



Effectiveness of Horizontal Sub-drain for Slope Stability on Crack Soil Using Numerical Model

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Abstract A landslide occurred in the hilly area of Tulakan District, Pacitan, East Java Province, Indonesia. This was due to a period of heavy rain, resulting in a cumulative intensity of over 1000 mm in one month and a maximum daily rainfall exceeding 300 mm. Previous reports have suggested the use of horizontal sub-drains to manage groundwater levels and rainwater seepage to reduce the impact on slope stability. Therefore, this study aimed to determine the effectiveness of horizontal sub-drain as an alternative for managing groundwater and rainwater that seeped into the soil to increase the slope factor of safety by using numerical model. It also considered various factors such as the effect of real-time rainfall over a 30-day period before the landslide, hydraulic conductivity, soil parameter due to cracking and weathering, and the existing groundwater level. The coupled programs SEEP/W and SLOPE/W were used for analyses. The result showed that the horizontal sub-drain only increased the safety factor by less than 2% in the presence of a vertical crack and up to 7.7% with vertical cracks and weak layers in high ground

water levels. In addition, this study found that horizontal sub-drains could be more effective in increasing the safety factor up to 11.5% when the rainfall intensity was higher (between $1.41 \times 10^{-0.5}$ and $1.85 \times 10^{-0.7}$ m/s) and lasted for 14 days. The installation position of the drains, soil conditions, rainfall condition, and contour topography were some of the factors that influenced the effectiveness of the horizontal sub-drains in increasing slope stability.

Keywords Landslide · Rainfall · Coupled program seep/w and slope/w · Horizontal sub-drain, slope stability

1 Introduction

Slope failure, in which large amounts of soil move downslope under the force of gravity, occurs commonly globally. It occurs when the shear stress exceeds the shear strength of the slope (Jeong 2022). Several studies have been conducted to identify the primary causes of landslides, which are becoming increasingly frequent in both saturated and unsaturated soil conditions. Based on previous reports on the mechanism of occurrence in form of laboratory testing, numerical modeling, and field, it was discovered that landslides occur because of many factors related to the hydrological condition. Changes in rainfall patterns affect the hydrogeological and water fluctuation conditions, as well as the fracture conditions

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of the soil, which are primarily influenced by the rainfall behavior and topography of the area.

Past rainfall conditions that have triggered landslides change over extended periods or vary in the future due to environmental and climatic changes, including changes in intensity, frequency, and patterns of meteorological triggering events (Gariano et al. 2015). Variations in the intensity and frequency of rainfall events can have an impact on the prevalence of landslides induced by rainfall (Luigi and Guzzetti 2017). Changes in rainfall patterns can also affect the boundary conditions of water flow, such as infiltration and evapotranspiration, which in turn impact water pressure in the soil. As rainwater seeps through soil pores, soil moisture content increases, and the groundwater table is raised, particularly in soils with seepage coefficients greater than the rainfall intensity. This causes an increase in pore-water pressure and a decrease in effective stress, reducing the shear strength of the soil to withstand loading. When the shear strength mobilized along a critical slip surface is no longer sufficient to support the shear stress, the soil mass slips, and the slope fails.

Several studies, including (Rupp 2022; Rahimi et al. 2011) showed that antecedent rainfall was the primary cause of landslides, because it affected the stability of low-conductivity slopes more than high-conductivity slopes. Different rainfall patterns have been found to impact varying types of slopes. High-conductivity slopes tend to reach their minimum factor of safety under delayed rainfall patterns, where the intensity increases with time and reaches a maximum near the end of the event. In contrast, low-conductivity slopes reach their minimum factor of safety under advanced rainfall patterns, where the intensity is high at the beginning and decreases with time. Another study was also carried out to determine the landslides by comparing their prevalence during the rainy season with a various rainfall intensity and dry seasons (Kristo et al. 2017; Ciabatta et al. 2016). The results showed that most landslides occur during the rainy season.

Geological conditions are a significant factor in the occurrence of landslides, with soil thickness and rock fragment cover identified by (Lee et al. 2022; Vasudevan and Ramanathan 2016) as important contributors to soil hydrological and landslide behaviors. Thinner soils have been found to exhibit higher infiltration capacity and lower erosion rates across

various rainfall events. Moisture content is also a critical parameter affecting slope stability. The study on cohesive soils found that high moisture content in slopes was due to surface water infiltration from rainfall. Moreover, a soil with moisture content near its liquid limit is expected to behave more similar with a liquid than those with little shear strength. This indicated that excessively high moisture content approximately close to liquid limits correlated to slope surface failures, thereby causing a decrease in the soil's shear strength. Most slope surface failures occur when their soils become saturated.

A study conducted by (Nyakundi et al. 2016) focused on the impact of rain on groundwater levels, which ultimately affected slope stability. The results showed that the rainfall played a significant role among the factors influencing groundwater levels, while others included the infiltration rate and land cover. Geological formations can also lead to low infiltration rates, which delay the reflection of rainfall in the area. Furthermore, (He et al. 2021) discovered a formula to determine the effect of rainfall on changes in groundwater levels. (Li et al. 2020) also compared the effect of rain on changes in groundwater levels and soil moisture to the influence of the population development in an area. Research by (Alsubal et al. 2018) investigated the changes in the slope factor of safety due to rainfall variation and found that slopes with high soil permeability exhibited a decrease in factor of safety from 1.312 to 1.292 and 1.093 after the third rainfall event for slopes with and without pumping groundwater, respectively. For slopes with moderate permeability, the factor of safety declined from 1.314 to 1.157 by the end of the third day but remained stable with groundwater pumping. This is in line with the study by (Ariesta 2019), where the results from SEEP/W and SLOPE/W indicated that the initial condition of the groundwater level highly influenced the decrease of the safety factor, while the wetting process due to rainfall did not cause a significant reduction. Similarly, an investigation on the effect of groundwater levels has also been carried out by (Ibeh 2020; Taib et al. 2017).

Previous studies showed that cracks in the soil contributed to landslides because they created pathways for water flow, which increased hydraulic conductivity and pore-water pressures in the soil mass (Wang et al. 2018). Field studies showed that landslides on cracked slopes and weak soil layers are

more prevalent, specifically during rainfall events (Hutagamissufardal and Mochtar 2018; Mukhlisin 2018; Suryo et al. 2015; Rogers and Selby 1980). In New Zealand, landslides were found to be caused by pore pressure in soil cracks after previous rains (Rogers and Selby 1980). Weak soil layers are also characterized by high permeability and compressibility, which can significantly affect slope behavior, leading to changes in infiltration and deformation responses during rainfall. Therefore, (Suryo et al. 2015) stated that the effect of the weak layer needed to be analyzed with a focus on the infiltration-deformation-slope failure relationship. Similarly, (Mukhlisin and Khiyon 2018; Kodikara and Costa 2013; Suryo 2013; Alexander et al. 2017) reported that landslides are caused by soil cracks, with increased slope instability during rainfall.

The main cause of many landslides in the world is rainwater or changes in groundwater levels, as shown by previous studies. This means there is a need for a cost-effective effort such as the installation of horizontal sub-drain to increase slope stability by managing rainwater and groundwater levels. According to Mukhlisin and Aziz (2016), a horizontal sub-drain is very effective in lowering the groundwater level. Similarly, (Salmasi et al. 2019) stated that it increased slope stability during rainfall, specifically for dangerous slopes and embankments. Other studies, by Lakruwan et al (2021); Lin et al. (2020); Rahardjo (2012); Lakruwan et al. (2022a); Koperkr et al. (2013); Ahmed et al (2012); Lin et al. (2016); Pfeiffer (2014); Amatya and Mori (2018) reported the effectiveness and economic viability of horizontal sub-drains in reducing groundwater levels and increasing the slope factor of safety. In summary, (Sari 2023) identified horizontal sub-drains as an effective approach to manage groundwater levels and increase slope stability through the reduction of water levels.

This study aims to determine the mechanism of landslides that occurred at Tulakan, Pacitan, East Java, Indonesia, including the effect of soil parameters, the presence of cracks and weathering as well as fluctuating rainfall intensity on slope stability. Additionally, it aims to assess the effectiveness of a horizontal sub-drain as a cost-effective solution for managing landslides in the area. The horizontal sub-drain referred to in this study is a PVC pipe that is installed lengthwise into the slope with a certain inclination angle. Generally, this horizontal pipe is covered by

a membrane that functions as a filter, hence, water enters through the pipe holes without carrying soil particles which can cause the pipe clogging. Furthermore, the changes in groundwater levels due to rainfall with and without horizontal sub-drain by using transient water flow modelling are also discussed. The effectiveness of the horizontal sub-drain was analyzed using 2-dimensional coupled program SEEP/W and SLOPE/W to determine the effect of seepage and soil hydrological conditions on the slope stability (GEO-SLOPE International Ltd 2008a, 2008b).

2 Case Study: Landslide in Tulakan

In early December 2017, a natural landslide occurred in Tulakan Village, Pacitan, East Java, Indonesia, following heavy rainfall in the preceding days. Pacitan Regency is situated at the southwestern end of East Java Province and bordered by Ponorogo and Wonogiri Regencies (Central Java) to the north, Trenggalek and Ponorogo Regencies to the east, the Indian Ocean to the south, and Wonogiri to the west. The area is mostly karst, which is part of the Sewu Mountains chain, and not suitable for agriculture due to its barren and dry nature, with low groundwater levels. The landslide occurred in Tulakan Village, which is located in an area with hilly contours. Based on the geological map by the Center for Geological Research and Development in 1999 (Amin et al. 1999), as shown in Fig. 1, Pacitan has varied geological conditions, specifically in the mountainous areas of southern Java. The location of the slide is in a geological formation, namely Lava Oligo Miocene (basaltic pillow lava, intercalated by sandstone, claystone and chert) and middle Miocene Sediment (alternating sandstone, siltstone, claystone with interaction of conglomerate or breccia, lenses of lignite or silicified wood, locally marl, limestone and tuff occur). In addition, because it is located in a hilly area, the area has a moderate to high potential for landslides based on the landslide potential map from the Indonesian ministry of energy and mineral resources of the geological agency.

The landslide occurred caused a displacement in the foundation of a high-voltage electricity tower located just a few meters above the site, as shown in Fig. 2. In the absence of prompt measures to anticipate future landslides, the power supply to several

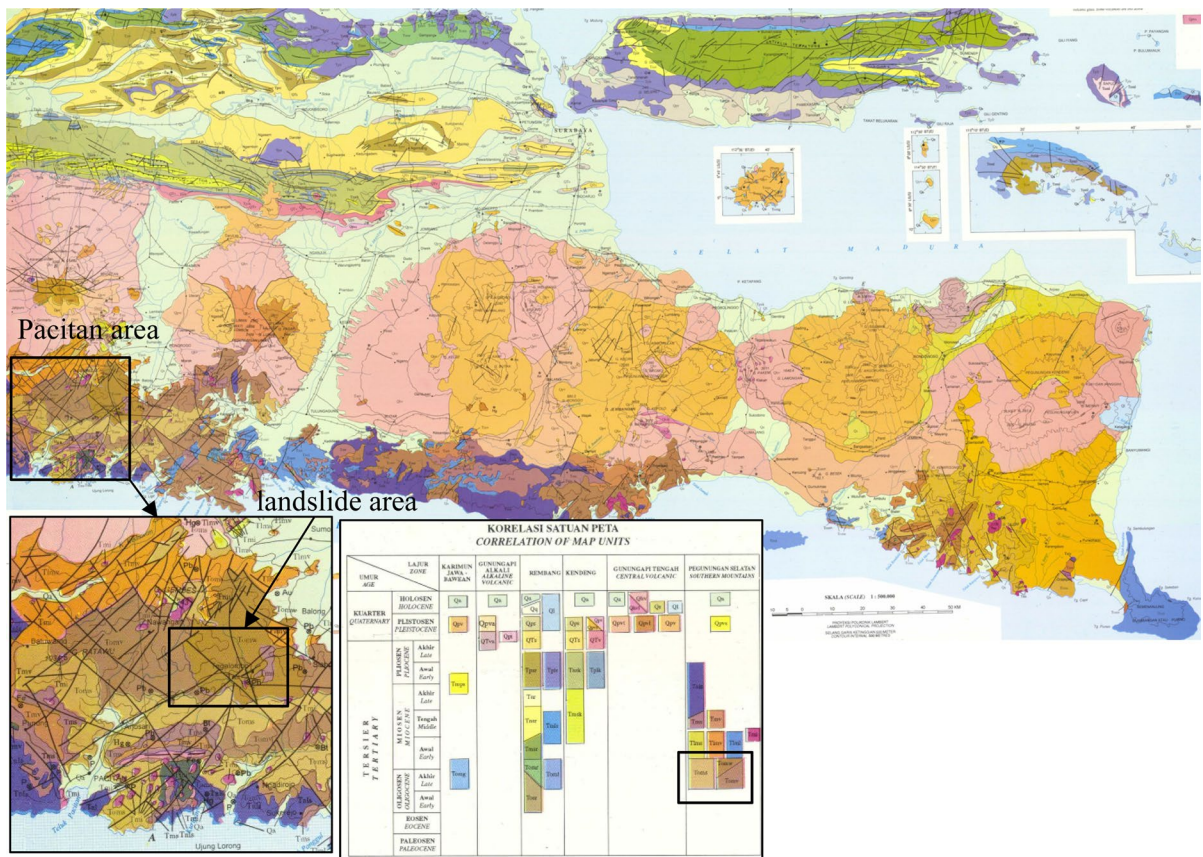


Fig. 1 Geological map of East Java, Indonesia and Pacitan as the study case locations (geology research and development center, 1999 (Amin et al. 1999))

areas in East Java could be affected. The area where the landslide took place is a sparsely populated hilly region, which has experienced minor landslides in the past. However, these landslides were shallow and did not require any action. This study focuses on the recent deep landslide that occurred in close proximity to the primary power source of East Java, necessitating a new approach to handle the situation.

