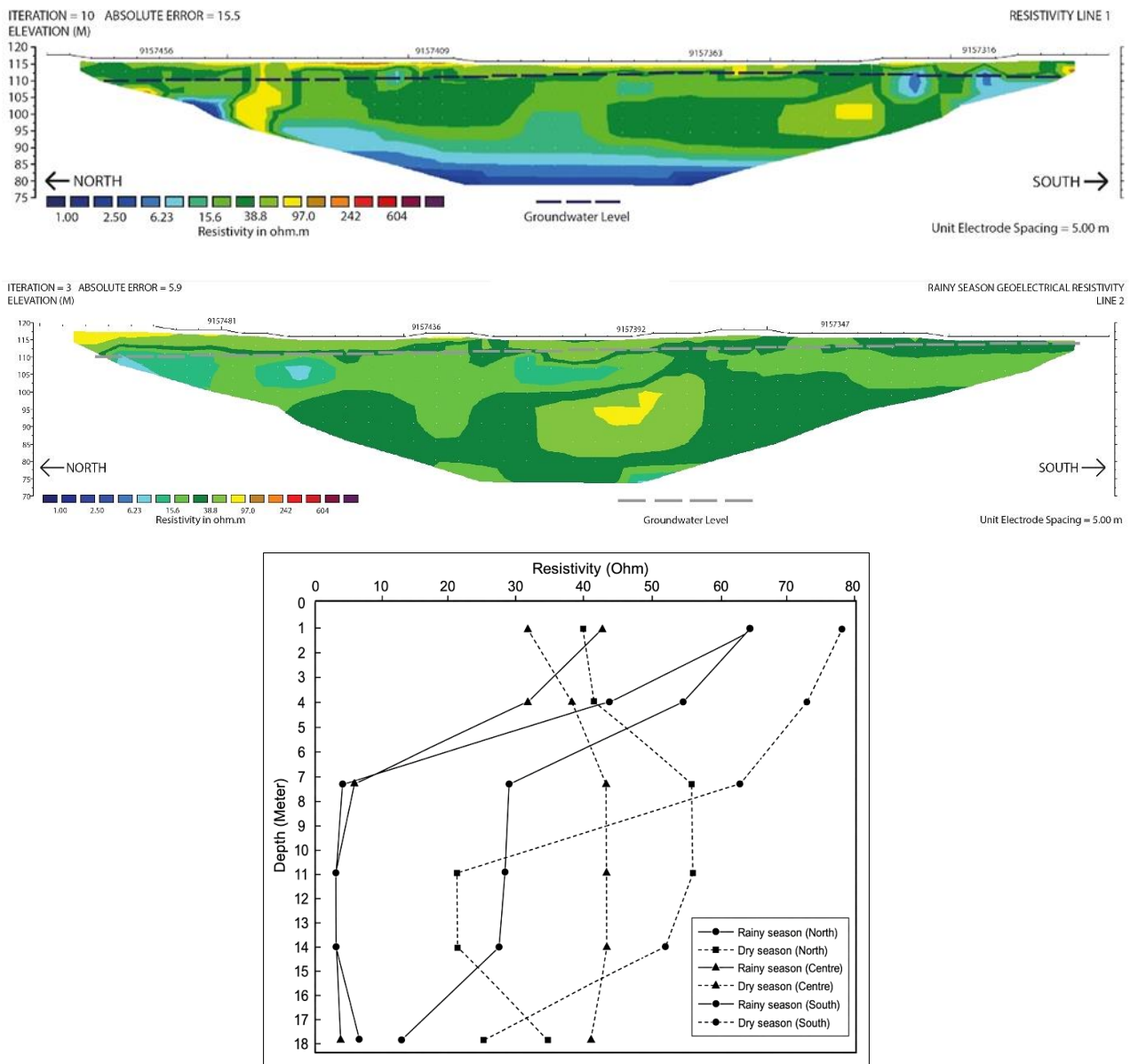


Figure 7. Results of soil resistivity tests conducted during the dry season and rainy season

The validation of vertical cracks' existence in the field required further confirmation. However, these results showed that subsurface zones exhibiting low resistivity values were a consequence of surface cracks. In its absence, rainwater could not rapidly permeate deeper layers, leading to the formation of a low-resistivity zone. This scenario played a relevant role in the research area, characterized by hilly terrain and rocky soil conditions, which caused a significantly low water infiltration rate.

4.2. Effect of Using a Horizontal Drain for Slope Stability on Cracked Soil

The results showed that the cracks generated zones of soil saturation, raising groundwater level. An effort to restore slope stability entailed removing water trapped inside the slope by using a horizontal drain. In this context, the horizontal drainage system made of PVC pipe, as previously investigated by Royster [47] and Barrett [48], was used. Figure 10 shows the slope and groundwater level condition after a horizontal drain had been installed at the base of the slope during rain. The comparison of the groundwater level increase with the horizontal drain in Figure 10 showed that it effectively maintained the water level, thereby preventing escalation. Similar results were also recorded regarding slope with dispersed cracks.

The installation of a horizontal drain improved slope stability and safety, apart from maintaining the groundwater level during rainy seasons. However, its effectiveness depended on the locations of the crack and drain. Several research reports indicated that the location of the installed drain significantly influenced its ability to improve slope stability [49-51]. Cook et al. [52] further stated that horizontal drains positioned to intercept water before reaching the unstable zone were more effective. These drains should be installed near the crack and saturated soil layer to enhance the safety factor of the slope. The effectiveness was maximized when installed in areas with cracked soil, provided that the groundwater

level was lower than the horizontal drain. Under these circumstances, the drains removed rainwater trapped in the slope found at the end of the crack, thereby increasing the safety factor.

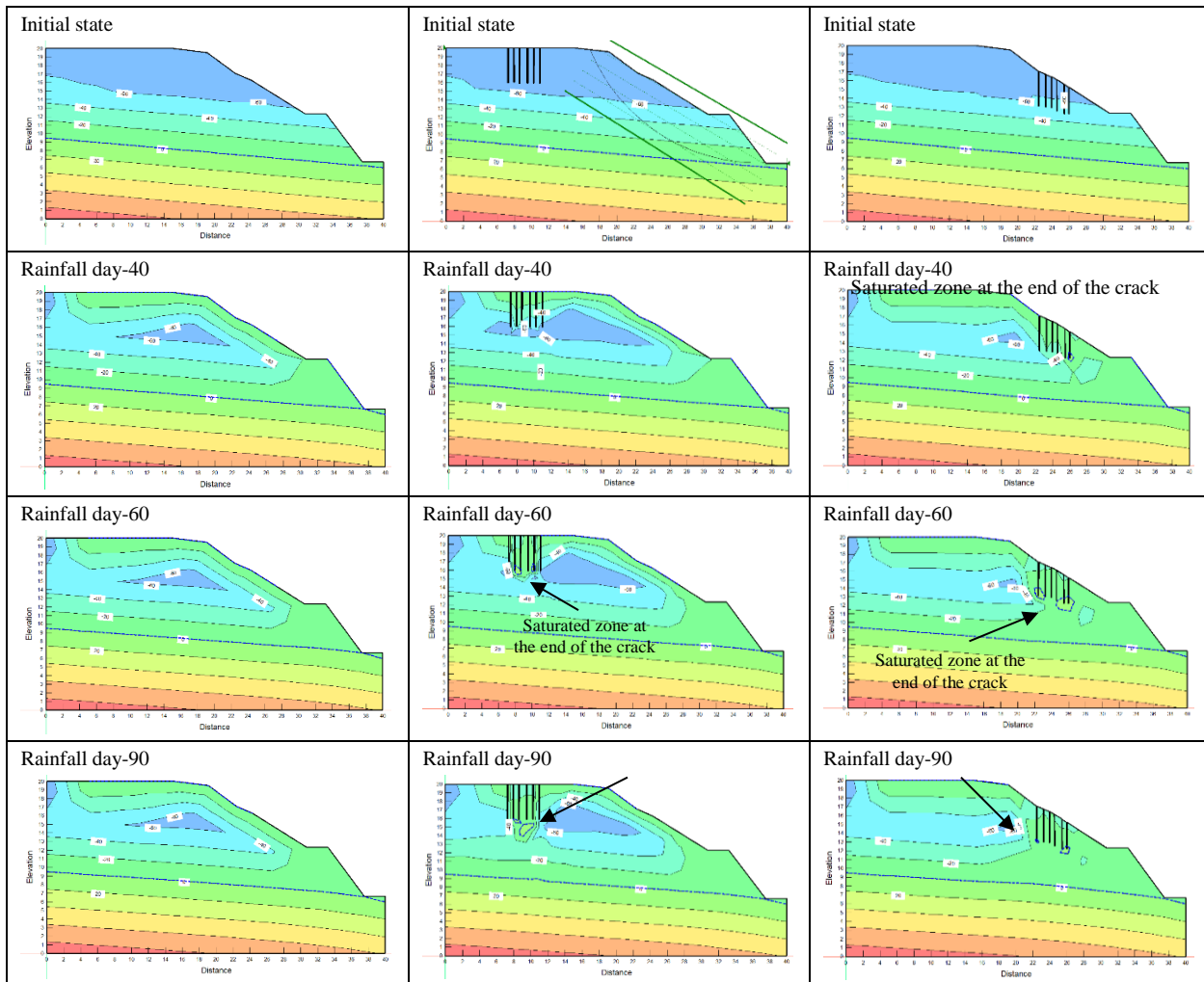


Figure 8. The condition of the slope and groundwater level that occurs when it rains after installing 1 horizontal drain at the toe of the slope

Figure 11 shows the impact of horizontal drains on the safety factor when the crack spreads on the surface of the ground. The outcome proved that the safety factor of soil with cracks was lower than the uncracked after over 27 days of rain. However, the horizontal drain enhanced the slope’s safety factor after more than 57 days of rainfall. This was because the rise in groundwater level on the lower side was observed after 57 days of continuous rain, enabling the horizontal drain positioned beneath the slope to effectively increase the safety factor. When the crack was located above the slope and far from the edge, the horizontal drain offered only a minor improvement to the safety factor, as in Figure 12.