According to observations from three nearby rain stations, the Pacitan area experienced extremely high levels of rainfall throughout November before the landslide occurred. The intensity of rain exceeded 1000 mm per month, with the highest value reaching 300 mm per day towards the end of the month, as shown in Fig. 3. The heavy rainfall is believed to be the primary cause of the landslide, which was further compounded by the weathered soil conditions and surface cracks.

The cause of the landslides was determined through several field tests, including Standard Penetration Test (SPT-N) and geophysics (resistivity and induced polarization). In addition, laboratory tests such as volumetric-gravimetric and unconfined tests were conducted to identify soil parameters. Topographic measurements were also performed in various locations to determine slope contours for current and long-term stability analysis, as shown in Fig. 4.

Field soil testing was conducted at four different locations, of which three were in a line with the landslide. Based on the Standard Penetration Test (SPT-N) results, the soil conditions were mainly characterized by hard soil layers with high SPT-N values, shown in Fig. 5a. Hard cohesive soil layers were also identified at shallow depths, up to approximately 10 m from the ground surface, while cohesionless and rocky layers were found at greater depths. At the landslide location, the soil layers were classified

Fig. 2 The landslide location in Tulakan Village as the study location

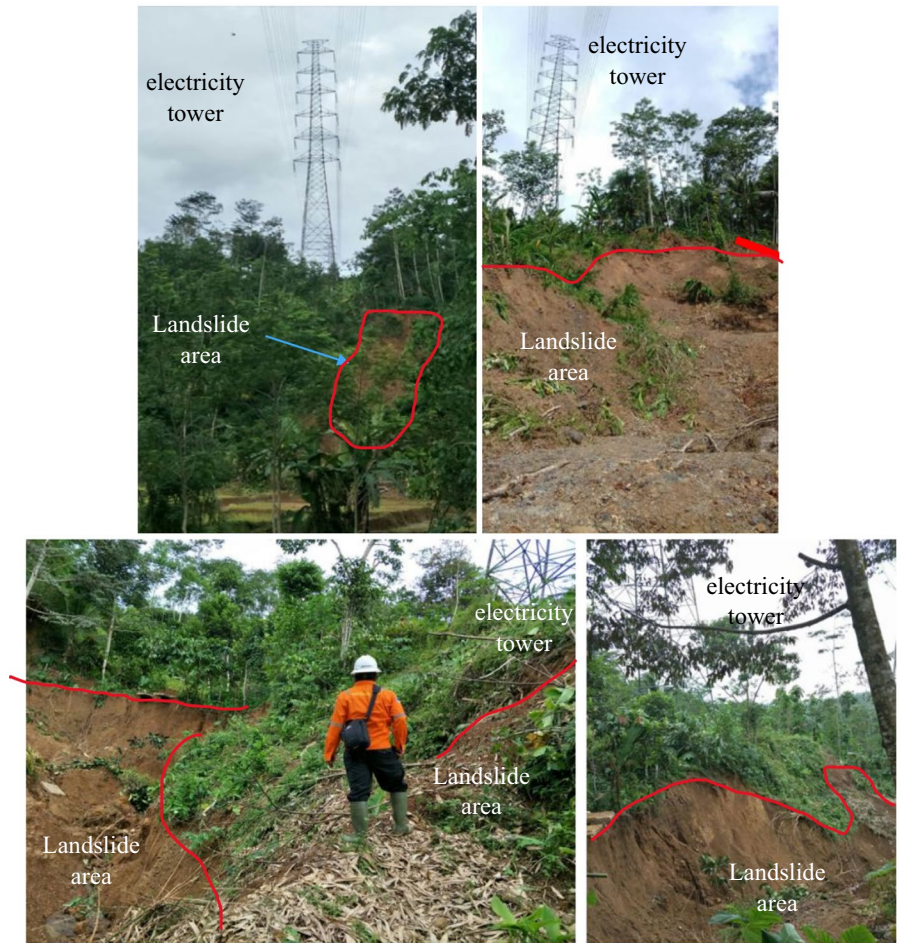
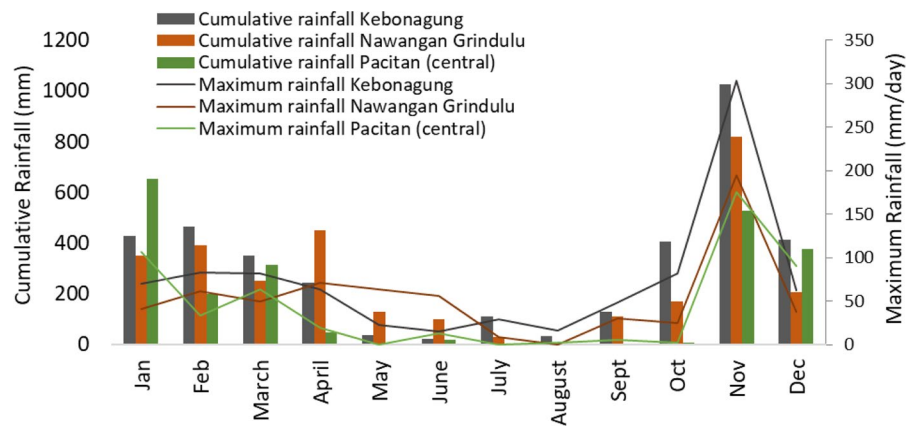


Fig. 3 The Rainfall intensity in Pacitan based on 3 rainfall stations in 2017 Cumulative rainfall and Maximum rainfall (data source: Ministry of Public Works and Public Housing of Indonesia-BBWS Bengawan Solo River)



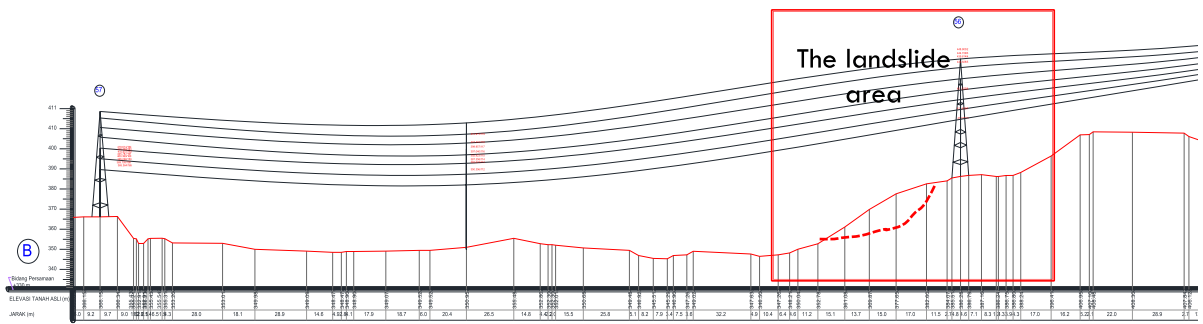


Fig. 4 The topographic contour of the landslide area

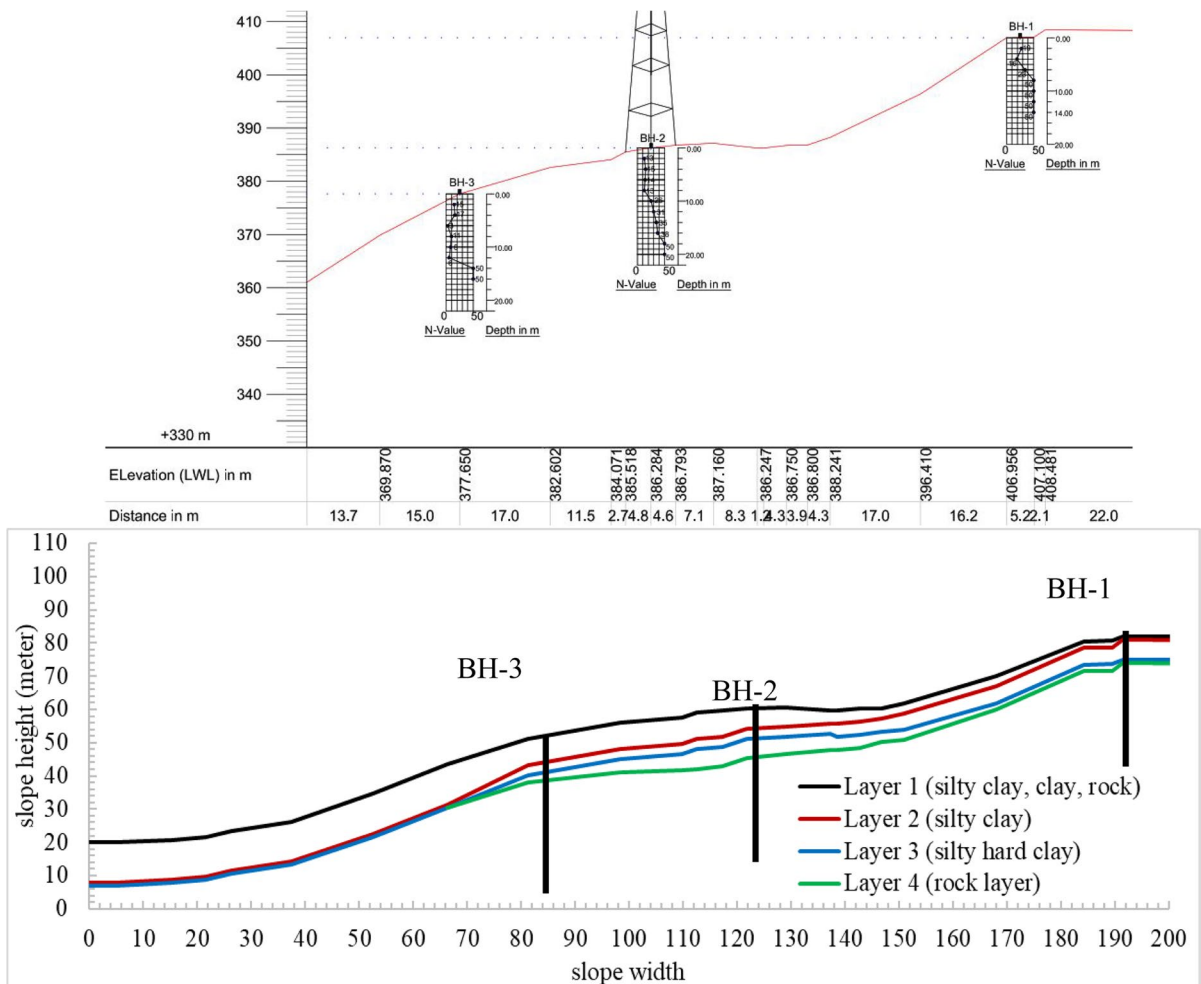


Fig. 5 Soil surface condition. **a** Standard Penetration Test (SPT-N) soil testing and testing location, **b** Soil layer under the landslide area

into four layers consisting of silty clay, clay, rock on the surface, silty clay on the second layer, silty hard clay on the third layer, and rock on the fourth layer, as shown in Fig. 5b.