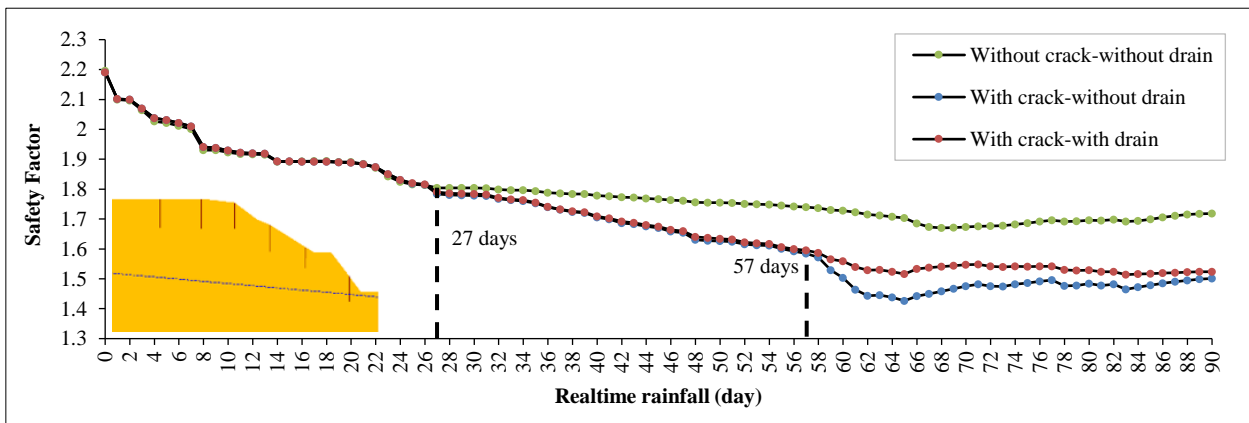


Figure 9. The influence of a horizontal drain on the safety factor if the crack is spreading on the ground surface

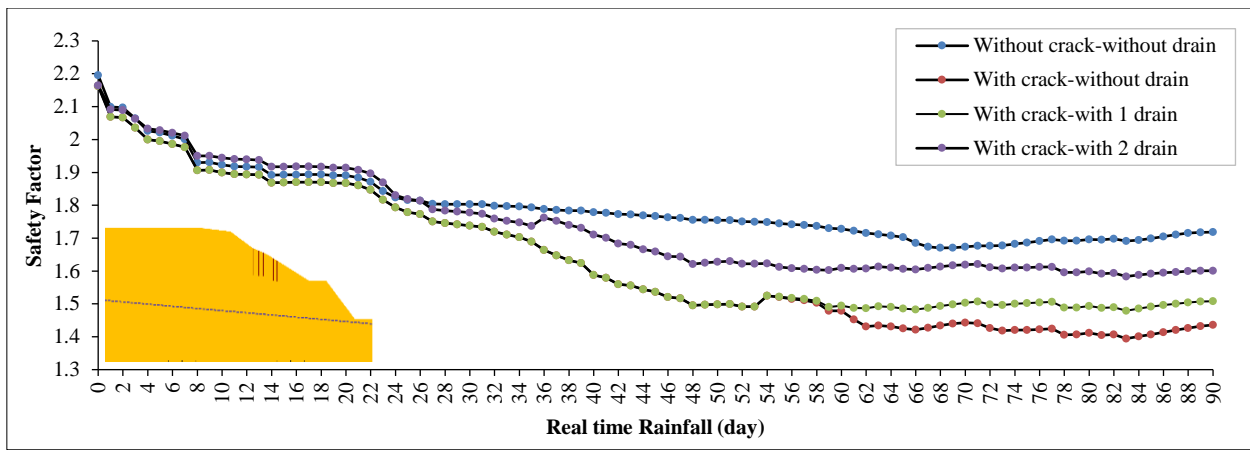


Figure 10. The effect of a horizontal drain on the safety factor if the crack is at the top of the slope

For the slope with a crack on the upper side, a horizontal drain was installed at the toe, resulting in a moderate increase in the safety factor. However, the effect of the horizontal drain under these conditions became noticeable only after the 60th day of continuous rainfall, as shown in Figure 13. A more significant improvement was achieved by installing a drain in the cracked area at the middle of the slope, which directly removed rainwater trapped in the saturated soil zone caused by the crack. The combined presence of two horizontal drains; one at the toe and one in the middle of the slope within the cracked area; resulted in a substantial and immediate increase in the safety factor at the onset of rainfall.

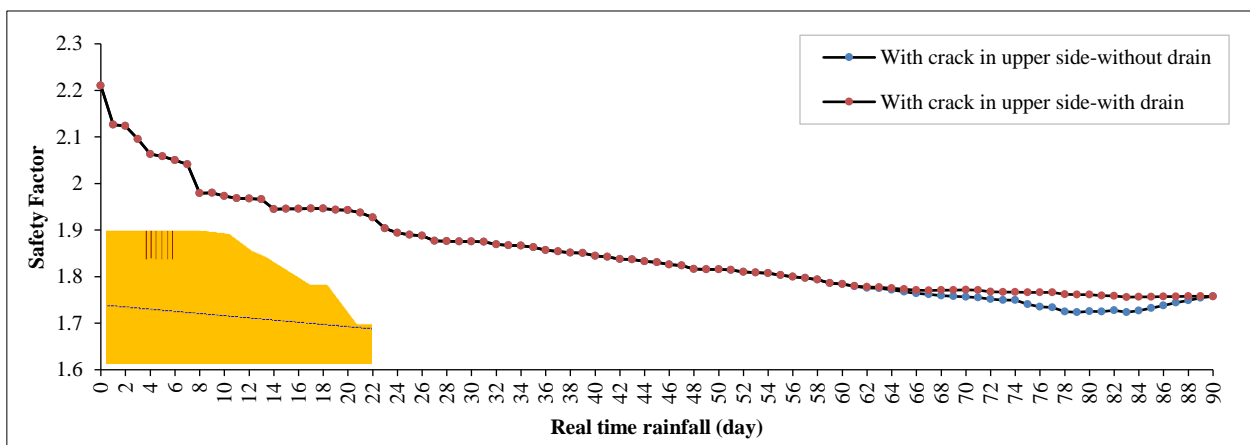


Figure 11. The influence of a horizontal drain on the safety factor if the crack is on the slope

The results of the analysis presented above showed that a crack in the ground affected the slope stability. In addition, Kang et al. [53] conducted a landslide case in China, outlining the role of soil cracks in the incidents. During the heavy rains in 2016, several cracks were formed, which prompted the installation of a crack meter to measure its speed. The results indicated that infiltration caused an average displacement rate exceeding 30 millimeter/year in the main crack. Furthermore, the soil with cracks has decreased shear strength during the first 30 d of continuous rainfall. This was caused by the interaction of soil and water. A similar scenario was observed, where the safety factor of the cracked slope decreased after 27 days of rain due to the formation of a saturated layer at the crack tip. Mukhlisin & Aziz [54], Alexander et al. [55], and Wang et al. [56] also found that the presence of cracks significantly reduced slope stability.

Several previous studies reported the efficacy of horizontal drains in reducing landslides by declining groundwater levels [57-59]. Investigation into the effectiveness of horizontal drains under rainy conditions was conducted using a higher hydraulic conductivity value. For example, Tang et al. [60] found that adding a horizontal drain raised the safety factor by approximately 25 percent when monitored for 48 hours after 9 hours of rainfall at a rate of 60 mm/hour, and the investigation was carried out on $K_s = 9.2 \times 10^{-6}$ m/s soil. Similarly, Rahardjo et al. [51] reported that installing a horizontal drain raised the SF from 1,193-1,303 when K_s was 2.1×10^{-7} m/s. These drains were placed at the toe of the slope, measuring 12-18 meters in length, with Tang et al.'s [60] installed within 25-30 meters in length. Liu et al. [2] reported that increasing the safety factor using horizontal drains combined with subsurface drainage raised the value from 1,098 to 1,228. Although horizontal drains had not been tested on cracked soil in previous research, it had been proven to increase the safety factor by reducing the groundwater level on the slope.

Matti et al. [61] reported the effectiveness of horizontal drains installed in Hong Kong for landslide reduction. Moreover, a typical observation was that not all horizontal drains functioned properly at the same location. Some drains tended to quickly reduce water, and others hardly emitted any fluid. This observation was consistent with the formation of saturated zones caused by vertical cracks that only occurred in certain locations because of faults in the soil. An anomaly in the effectiveness of horizontal drains was triggered by the crack that was formed previously. A horizontal drain that rapidly released water was installed in an area with a saturated zone due to this condition. Meanwhile, a drain that failed to emit water was installed in an unsaturated area. Ismail et al. [62] obtained similar results by assessing the difference in the efficiency of installed horizontal drains based on the resistivity values from geophysical tests in the field.