3 Theoretical Consideration

This study which concerned slope stability under the rainfall was carried out using 2 analyses. The first analysis was the seepage analysis, which utilized SEEP/W software to calculate the pore-water pressures. The second analysis was the slope factor of safety calculation, with SLOPE/W software used to evaluate soil slope stability. The governing equation for water flow, used in the software to solve a transient and two-dimensional seepage analysis, is expressed below:

$$m_w^2 \gamma_w \frac{\delta h_w}{\delta t} = \frac{\delta}{\delta_x} \left(-k_{wx} \frac{\delta h_w}{\delta_x} \right) + \frac{\delta}{\delta_y} \left(-k_{wy} \frac{\delta h_w}{\delta_y} \right) + q$$

where m_w^2 , γ_w , h_w , t , k_{wx} and k_{wy} , and q are the slope of the soil–water characteristic curve, unit weight of water, hydraulic or total head, time, coefficients of permeability to water as a function of matric suction in the x- and y-direction, as well as applied flux at the boundary. Soil–water characteristic curve (SWCC) and permeability function were the two primary soil properties used in the seepage analysis.

The shear strength equation for unsaturated soil used in the slope stability analyses that incorporated its contribution from negative pore-water pressure or matric suction of unsaturated soil, as shown below:

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

where τ , c' , $(\sigma_n - u_w)$, σ_n , u_a , u_w , ϕ' , $(u_a - u_w)$, and ϕ^b denote the shear strength of unsaturated soil, effective cohesion, net normal stress, total normal stress, pore-air pressure, pore-water pressure, effective angle of internal friction, matric suction, and the angle indicating the rate of increase in shear strength relative to the matric suction, respectively. Due to limited data on unsaturated soil conditions, the suction value parameter in this study was carried out by assuming the residual water content was 10% of the saturated water content of the soil in the SLOPE/W modeling coupled with SEEP/W. The Bishop simplified method was used to compute the slope safety factor (Bishop

1955). Based on the previous study, this method has less computational effort, time required for analysis, and is more accurate compared to others.

4 Methodology

The slope profile numerical model was created based on the existing field conditions, including topography, sub-surface layers, and hydrological conditions at the landslide location. Several rainfall-induced seepage and slope stability analyses were carried out using both finite element method (FEM) and limit equilibrium method (LEM), with and without horizontal sub-drain, and with and without considering surface crack and weathered soil layers. In the FEM seepage analysis, the pore-water pressure field was calculated, coupled with the LEM analysis along the potential sliding surface to determine the factor of safety. The effectiveness of horizontal sub-drains was evaluated using two-dimensional (2-D) numerical models to lower the groundwater levels and increase the factor of safety of the landslide. This study primarily focused on transient seepage modeling to show the method of integrating it into the stability analysis of complex landslides. The effectiveness of horizontal sub-drains and the influence of variations in groundwater levels, soil hydraulic conductivity, volumetric water content, and factor of safety of potential sliding bodies on the rainfall-induced seepage were also analyzed. Figure 6 shows the flowchart of the working procedure.

5 Numerical Model

5.1 Slope Properties and Boundary Conditions

Figure 7 shows the slope geometry and boundary condition to be analyzed. The stability and factor of safety are influenced by the slope geometry, including the angle and height. Based on previous study, the initial depth of the water table was also discovered to influence the stability of soil slope because it mainly affects the initial value of the slope factor of safety. Therefore, the slope geometry was determined meticulously based on the field conditions and the groundwater level in the existing conditions during this analysis.

Fig. 6 Flow chart of a working procedure for this study

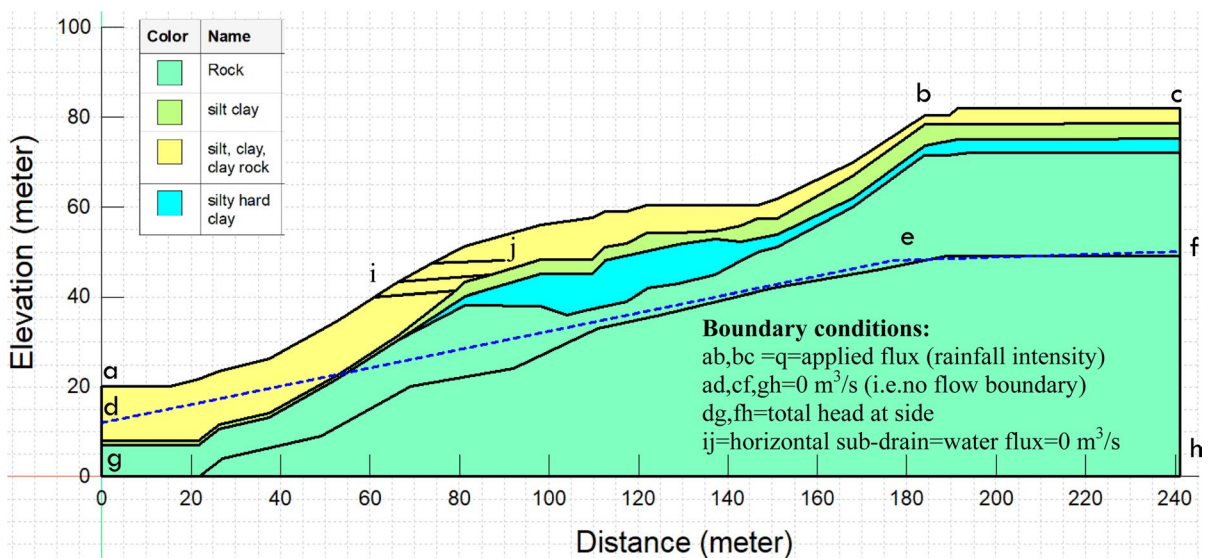
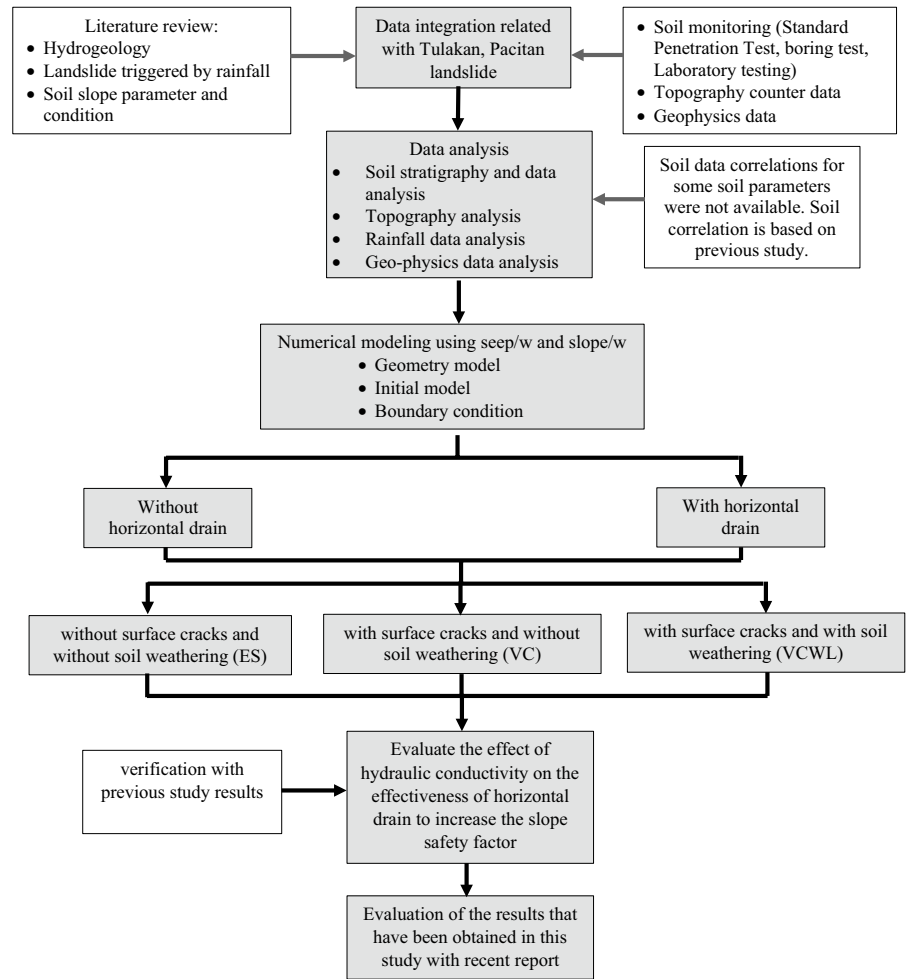


Fig. 7 The existing slope geometry and boundary condition

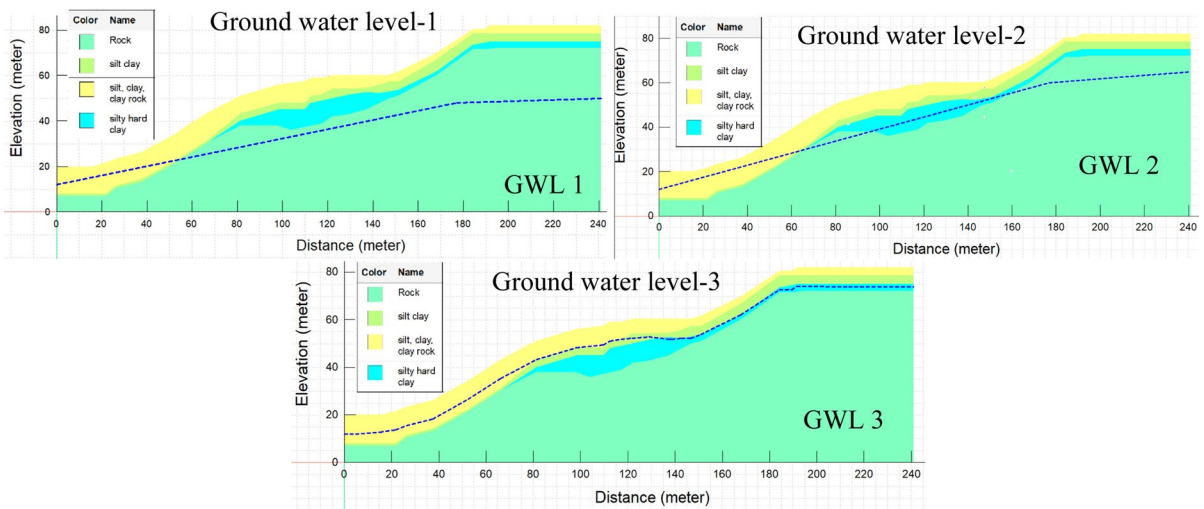


Fig. 8 Groundwater level variations GWL-1, GWL-2 and GWL-3

The effect of different initial groundwater levels (GWL-1, GWL-2, and GWL-3) on slope stability during a 30-day period of rainfall with varying intensities was analyzed, as shown in Fig. 8. The shear strength properties of the soil were determined through laboratory testing using the unconfined test method. In addition, soil data correlation is also carried out on layers of soil that do not have complete data. An effective cohesion range in each layer, $c' = 0\text{--}90$ kPa, the effective angle of internal friction, $\phi' = 1\text{--}40^\circ$, and unit weight of soil, $\gamma = 17\text{--}19$ kN/m³, were used in the slope stability analyses, as shown in Table 1. Constant shear strength parameters were used in all cases, to ensure that changes in slope stability were solely due to pore-water pressure (or matric suction) in the soil.

In this study, previous investigations by Suryo (2013); Lin et al. (2016), and others were used to determine the boundary conditions. Figure 7 shows the boundary conditions used for the transient

seepage analysis. A boundary flux (q), equal to the rainfall intensity (I_r) was applied to the slope surface, while nodal flux with a value of zero was assigned along the sides of the slope above the water table and the bottom to simulate a no-flow zone. A boundary condition equal to the total head (h_w) was applied along the sides of the slope below the water table line with significant effect on the groundwater level. The determination of boundary conditions for horizontal sub-drains was based on Lin et al. (2016), with a constant water rate value of zero and Q (potential seepage face review) equal to 0. Three horizontal sub-drains were modeled in this study with lengths between 16 and 20 meters with vertical distances between drains is 4 and 5 m.