Based on these results and other validated research, crack presence significantly reduced slope stability. The crack in soil created a new saturated zone at its tip after several days of rain, and the position influenced the formation of the saturated zone. The duration of rainfall required for the formation and subsequent reduction in slope safety factor was also observed. Fortunately, this negative impact could be reduced by installing horizontal drains in the appropriate position. Appropriately placed horizontal drains tended to effectively increase the slope safety factor during extended periods of rainfall. Crack position in the ground must be considered when determining the optimal location for drain installation.

5. Conclusion

In conclusion, the critical influence of crack position on slope stability and the effectiveness of horizontal drains as a mitigation measure, analyzed through integrated transient seepage and limit equilibrium methods, were successfully investigated. The results can be summarized as follows. Cracks accelerated infiltration and weakened slopes. Their presence in unsaturated soil triggered rainwater infiltration, leading to a rapid build-up of pore water pressure and the formation of localized saturated zones at crack tips. This process was observed after 40 days of continuous rainfall, resulting in the development of weak layers within the slope. In addition, it significantly reduced the safety factor, thereby compromising long-term stability.

Crack location was another determining factor, as it influenced the failure mechanism. Cracks located on the slope face led to faster formation of saturated zones compared to those at the crest. Furthermore, cracks near the groundwater table rapidly caused a rise in the water level, intensifying instability. The effectiveness of horizontal drains was strongly dependent on their location. Drains installed near crack locations and associated saturated zones were highly effective, increasing the safety factor by approximately 13%. In contrast, drains positioned away from these critical zones provided minimal improvement, challenging conventional uniform installation approaches.

Field validation and practical application using ERT revealed deeper rainwater infiltration patterns during the wet season, supporting the numerical model predictions and reinforcing the practical relevance of the results. Therefore, a proactive, diagnosis-based approach is essential for effective landslide mitigation. Identifying crack locations and understanding their roles in forming critical zones enable optimized placement of horizontal drains to intercept and remove trapped water. This strategy ensures efficient use of mitigation resources and significantly enhances slope stability in cracked soil environments subjected to prolonged rainfall.

6. Declarations

6.1. Author Contributions

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

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

7. References

- [1] Nam, S., Gutierrez, M., Diplas, P., & Petrie, J. (2021). Laboratory and in situ determination of hydraulic conductivity and their validity in transient seepage analysis. *Water (Switzerland)*, 13(8), 1–20. doi:10.3390/w13081131.
- [2] Liu, H., Lei, T. W., Zhao, J., Yuan, C. P., Fan, Y. T., & Qu, L. Q. (2011). Effects of rainfall intensity and antecedent soil water content on soil infiltrability under rainfall conditions using the run off-on-out method. *Journal of Hydrology*, 396(1–2), 24–32. doi:10.1016/j.jhydrol.2010.10.028.
- [3] Que, Y., Lin, P., & Lin, D. (2018). Integrative Analysis of Surface Runoff and Macropore Flow for Slopes under Rainfall Conditions. *Mathematical Problems in Engineering*, 2018(9458410). doi:10.1155/2018/9458410.
- [4] Alessander, S., Mochtar, I. B., & Utama, W. (2017). The measurements of water intrusion through cracks propagation inside slopes to explain the cause of slope failure: Case study of embankment in the Sanggu–Buntok Airport, Central Kalimantan, Indonesia. *Electronic Journal of Geotechnical Engineering (EJGE)*, 5347–5363.
- [5] Hutagamissufardal, Mochtar, I. B., & Endah Mochtar, N. B. (2018). The Effect of Soil Cracks on Cohesion and Internal Friction Angle at Landslide. *Journal of Applied Environmental and Biological Sciences*, 8(3), 1–5.
- [6] Wei, X., Gao, C., Yan, D., & Liu, K. (2020). Experimental Study on Cracking Behavior and Mechanism in Desiccating Soils in Xi'an, Shaanxi Province, China. *Advances in Civil Engineering*, 8874986. doi:10.1155/2020/8874986.
- [7] Mukhlisin, M., & Khiyon, K. N. (2018). The Effects of Cracking on Slope Stability. *Journal of the Geological Society of India*, 91(6), 704–710. doi:10.1007/s12594-018-0927-5.
- [8] Suryo, E., Gallage, C., & Trigunarsyah, B. (2015). A method for predicting rain-induced instability of an individual slope. *Proceedings of the 9th Annual International Conference of the International Institute for Infrastructure Renewal and Reconstruction, Brisbane, Australia, 8-11 July, 2013*.
- [9] Gofar, N., Lee, M. L., & Asof, M. (2006). Transient seepage and slope stability analysis for rainfall-induced landslide: A case study. *Malaysian Journal of Civil Engineering*, 18(1), 1-13.
- [10] Cai, S., Zhang, Z., Liu, X., Lv, Q., Lai, R., & Yang, X. (2025). Effect of Cracks on Soil Slope Stability under Different Rainfall Intensities. *Iranian Journal of Science and Technology - Transactions of Civil Engineering*, 1-19. doi:10.1007/s40996-025-01958-4.
- [11] Zhang, L., Jiang, X., Sun, R., Gu, H., Fu, Y., & Qiu, Y. (2024). Stability analysis of unsaturated soil slopes with cracks under rainfall infiltration conditions. *Computers and Geotechnics*, 165, 105907. doi:10.1016/j.compgeo.2023.105907.
- [12] Zhang, J., Dong, J., Zhao, Y., Wang, Y., & Cheng, Y. (2025). Stability of Non-Uniform Soils Slope with Tension Cracks Under Unsaturated Flow Conditions. *Buildings*, 15(12), 2123. doi:10.3390/buildings15122123.
- [13] Ferreira, S. R. de M., Araújo, A. G. D. de, Barbosa, F. A. S., Silva, T. C. R., & Bezerra, I. M. de L. (2020). Analysis of changes in volume and propagation of cracks in expansive soil due to changes in water content. *Revista Brasileira de Ciência Do Solo*, 44. doi:10.36783/18069657rbcS20190169.
- [14] Cheng, Q., Tang, C. S., Xu, D., Zeng, H., & Shi, B. (2021). Water infiltration in a cracked soil considering effect of drying-wetting cycles. *Journal of Hydrology*, 593, 125640. doi:10.1016/j.jhydrol.2020.125640.
- [15] Feng, H., Xing, X., Xing, J., Du, J., & Li, D. (2025). Performance and modeling of infiltration flow in cracked saline soils. *Journal of Hydrology*, 656, 133054. doi:10.1016/j.jhydrol.2025.133054.
- [16] Xing, X., Nie, W., Chang, K., Zhao, L., Li, Y., & Ma, X. (2023). A numerical approach for modeling crack closure and infiltrated flow in cracked soils. *Soil and Tillage Research*, 233, 105794. doi:10.1016/j.still.2023.105794.
- [17] Zhang, Z., Zeng, R., Meng, X., Zhao, S., Wang, S., Ma, J., & Wang, H. (2023). Effects of changes in soil properties caused by progressive infiltration of rainwater on rainfall-induced landslides. *Catena*, 233, 107475. doi:10.1016/j.catena.2023.107475.
- [18] Lakruwan, M., Oikawa, H., Kamura, A., & Kazama, M. (2025). Effect of Perforation Arrangement on Entrance Head Loss of Horizontal Drains and Selection Criterion for Permeability of Geotextile Envelope. *Journal of Irrigation and Drainage Engineering*, 151(1), 04024034. doi:10.1061/jidedh.ireng-10362.
- [19] Dourte, D., Shukla, S., Singh, P., & Haman, D. (2013). Rainfall Intensity-Duration-Frequency Relationships for Andhra Pradesh, India: Changing Rainfall Patterns and Implications for Runoff and Groundwater Recharge. *Journal of Hydrologic Engineering*, 18(3), 324–330. doi:10.1061/(asce)he.1943-5584.0000625.
- [20] Zheng, W., Wang, S., Sprenger, M., Liu, B., & Cao, J. (2019). Response of soil water movement and groundwater recharge to extreme precipitation in a headwater catchment in the North China Plain. *Journal of Hydrology*, 576(May), 466–477. doi:10.1016/j.jhydrol.2019.06.071.
- [21] He, Y., Sun, R., Xu, Z., & Tang, W. (2021). The dynamic change and effect of rainfall induced groundwater flow. *Water (Switzerland)*, 13(19), 2625. doi:10.3390/w13192625.