The slope conditions with the presence of vertical cracks on the surface and a weak layer due to soil weathering were also analyzed. This analysis was based on the results of resistivity testing in the field as shown in Figure 9, indicating the existence of a layer

Table 1 Soil parameters used in the analysis

layer	Layer	γ_{soil} (Kn/m ³)	ϕ'	Cu (Kpa)	Ksat (m/s)	n
1	Silty, clay, clay rock	17	1	50	2.34×10^{-8}	0.53
2	Silty clay	17	1	70	2.3×10^{-8}	0.53
3	Silty hard clay	17.3	1	90	2.13×10^{-8}	0.53
4	rock	19	40	0	2.3×10^{-8}	0.33
5	Vertical crack	15	0	0	0.01	0.53
6	Weathered layer	15	17.5	5.4	0.001	0.43

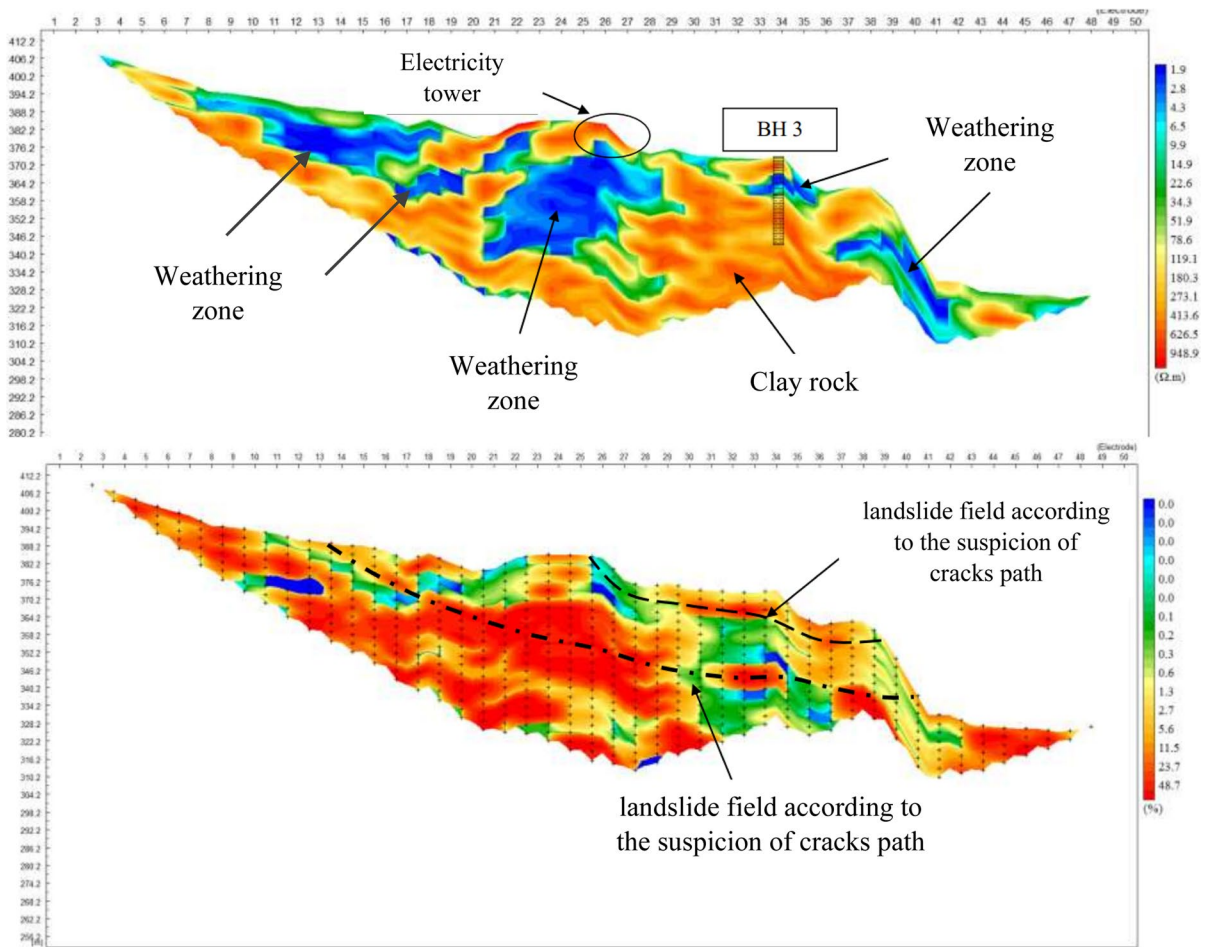


Fig. 9 Resistivity and induced polarization test results at the landslide site

with a low resistivity value. Moreover, one of the soil zones with low resistivity values is located under the electric tower, an area affected by landslides. According to Kowalczyk et al. (2014), the changes in resistivity were related to the variations in the degree of saturation and growth of the crack. Study by Ahmed (2014) showed that the resistivity of a clay is a function of moisture content and degree of saturation. Ronning et al. (2014) stated that high-water content and weak zones was determined as low resistivity regions by the methods used in this study. The report by another research was also conducted to determine the debris flow in the soil using Geoelectrical Resistivity Surveys.

The resistivity data in Figure 9a showed the presence of zones beneath the surface with low resistivity values, indicating high moisture content or

weathering. Calibration of the geoelectrical results with the SPT test showed that areas with resistivity values between 0.5 and 4.8 ohm.m exhibit high weathering with low SPT values ranging from 1 to 7. This indicated that the location had a higher water content compared to the zone with a greater resistivity value (Phanjaya et al. 2022; Aleksander et al. 2017). The high-water content zone is considered a weak layer, which may be in the form of cracks or soil weathering as indicated by the resistivity and induced polarization test results in Figures 9a and b. Several theories propose that surface cracks initiate weak layers in the soil, with main cracks propagating into deeper ones and causing the formation of a surrounding weak zone (Zeng et al. 2020; Wang et al. 2022; Suryo et al. 2013; Aleksander et al. 2017). According to (Suryo et al. 2015; Suryo 2013), cracks caused

direct infiltration of rainwater into the soil slope. A very high hydraulic conductivity of thin material (less than 20 cm) was introduced in the crack modeling to facilitate the directly infiltrate proses in the centerline of the weak zone. This study also modeled a weak layer as a silty soil surface disturbed by direct rainwater infiltration through the deep crack.

The presence of a weak layer beneath the soil surface due to cracks that infiltrate rainwater led to changes in soil parameters. According to previous research by (Suryo et al. 2015), the increase in moisture content from 13.5 to 30% decreased the shear strength to 80% from the initial value. Additionally, previous study adopted by (Suryo 2013) stated that the shear strength of the crack material is zero, indicating very low soil particle interaction or bonding. Another parameter that is different from the existing one is the value of hydraulic conductivity (K_{sat}) in the soil. The hydraulic conductivity of the crack material was assigned as 10 cm/sec, and it was assumed by this research to be porous like gravel. The K_{sat} of the weak material can be assumed to be similar to those with high permeability, such as coarse or fine sand, due to the presence of deep cracks. The crack parameters in unsaturated soil conditions have also been developed through the determination of the SWCC graph and crack soil hydraulic conductivity for random aperture. Furthermore (Zhang et al. 2021) used the permeability ratio (K_y/K_x) by applying 3 various data, namely 0.1 (the crack is still filled with rock clasts and downward infiltration is blocked), 1 (the filling inside the crack is residual soil or other homogeneous materials), and 10 (there are no fillings inside the crack and the rainfall can reach the bottom of the crack in a short time since the rainfall starts).

Based on the resistivity test results which showed the presence of a weak layer in the subsurface, the following are the several modeling conducted in this study:

- ES condition (Existing Slope condition).

Based on the available data from soil observations using Standard Penetration Test (SPT-N) and laboratory testing, there were no indications of weak layers, weathering, or cracks in the soil. This suggests that the soil parameters in the area are strong and mainly composed of stiff clay, with a very low hydraulic conductivity. Therefore, rainfall

is not expected to significantly impact the slope stability. Landslides still occurred in the area after heavy rainfall, indicating that other factors have contributed to the instability. Modeling in this condition can be seen in Figure 10a.

- VC condition (a condition with Vertical Crack on the surface)

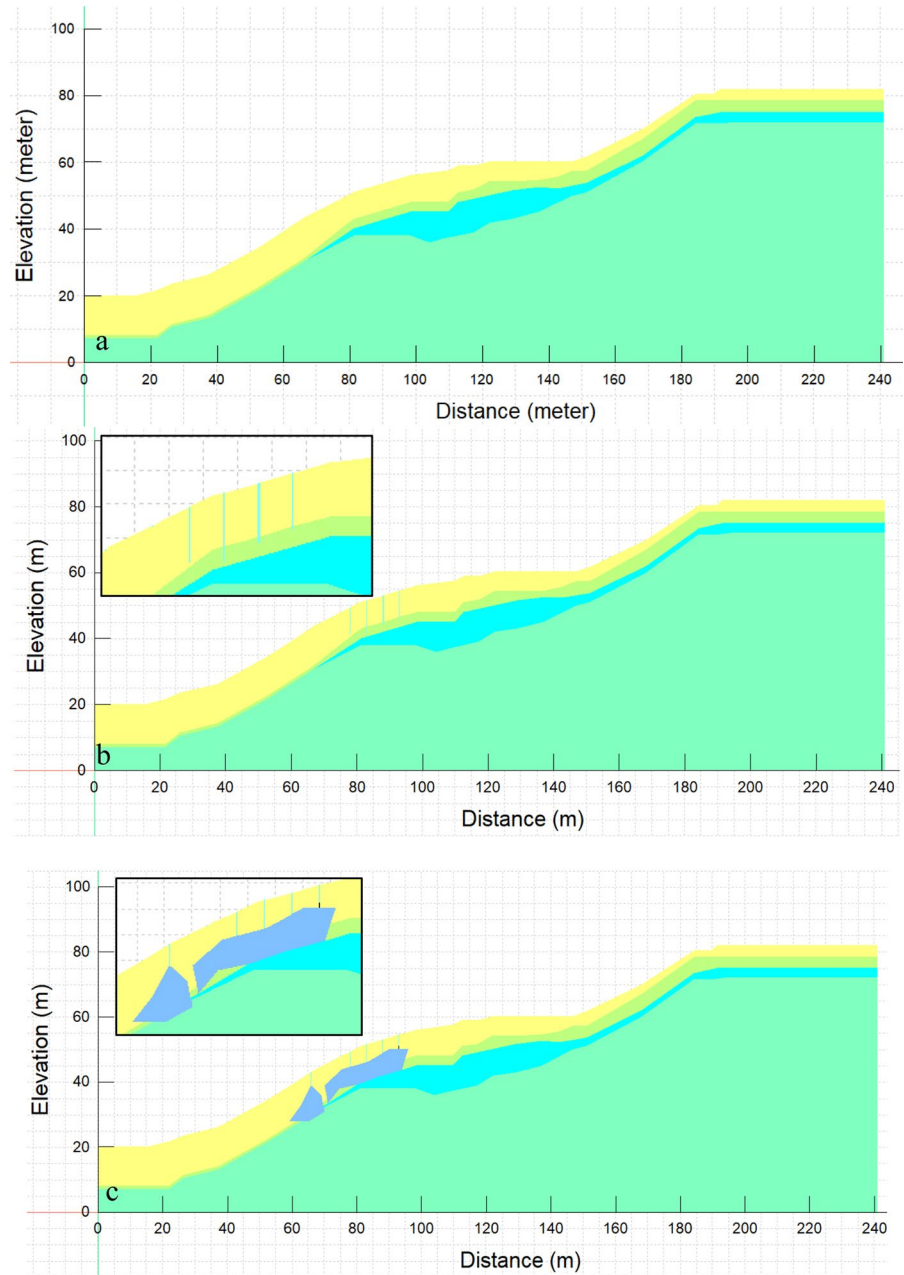
This analysis was carried out based on observations from resistivity testing. According to the results, there is a zone with a low value with a high-water content based on the existing report. The high-water content in the deeper soil originated from surface cracks that allow rainwater to infiltrate and increase the water content. Therefore, the slope stability under the presence of a weak layer due to VC conditions was analyzed. The parameters used for VC analysis were based on (Suryo 2013), with a unit weight (γ) of 15 kN/m³, cohesion (C') of 0, angle of internal friction (ϕ') of 0, hydraulic conductivity (K_{sat}) of 0.01 m/s, and porosity (n) of 0.8. The dimensions of the surface crack in this condition are 4–7 m long and less than 10 cm wide. Modeling in this condition assumes that there are 6 cracks on the slope surface, as shown in Figure 10b.