- [22] Sangrey, D. A., Harrop-Williams, K. O., & Klaiber, J. A. (1984). Predicting ground-water response to precipitation. *Journal of Geotechnical Engineering*, 110(7), 957–975. doi:10.1061/(ASCE)0733-9410(1984)110:7(957).
- [23] Mein, R. G., & Larson, C. L. (1973). Modeling Infiltration during a Steady Rain. *Water Resources Research*, 9(2), 384-394. doi:10.1029/wr009i002p00384.
- [24] Sasekaran, M. (2009). Impact of permeability and surface cracks on soil slopes. Master Thesis, The University of Manchester, Manchester, United Kingdom.
- [25] Lumb, P. (1975). Slope failures in Hong Kong. *Quarterly Journal of Engineering Geology and Hydrogeology*, 8(1), 31-65. doi:10.1144/gsl.qjeg.1975.008.01.02.
- [26] Heber Green, W., & Ampt, G. A. (1911). Studies on soil physics. *The Journal of Agricultural Science*, 4(1), 1–24. doi:10.1017/S0021859600001441.
- [27] Pradel, D., & Raad, G. (1993). Effect of permeability on surficial stability of homogeneous slopes. *Journal of Geotechnical Engineering*, 119(2), 315–332. doi:10.1061/(ASCE)0733-9410(1993)119:2(315).
- [28] Richards, L. A. (1931). Capillary conduction of liquids through porous mediums. *Journal of Applied Physics*, 1(5), 318–333. doi:10.1063/1.1745010.
- [29] Fredlund, D. G., & Rahardjo, H. (1993). *Soil mechanics for unsaturated soils*. John Wiley & Sons, Hoboken, United States. doi:10.1002/9780470172759.
- [30] Thieu, N. T. M., Fredlund, M. D., Fredlund, D. G., & Hung, V. Q. (2001). Seepage modeling in a saturated/unsaturated soil system. *Proceedings of the international conference on management of the land and water resources*, 20-22 October, 2001, Hanoi, Vietnam.
- [31] Lam, L., Fredlund, D. G., & Barbour, S. L. (1987). Transient seepage model for saturated-unsaturated soil systems: a geotechnical engineering approach. *Canadian Geotechnical Journal*, 24(4), 565–580. doi:10.1139/t87-071.
- [32] Fredlund, D. G., & Anqing Xing. (1994). Equations for the soil-water characteristic curve. *Canadian Geotechnical Journal*, 31(4), 521–532. doi:10.1139/t94-061.
- [33] Sari, P. T. K., Lastiasih, Y., & Shoffiana, N. A. (2022). Comparison of Safety Factor and Geosynthetic Reinforcement Requirement for Slope Stability Using 2-D and 3-D Analysis Method. *Journal of Applied Engineering Science*, 20(4), 1016–1026. doi:10.5937/jaes0-34051.
- [34] Wang, Z. F., Li, J. H., & Zhang, L. M. (2011). Influence of cracks on the stability of a cracked soil slope. *Proceedings of the 5th Asia-Pacific Conference on Unsaturated Soils*, 14-16 November, 2011, Dusit Thani Pattaya, Thailand.
- [35] Zhang, Z., Tao, M., & Morvant, M. (2005). Cohesive Slope Surface Failure and Evaluation. *Journal of Geotechnical and Geoenvironmental Engineering*, 131(7), 898–906. doi:10.1061/(asce)1090-0241(2005)131:7(898).
- [36] Suryo, E. A. (2013). Real-time prediction of rainfall-induced instability of residual soil slopes associated with deep cracks. Ph.D. Thesis, he Queensland University of Technology, Brisbane, Australia.
- [37] Sari, P. T. K., Mochtar, I. B., & Chaiyaput, S. (2023). Effectiveness of Horizontal Sub-drain for Slope Stability on Crack Soil Using Numerical Model. *Geotechnical and Geological Engineering*, 41(8), 4821–4844. doi:10.1007/s10706-023-02550-1.
- [38] Lin, D.-G., Hung, S.-H., Ku, C.-Y., & Chan, H.-C. (2016). Evaluating the efficiency of subsurface drainages for Li-Shan landslide in Taiwan. *Natural Hazards and Earth System Sciences Discussions*, 1(January), 1–22. doi:10.5194/nhess-2015-309.
- [39] jetvaj V., Znidarčič D., Nossan A.S., & Popovič N. (2009). Increase of slope stability with time by drilled drains. *Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering.* doi:10.3233/978-1-60750-031-5-1714.
- [40] Rahardjo, H., Nio, A. S., Leong, E. C., & Song, N. Y. (2010). Effects of Groundwater Table Position and Soil Properties on Stability of Slope during Rainfall. *Journal of Geotechnical and Geoenvironmental Engineering*, 136(11), 1555–1564. doi:10.1061/(asce)gt.1943-5606.0000385.
- [41] Rahimi, A., Rahardjo, H., & Leong, E. C. (2010). Effect of hydraulic properties of soil on rainfall-induced slope failure. *Engineering Geology*, 114(3–4), 135–143. doi:10.1016/j.enggeo.2010.04.010.
- [42] Zhao, L. H., Cheng, X., Zhang, Y., Li, L., & Li, D. J. (2016). Stability analysis of seismic slopes with cracks. *Computers and Geotechnics*, 77, 77-90. doi:10.1016/j.compgeo.2016.04.007.
- [43] Liu, D., & She, D. (2020). The effect of fracture properties on preferential flow in carbonate-derived laterite from karst mountainous agroforestry lands. *Soil and Tillage Research*, 203, 104670. doi:10.1016/j.still.2020.104670.
- [44] Acosta, J. A., Gabarrón, M., Martínez-segura, M., Martínez-martínez, S., Faz, Á., Pérez-pastor, A., Gómez-lópez, M. D., & Zornoza, R. (2022). Soil Water Content Prediction Using Electrical Resistivity Tomography (ERT) in Mediterranean Tree Orchard Soils. *Sensors*, 22(4), 1365. doi:10.3390/s22041365.