- VCWL condition (a condition with vertical crack and weak layer)

In this analysis, the weak layer below the soil surface was considered the result of the vertical cracks observed in the resistivity testing. The increased water content in the weak layer led to a change in soil parameters, with the slope stability analyzed using VC. The parameters used in this analysis are based on previous studies by (Suryo et al. 2015; Suryo 2013), with a density (γ) of 15 KN/m³, cohesion (C') of 5.4 Kpa, internal friction angle (ϕ') of 17.5°, hydraulic conductivity (K_{sat}) of 0.001 m/s, and porosity (n) of 0.43. The dimensions of the surface crack in this condition are 4–7 meters long and less than 10 cm wide. Modeling in this condition assumes that there are 6 cracks and 18 cracks on the surface of the slope that are connected to the weak layer below, as shown in Figure 10c.

The three conditions used in the modeling in this study are shown in Fig. 10.

Fig. 10 Slope modeling, **a** ES condition (Existing Slope condition), **b** VC condition (a condition with Vertical Crack on the surface), **c** VCWL condition (a condition with vertical crack and weak layer)



5.2 Rainfall Data

The rainfall parameters obtained from observations at three stations in Pacitan in 2017 were evaluated. Figure 3 shows that the highest rainfall intensity of 1027 mm was recorded in November at the Kebon Agung station. It is situated closer to the study area compared to the other stations. Therefore, data obtained from this station was used for numerical analysis.

The landslide incident occurred in early December, the rainfall data acquired for 30 days in the month of November was considered, and Figure 11a shows the intensity per day. The results indicated that the highest rainfall intensity was recorded on the 27th and 28th, of November 2017 and subsequently decreased the following day. Although there were no official records of the daily duration of rainfall, it was discovered that the highest intensity usually lasted for

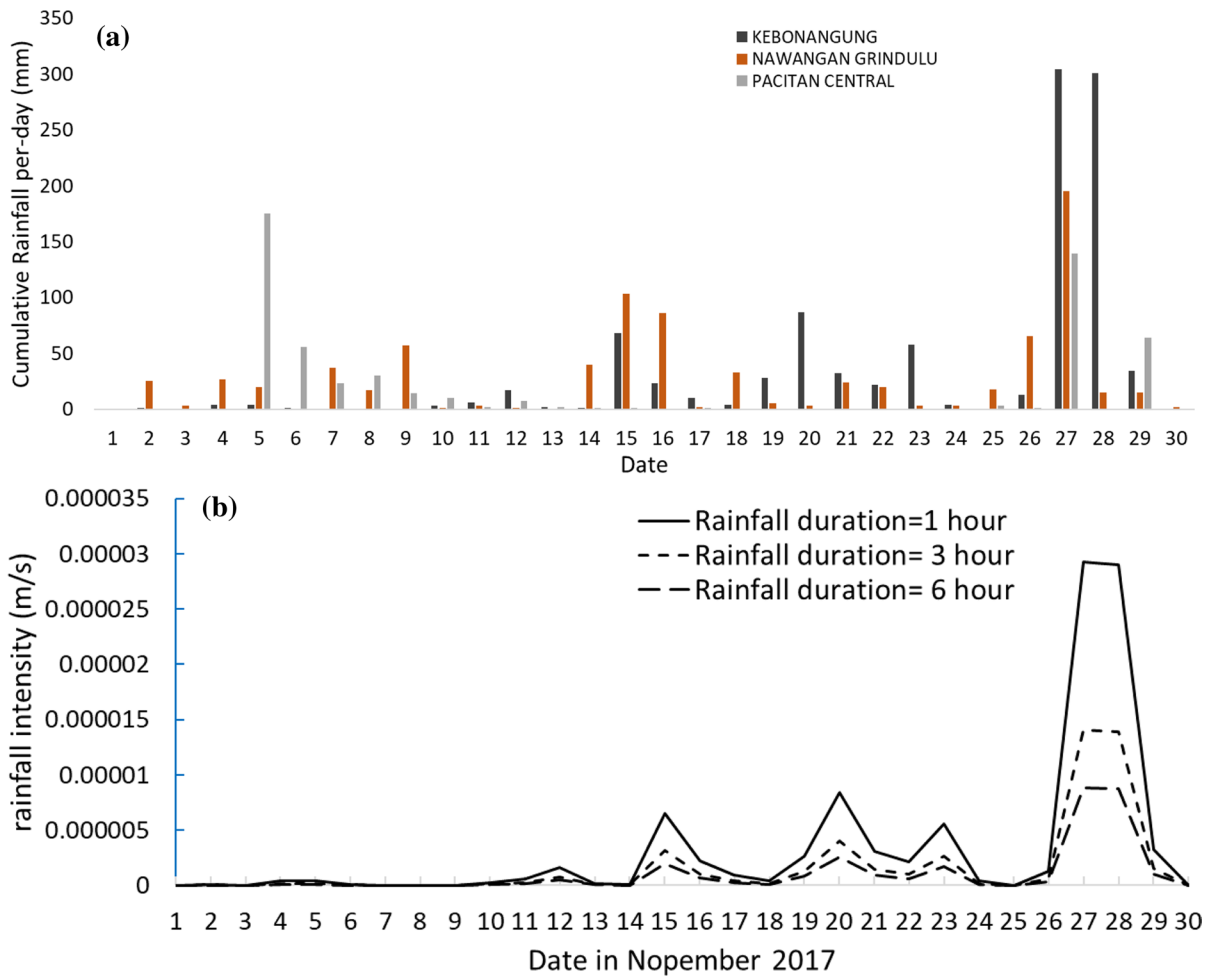


Fig. 11 Rainfall data in November 2017, **a** Cumulative rainfall per day (mm), **b** Rainfall intensity per day (m/s)

a maximum of 6 h per day. The duration of rainfall was evaluated under three scenarios, namely 1, 3, and 6 h/day, which were uniformly applied daily for the 30 days in November. Figure 11b shows the rainfall intensity in m/s for each of the earlier mentioned scenarios.

The SEEP/W model was measured in respect to the boundary flux (q) unit of $m^3/s/m^2$, however, the raw data obtained represents the maximum daily rainfall in mm. In order to correlate the acquired data to a boundary flux unit with the same dimensions, the Mononobe formula was used to calculate the rainfall intensity. This formula has been widely applied in several studies, particularly when only daily rainfall data are available, and that of short-term is not accessible. The outcomes of this calculation were

expressed in m/sec. Based on previous studies, (Rahardjo 2012; Lin et al. 2016) the data can be input as boundary flux (q) measured in $m^3/sec/m^2$.

6 Result and Discussion

The results of the analysis are presented through various discussions, these include examining the influence of the existing groundwater level elevations on slope stability, evaluating the impact of horizontal sub-drain on slope stability under different water levels, assessing the effect of vertical cracks and weak layers on slope stability, as well as determining the effectiveness of horizontal sub-drain in managing rainwater and increasing the factor of safety to

mitigate landslides. However, these discussions were conducted to identify the landslide mechanism at the study location, understand the impact of cracks and weak layers on slope stability, and assess the effectiveness of horizontal sub-drain as a landslide mitigation measure.

6.1 Existing Slope Condition Result (ES Condition)

In ES condition, the safety factor of the slope is significantly impacted by the elevation of the existing groundwater. The safety factor of the slope increases with decreasing groundwater level elevation, as shown in Fig. 12. However, under real-time rain conditions, the daily factor of safety decreases due to the absence of significant changes in the water level. When the hydraulic conductivity of soil is much lower than the intensity of rain, most rainwater becomes surface runoff instead of seeping into the soil, and it does not significantly impact slope stability. In this condition, the soil hydraulic conductivity value is less than the intensity of rain that occurs during landslide. This finding is supported by (Zhang et al. 2014), stating that when rainfall intensity exceeds the soil matrix infiltration capacity, water cannot infiltrate the matrix. In this condition, the horizontal sub-drain (HD) has limited effect on slope stability. The installation positions of horizontal sub-drains at locations 1, 2, and 3 did not affect the factor of safety under various groundwater level conditions, as shown in Fig. 13. These results indicate that 30 days of rain does not significantly impact slope stability when the

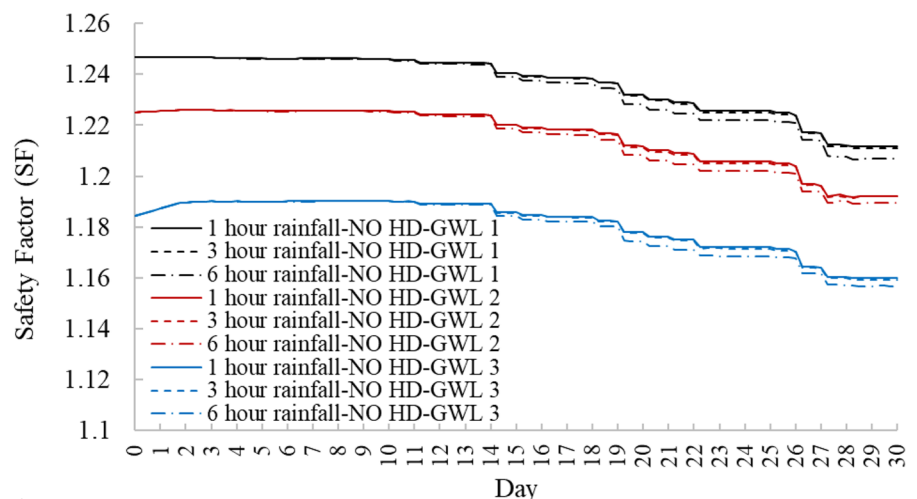
hydraulic conductivity is much lower than the rainfall intensity, and the use of a horizontal sub-drain as a landslide mitigation measure is ineffective in this condition.

During the 30 days of heavy rainfall in November 2017, most of the ES condition showed a factor of safety greater than 1.1, which is considered safe because it is greater than the critical slide limit (safety factor = 1). The soil parameters used in the evaluation were based on conventional tests. These include Standard Penetration Test (N) and laboratory analysis that may not accurately capture the presence of weathered conditions or weaker layers beneath the soil surface. The conventional test was conducted at only three points in a large landslide area, which may not represent the actual field conditions. The analysis results indicate that the slope stability is safe against landslides under the given conditions. Further geophysical observations were carried out, including resistivity tests that revealed zones indicating the presence of cracked soil and weak layers. These observations were interpreted in the context of vertical crack (VC) and vertical crack with weak layer (VCWL) conditions.

6.2 Vertical Crack on the Surface Condition Result (VC Condition)

Similar to ES condition, the VC analysis also showed that the elevation of groundwater level affected the factor of safety on the slope. The higher the groundwater level, the lower the factor of safety as shown in

Fig. 12 Effect of differences in the existing groundwater level on slopes without horizontal sub-drains in ES conditions



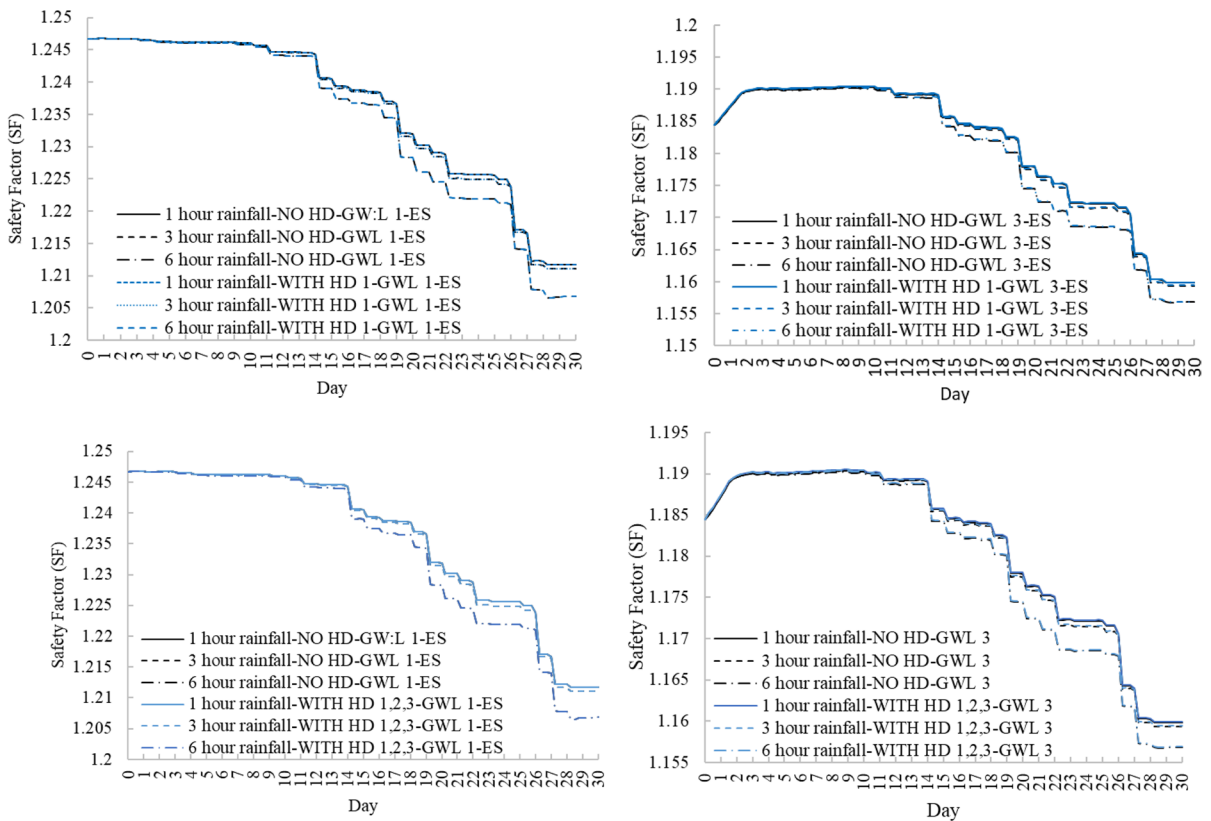


Fig. 13 The effect of differences in ground water level (a, b) and the installation location of the horizontal sub-drain on changes in safety factor (c, d) during 30 days of rain in ES conditions

Fig. 14 Effect of differences in the existing ground water level on a slope without horizontal sub-drain in VC conditions

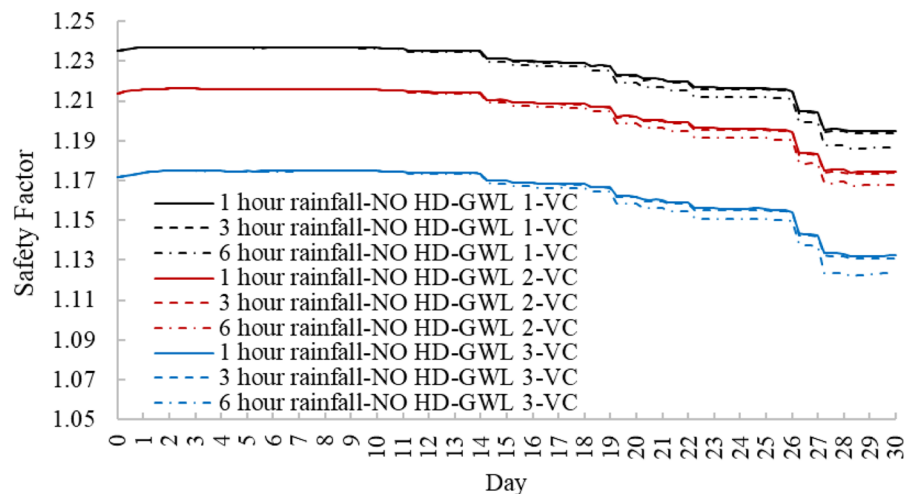


Fig. 14. The results were different when a horizontal sub-drain was used. In ES condition, the horizontal sub-drain ineffectively elevated slope stability, but

it increased the factor of safety under VC condition. The safety factor increased after installing a horizontal sub-drain when the existing groundwater level

was high (GWL 3). Among the three horizontal sub-drain positions, HD 1 was the most effective in terms of increasing the safety factor on the slope, although the increase was extremely small (<2%). In HD 2 and 3, the safety factor increased after 26 days of rain as shown in Fig. 15. A significant decrease could also occur due to accumulated rainfall from the previous day. According to (Suryo 2013), a change in the factor of safety in vertical cracked conditions occurred after more than 70 days of rain. The decrease in safety factor was influenced by soil hydraulic conductivity value, rainfall intensity, number, position, and dimensions of cracks. The factor of safety value was compared to the presence of vertical cracks in varying positions, which showed a decrease in its value.

The effectiveness of a horizontal sub-drain in improving slope stability is influenced by its placement. When the groundwater level is high (GWL 3),

HD 1, which is placed in a lower position, is more effective in enhancing slope stability compared to HD 3, positioned at a higher elevation as shown in Fig. 15. However, when the groundwater level is at shallow depths (GWL 1 and 2) and there are vertical surface cracks present, the horizontal sub-drain does not improve slope stability since it does not increase the infiltration of rainwater into the soil. It does not affect the groundwater level at deep elevations. The results obtained tend to vary, assuming there are more surface and longer cracks on the slope. The effectiveness of the horizontal sub-drain in relation to its position was also supported by (Ghazali et al. 2013; Rahardjo 2012), in their parametric study and field validation. Study by (Ismail et al. 2017) also obtained similar results on the evaluation of the relationship between the horizontal position of the sub-drain and its effectiveness.

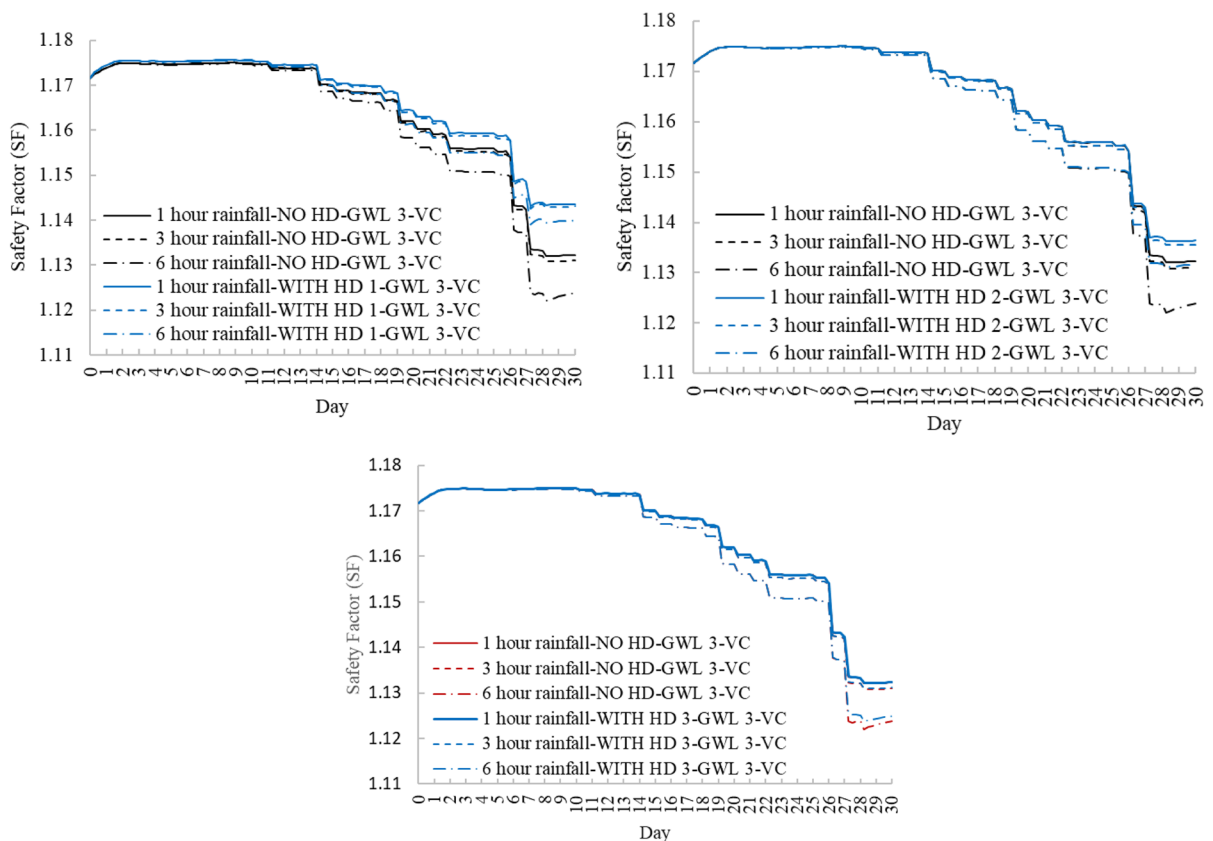


Fig. 15 The effect of the horizontal sub-drain installation position on the increase in the value of the safety factor on the slope of VC condition

6.3 Vertical Crack and Weak Layer condition Result (VCWL Condition)

The results of the VCWL analysis showed that the factor of safety decreases as the groundwater level rises, and this is consistent with the findings from ES and VC conditions, as shown in Fig. 16. This implies that the elevation of the groundwater level is a critical factor affecting slope stability. However, at low groundwater levels, the horizontal sub-drain did not increase the slope factor of safety as shown in Fig. 16. This is because the weak layer is situated far above the groundwater level at low elevations, and the horizontal sub-drain cannot reach the groundwater. The low hydraulic conductivity (K_s) of the soil limits the penetration of rainwater into the weak layer, rendering the horizontal sub-drain ineffective. Even when a horizontal sub-drain is installed at GWL 2, the increase in the factor of safety is minimal ($< 1\%$) and only observed when it rains for 6 h/day after 27 days of incessant rain as shown in Fig. 16b. The location of the horizontal sub-drain and the duration of one

day of rain have a significant impact on its effectiveness. As shown in Fig. 17, HD 3, which is located at the top, has no effect on the factor of safety of the slope, because it is only in the small part of the weak layer. It was presumed that the area and location of the weak layer played a vital role in determining the appropriate placement of the horizontal sub-drain for landslide mitigation. This finding is consistent with the study by (Ghazali et al. 2013), where water from the Horizontal sub-drain is installed at the same elevation while there are various discharge points in the view location. According to Ismail et.al. [50], the horizontal sub-drain that emits the largest water discharge is located only at certain points in their study area with low resistivity values. The use of a horizontal sub-drain in the GWL 3 condition can increase the safety factor by approximately 7.7% compared to slopes without a horizontal sub-drain.

In addition, a minor anomaly was observed in VCWL scenario at GWL 2 and 3, where there was a slight rise in the factor of safety at the onset of rainfall. This phenomenon was attributed to the changes