- [45] Kazmi, D., Qasim, S., Siddiqui, F. I., & Azhar, S. B. (2016). Exploring the relationship between moisture content and electrical resistivity for sandy and silty soils. *International Journal of Engineering Science Invention*, 5(6), 33-35.
- [46] Rostami, H., & Osouli, A. (2021). Electrical Resistivity Changes in Wet and Dry Side of Optimum Moisture Content for Soils with Low to High Fines Content. *Advances in Transportation Geotechnics IV*, 829–836. doi:10.1007/978-3-030-77234-5_68.
- [47] Royster, D. L. (1980). Horizontal drains and horizontal drilling: an overview. *Transportation Research Record*, 783, 16-20.
- [48] Barrett, R. K. (1980). Use of horizontal drains: Case histories from the colorado division of highways (No. 783). 59th Annual Meeting of the Transportation Research Board, 21-25 January, 1980, Washington, United States.
- [49] Lau, K. C., & Kenney, T. C. (1984). Horizontal drains to stabilize clay slopes. *Canadian Geotechnical Journal*, 21(2), 241–249. doi:10.1139/t84-027.
- [50] Rahardjo, H., Hritzuk, K. J., Leong, E. C., & Rezaur, R. B. (2003). Effectiveness of horizontal drains for slope stability. *Engineering Geology*, 69(3–4), 295–308. doi:10.1016/S0013-7952(02)00288-0.
- [51] Rahardjo, H., Santoso, V. A., Leong, E. C., Ng, Y. S., & Hua, C. J. (2011). Performance of horizontal drains in residual soil slopes. *Soils and Foundations*, 51(3), 437–447. doi:10.3208/sandf.51.437.
- [52] Cook, D. I., Santi, P. M., & Higgins, J. D. (2008). Horizontal landslide drain design: State of the art and suggested improvements. *Environmental and Engineering Geoscience*, 14(4), 241–250. doi:10.2113/gseegeosci.14.4.241.
- [53] Kang, X., Wang, S., Wu, W., Xu, G., Zhao, J., & Liu, F. (2022). Soil–water interaction affecting a deep-seated landslide: From field monitoring to experimental analysis. *Bulletin of Engineering Geology and the Environment*, 81(2), 82. doi:10.1007/s10064-021-02556-0.
- [54] Mukhlisin, M., & Aziz, N. A. B. A. (2016). Study of horizontal drain effect on slope stability. *Journal of the Geological Society of India*, 87(4), 483–490. doi:10.1007/s12594-016-0417-6.
- [55] Aleksander, S., Mochtar, I. B., & Utama, W. (2018). Field validated prediction of latent slope failure based on cracked soil approach. *Lowland Technology International*, 20(3), 245–258.
- [56] Wang, L., Li, R., Zhang, S., Li, R., Bai, W., & Xiao, H. (2022). Function of a Deep-Buried Isolated Trench and Its Effect on Cracking Failure Characteristics of a Slope under Artificial Rainfall. *Water (Switzerland)*, 14(7), 1123. doi:10.3390/w14071123.
- [57] Sari, P. T. K. (2022). The Performance of Horizontal Drain as a Landslide Mitigation Strategy. *Proceedings of the 5th International Conference on Rehabilitation and Maintenance in Civil Engineering*, 449–456. doi:10.1007/978-981-16-9348-9_39.
- [58] Lakruwan, M., Oikawa, H., Kamura, A., & Kazama, M. (2021). Experimental evaluation of effect of perforation arrangement on performance of horizontal drains in landslide mitigation. *Landslides*, 18(11), 3707–3714. doi:10.1007/s10346-021-01724-3.
- [59] Rahim, M. S. M., Taib, A. M., Rahman, N. A., Fauzi, N. H. A. M., & Ramli, A. B. (2021). Study of Residual Soil Slope Stability With the Application of Horizontal Drainage. *Journal of Southwest Jiaotong University*, 56(4), 394–401. doi:10.35741/issn.0258-2724.56.4.35.
- [60] Tang, L., Tang, X., & Liu, W. (2011). A case study of effect of horizontal drains on rainfall-induced landslide. *Advanced Materials Research*, 250–253, 1834–1837. doi:10.4028/www.scientific.net/AMR.250-253.1834.
- [61] Matti, B., Tacher, L., & Commend, S. (2012). Modelling the efficiency of a drainage gallery work for a large landslide with respect to hydrogeological heterogeneity. *Canadian Geotechnical Journal*, 49(8), 968–985. doi:10.1139/T2012-061.
- [62] Ismail, M. A. M., Ng, S. M., & Abustan, I. (2017). Parametric study of horizontal drains for slope stability measure: A case study in Putrajaya, Malaysia. *KSCE Journal of Civil Engineering*, 21(6), 2162–2167. doi:10.1007/s12205-016-1084-2.