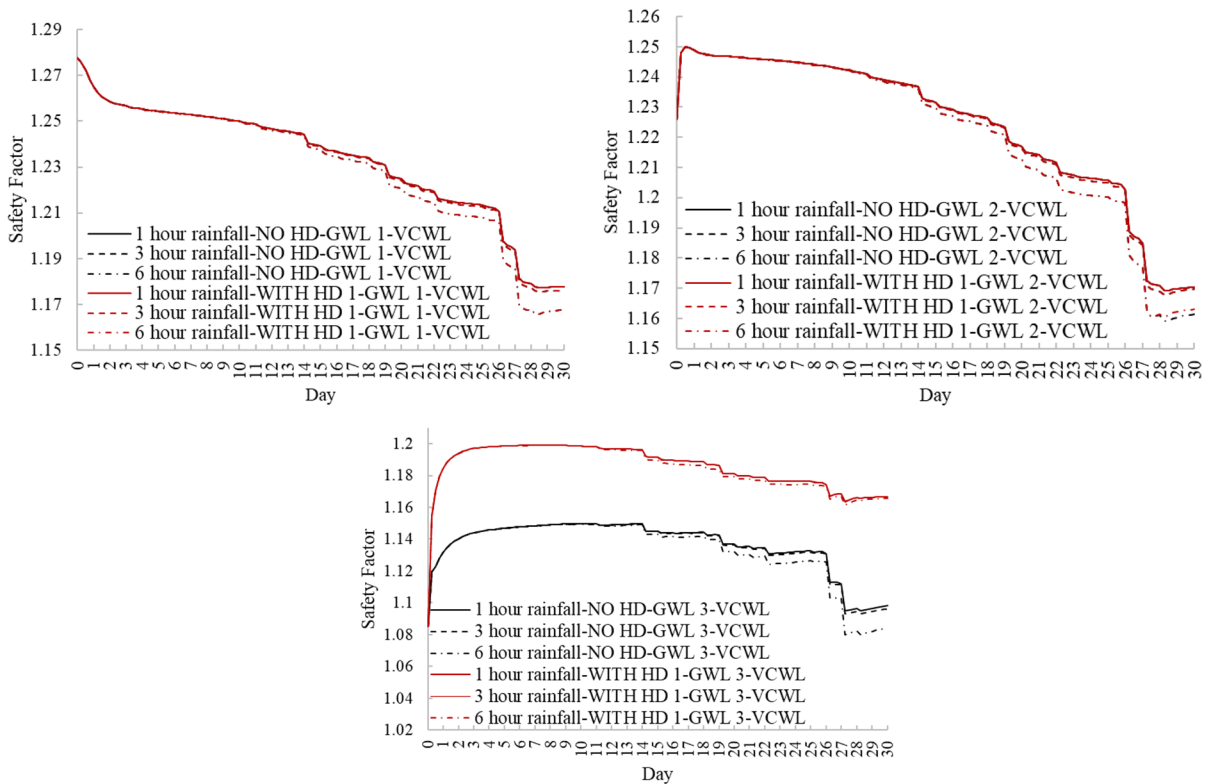
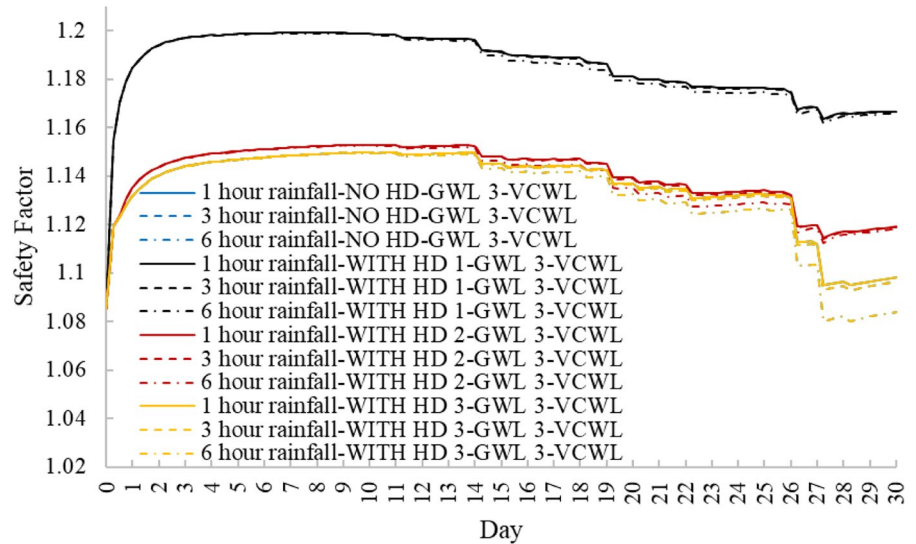


Fig. 16 Changes in factor of safety due to 30 days of rain with differences in ground water level elevation in VCWL conditions

Fig. 17 The effect of the horizontal sub-drain position at a high ground water elevation (GWL 3) on the increase in the safety factor slope



in groundwater level during precipitation. These fluctuations in groundwater level are distinct from those observed in ES and VC because of the presence of a weak zone with a higher K_s parameter. According to (Galeandro et al. 2013), the hydraulic conductivity parameters play a crucial role in groundwater level variations. Such fluctuations result in a rise in the factor of safety. It is noteworthy that the increase in the factor of safety at the beginning of the rain is not observed when the existing groundwater level is extremely low.

6.4 Comparison Between ES, VC and VCWL Conditions Without Horizontal Sub-drain

In this study, the impact of the vertical crack and weak layer with no horizontal sub-drain condition was also examined. Figure 18 shows the changes in the factor of safety for the 30 days of rain, considering variations in groundwater level and soil parameters. In GWL 1 and 2, as shown in Figs. 18a and b, the factor of safety under VCWL conditions was highest at the beginning of the rain but decreased to the lowest when subjected to ES and VC conditions. However, in GWL 3 as shown in Fig. 15c, which is the highest groundwater level, the factor of safety for VCWL was much lower compared to ES and VC conditions. This indicates that at high groundwater levels, the presence of cracks and weak layers substantially decreases the slope stability. At lower groundwater levels, the decrease in the factor of safety in VCWL conditions

only occurred after several days of rain. Based on these findings, the slope stability which experiences rain with varying intensities daily, is influenced by various factors such as soil conditions, including the presence or absence of cracks and weak layers, elevation of the existing groundwater level, and contour topography.

6.5 Effect of the Number of Vertical Cracks with a Weak Layer and Rain Intensity on Slope Stability

Another experiment was carried out by adding 6 pieces of vertical cracks under VCWL conditions to 18 pieces to determine the effect of rainwater, which steps into the ground at low ground water level elevations. The addition of vertical cracks into 18 pieces with a length of 4–10 m connecting to a weak layer is illustrated in Fig. 19. The analysis results of the value of the safety factor due to the difference in the number of cracks in the soil is shown in Fig. 20. This indicates that an increase in the number of surface cracks leads to a decrease in the safety factor. The horizontal sub-drain (HD-1) also became effective during heavy rainfall on day 27, as shown in Fig. 20, indicating that the effectiveness of the horizontal sub-drain can be influenced by the day it rained.

The effectiveness of the horizontal sub-drain can also be affected by the intensity and duration of the rain. As shown in Fig. 21, the incessant rainfall, which lasted for 14 days had high intensities within the range of 1.41×10^{-05} to 1.85×10^{-07} m/s, while

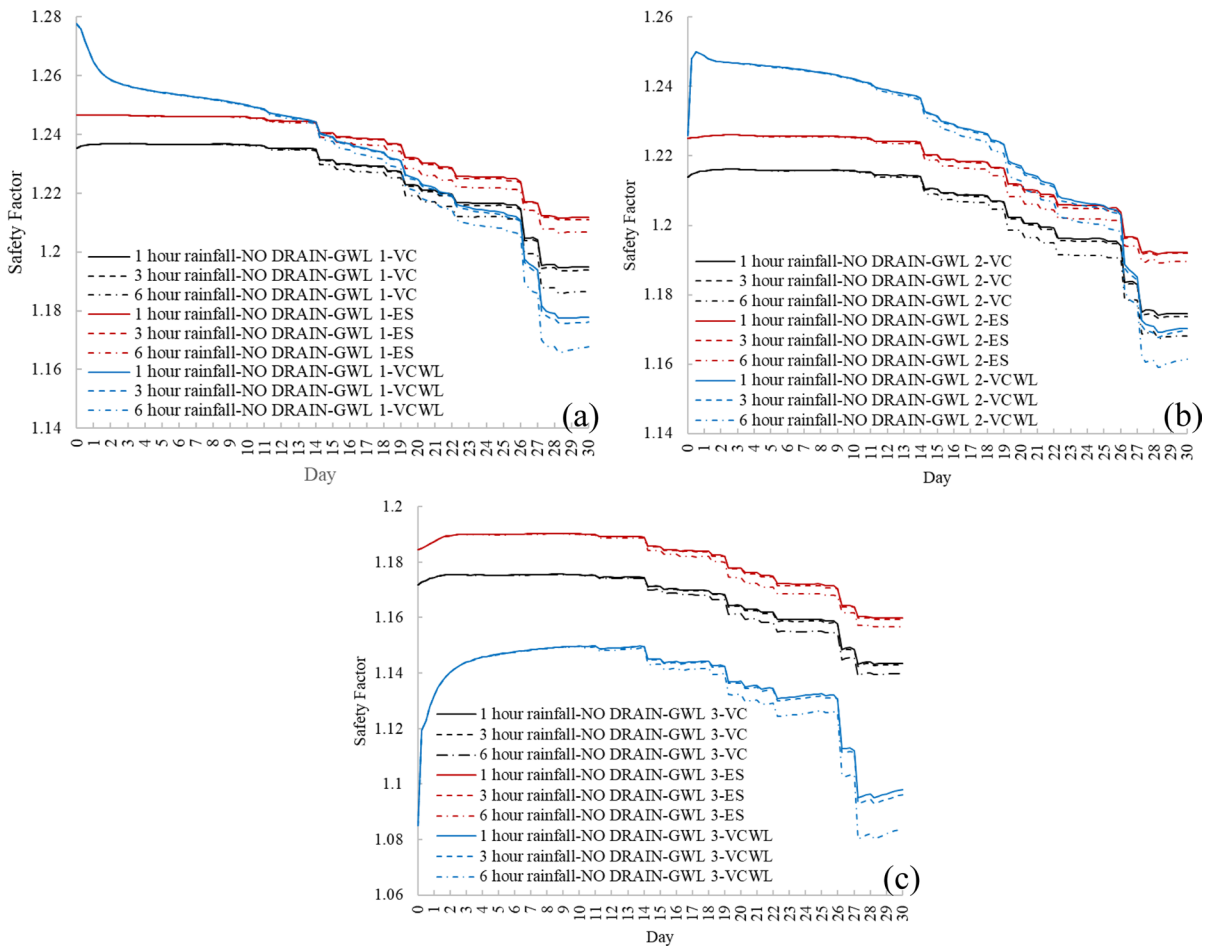


Fig. 18 Effect of vertical crack and weak layer without horizontal sub-drain condition; **a** Ground water level 1; **b** Ground water level 2; **c** Ground water level 3

Fig. 19 Addition of a vertical crack that connects the weak layer on the slope

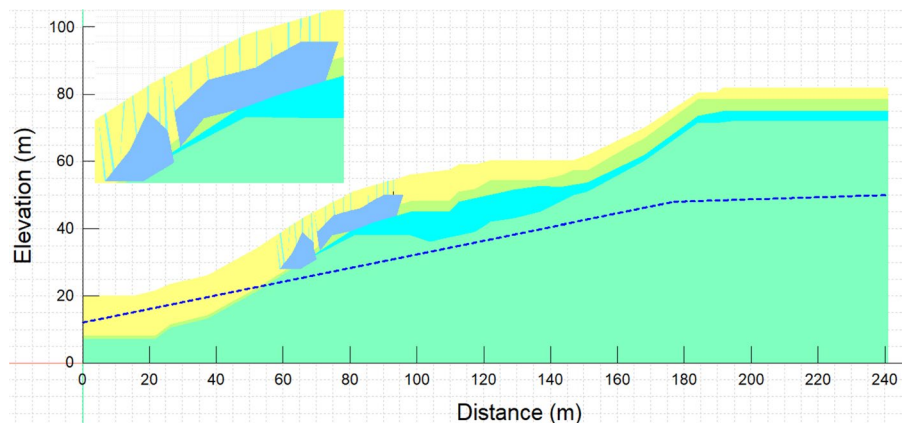


Fig. 20 Changes in safety factor during 30 days of rain; **a** The effect of the number of vertical cracks on the safety factor; **b** Effect of horizontal sub-drain with different number of vertical cracks

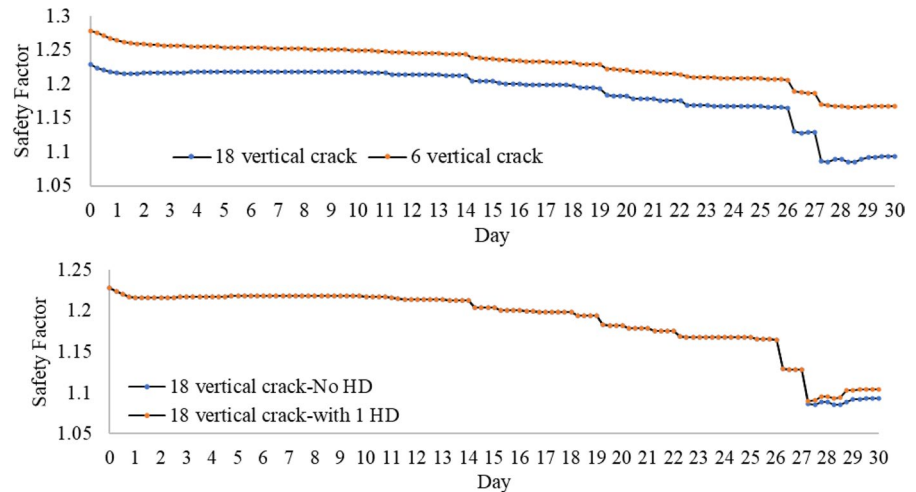
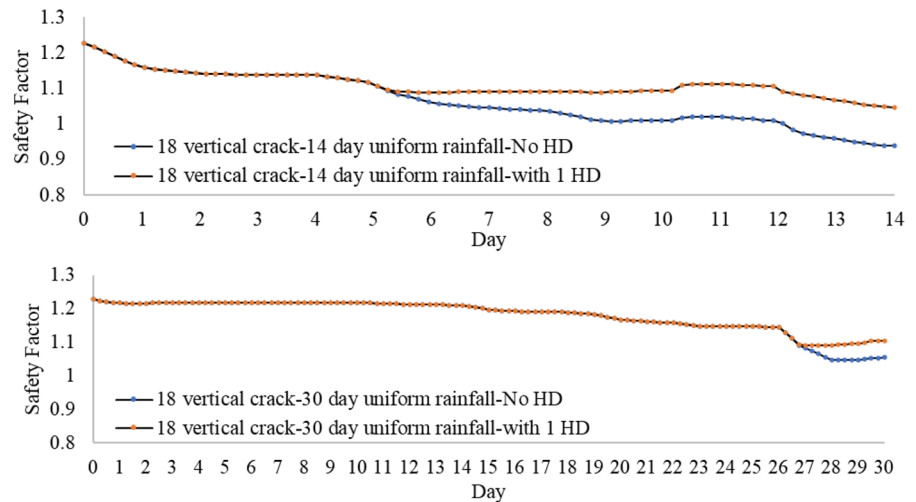


Fig. 21 Changes in safety factor during 14 and 30 days of rain; **a** Effect of horizontal sub-drain due to rain for 14 days and occurs throughout the day with high intensity; **b** Effect of horizontal sub-drain due to 30 days of rain and occurs in the day with lower intensity



the horizontal sub-drain increased the safety factor by approximately 11.5%. On the other hand, the incessant rain, which occurred for 30 days had lower intensities within the range of 3.52×10^{-06} to 1.16×10^{-08} m/s, the horizontal sub-drain can only increase the safety factor when it rains at a higher intensity, specifically on days 27 and 28 as shown in Fig. 21. These findings suggest that the effectiveness of the horizontal sub-drain in increasing slope safety factor can be influenced by the number of cracks, the intensity, and the duration of the rain.

The effectiveness of horizontal sub-drains during the rainy season was investigated with a higher hydraulic conductivity value. A Study by Mukhlisin and Azis (2016) stated that the presence of a

horizontal sub-drain increased the factor of safety by relatively 25% when monitored for 48 h after 9 h of rainfall at a rate of 60 mm/hour. This study was conducted on soil with $K_s = 9.2 \times 10^{-6}$ m/s. Similarly, (Rahardjo 2012) reported that the presence of a horizontal sub-drain increased the SF from 1193 to 1303 with $K_s = 2.1 \times 10^{-7}$ m/s. The horizontal sub-drains were installed at the foot of the slope, with lengths ranging from 12 to 18 m while in the study conducted by (Rahardjo 2012), it was within 25–30 m. In another study by (Lin et al. 2016), the combination of horizontal sub-drains and sub-surface drainage increased the factor of safety for the slope from 1098 to 1228.

The effectiveness of the horizontal sub-drain is influenced by both its position and length. In this present study, it was observed that under certain conditions, the installed sub-drain did not reach the groundwater level. As reported in a research study, drains need to extend into the slope to ensure desired water level drawdown in the entire slope. It is also important for drains to penetrate through the slip zone to effectively remove water from that area. Additionally, it is essential to consider both the minimum and maximum length of the horizontal sub-drain. A study adopted by Martin (2013), stated that drains need not extend more than 3–5 m beyond the slip surface. Similarly, another study reported that installing drains beyond the critical intersection point of the slip surface and the top of the slope did not provide any additional benefits. This finding was supported by previous study, which reported the maximum reduction in subsurface water was not affected by the further extension of the drain beyond a certain critical length. According to (Salmasi et al. 2019), increase in the factor of safety becomes less significant when drains exceed this critical length. It is economically impractical and can potentially lead to increased water flow into the failure zone to install drains that significantly surpass the slip surface (Mattei et al. 2020).

In the case of this landslide, the soil at the study location is characterized by hard clay and rock with high shear strength, however, several weathered layers exist beneath the soil surface. These conditions caused a slight decrease in the factor of safety under both ES and VC conditions, with and without horizontal sub-drain installation. Numerical analysis showed that the decrease in safety factor value ranges from 0.01 to 0.03, and 0.02 to 0.035 in ES and VC conditions, respectively. The decrease in the safety value under the VCWL condition is slightly higher, relatively 0.11. The presence of a horizontal sub-drain increases the factor of safety in the slope, with an increase ranging from 0.02 to 0.083 during the 30 days rainfall. This increase is slightly smaller compared to the results of the study by (Rahardjo 2012), due to the K_s parameter being much smaller than the rainfall intensity. The soil shear parameters and the length of the horizontal sub-drain also play a critical role in the effectiveness of the sub-drain.

According to (Ismail et al. 2017), the efficacy of horizontal sub-drain in cutting slopes with high groundwater level (GWL) can be optimized by

varying length. It was reported that a horizontal sub-drain with a minimum length of 22.5 m was most effective in increasing safety, with the factor of safety increasing from 1,021 without a horizontal sub-drain to 1456 with a 25-m one. However, the investigation was conducted on a cutting slope with lower shear strength and K_s parameters than the current case study. Ismail stated that the factor of safety value obtained after the installation of a horizontal sub-drain was greater than the results of this present study, (Rahardjo 2012; Lin et al. 2016; Mukhlisin and Azis 2016), had similar outcomes. The effectiveness of horizontal sub-drain is highly sensitive and influenced by several factors such as soil parameters, topography slope, groundwater level conditions, rainfall intensity and duration, length, and horizontal position of the drain. When installed in a suitable location, its effective length can significantly improve the factor of safety by reducing the groundwater level and mitigating the impact of rain on slope stability.

Several numerical and case studies highlighted the efficacy of horizontal sub-drains in enhancing slope safety during the rainy season. This present study reveals that the efficiency of horizontal sub-drains may not be apparent in certain conditions. Specifically, in this case study, the safety factor (SF) increased by only 7.7% from the original SF, and this only occurred under the scenario of extremely high ground water level (VCWL). The SF would increase to 11.5% only under continuous and intense rainfall, for several days. Such conditions are rare in Indonesia and did not occur at the time of this landslide. Many factors, including rainfall intensity, influence the percentage increase in SF. The results obtained show that horizontal sub-drains are more effective during high-intensity and long-duration rainfall, such as those during typhoons in Taiwan and its surroundings. It has been reported that the horizontal sub-drain is an effective method for landslide prevention based on case studies in Taiwan, Hong Kong, and surrounding areas. Soil hydraulic conductivity is another influential parameter. Heterogeneous soil conditions result in varying K_s values, and surface cracks and weak layers in the soil can cause differences in hydraulic conductivity values. Therefore, the efficacy of using horizontal sub-drains depends on the K_s condition of the soil and its heterogeneity. In cracked soil conditions and the presence of a weak layer, horizontal

sub-drains exhibit greater efficacy compared to hard soil without cracks.

7 Conclusion

In conclusion, the landslide that occurred at the study location was caused by the presence of a weak layer beneath the surface, while vertical cracks in the soil were due to heavy rain. However, in the absence of weak layers and vertical cracks, the soil parameters at this location are extremely good and landslides are bound not to occur. Geophysical examination using resistivity parameters revealed the presence of a weak zone in the subsurface, which was not detected by conventional soil testing. The subsurface with low resistivity indicates high water content, causing a decrease in soil shear stress parameters and slope stability. Vertical cracks on the surface cause rainwater to seep into the ground, leading to a weak zone in the subsurface layer. Cracked soil conditions and weak layers have greater hydraulic conductivity parameters than slope soils, which affect the groundwater level and slope stability. The use of horizontal sub-drains was considered effective in increasing the slope factor of safety, although slightly, relatedly 7.7% of the safety factor without a drain. The percentage increase in the safety factor slope after horizontal sub-drain installation can reach 10% under high intensities and when it rains consecutively for several days. It is influenced by many factors, including cracks and weak layers, seepage parameters, and the intensity and duration of rain. Therefore, it is important to balance the determination of horizontal sub-drain installation with complete subsurface data, such as geophysics, to determine the real condition of the soil and important parameters that can increase the role of horizontal sub-drain as a landslide disaster mitigation. In addition, it is recommended to installing geotechnical instrumentation or sensors as an early warning system can detect horizontal movements and changes in pore water pressure on slopes, especially due to rain.

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Authors' Contributions PTKS collected secondary data from several related agencies and processed it for analysis. Furthermore, a numerical analysis with SEEP/W and SLOPE/W were performed and a draft written for publication. IBM Analyzed the results of numerical modeling and proofread the manuscript, thereby making it ready for publication. SC provided recommendations on various aspects that must be reviewed in performing numerical analysis. All authors read and approved the final manuscript.

Data Availability The datasets generated and/or result analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing Interests The authors declared no conflict of interest.

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References

- Ahmed J, Ghazali M (2012) Mukhlisin AM (2012) Effectiveness of horizontal sub-drains in improving slope stability: a case study of landslide event in Putra Jaya. *Unsat Soils Theory Practice* 2011:753–758
- Ahmed HA (2014) Electrical Resistivity Method for Water Content Characterisation of Unsaturated Clay Soil, Durham theses, Durham University. Available at Durham E-Theses Online: <http://etheses.dur.ac.uk/10806/>
- Alexsander S, Mochtar IB, 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. *EJGE*, pp. 5347–5363, 2017.
- Alsual S, Sapari N, Harahap ISH (2018) The rise of groundwater due to rainfall and the control of landslide by zero-energy groundwater withdrawal system. *Int. J. Eng. Technol.* 7:921–926. <https://doi.org/10.14419/ijet.v7i2.29.14284>
- Amatya SC, Mori M (2018) Horizontal drilling drainage as a preventive measure for water induced landslide risk

- reduction : a case study from Sindhuli Road, Section I Nepal. *J Nepal Geol Soc* 55:109–122. <https://doi.org/10.3126/jngs.v55i1.22800>
- Amin TC, Ratman N, Gafoer S (1999). Geological Map of Central Java Sheet. Geological Research and Development Center (In Bahasa)
- Ariesta D (2019) The effect of initial groundwater table and rainfall wetting towards slope stability (Case study of landslide in Tangkil Hamlet, Banaran Village, Pulung Subdistrict, Ponorogo Regency). *J Civ Eng Forum*. 5(2):149–160. <https://doi.org/10.22146/jcef.43804>
- Bishop AW (1955) The use of the slip circle in the stability analysis of earth slopes. *Géotechnique* 5(1):7–17
- Ciabatta L, Camici S, Brocca L, Ponzianni F, Stelluti M, Berni N, Moramarco T (2016) Assessing the impact of climate-change scenarios on landslide occurrence in Umbria Region. Italy. *J. Hydrol.* 541:285–295. <https://doi.org/10.1016/j.jhydrol.2016.02.007>
- Galeandro A, Doglioni A, Simeone V, Simunek J (2013) Analysis of rainfall infiltration effects on the stability of pyroclastic soil veneer affected by vertical drying shrinkage fractures. *Bull Eng Geol Env* 72:447–455. <https://doi.org/10.1007/s10064-013-0492-5>
- Gariano SL, Petrucci O, Guzzetti F (2015) Changes in the occurrence of rainfall-induced landslides in Calabria, southern Italy, in the 20th century. *Nat Hazards Earth Syst Sci* 15:2313–2330. <https://doi.org/10.5194/nhess-15-2313-2015>
- Ghazali MA, Rafek AG, Desa K, Jamaluddin S (2013) Effectiveness of geoelectrical resistivity surveys for the detection of a debris flow causative water conducting zone at KM 9 Gap-Fraser's Hill Road (FT 148) Fraser's Hill, Pahang, Malaysia. *J Geol Res.* <https://doi.org/10.1155/2013/721260>
- He Y, Sun R, Xu Z, Tang W (2021) The dynamic change and effect of rainfall induced groundwater flow. *Water* 13:2625. <https://doi.org/10.3390/w13192625>
- Hutagamissufardal MIB, Mochtar NE (2018) The effect of soil cracks on cohesion and internal friction angle at landslide. *J Appl Environ Biol Sci* 8(3):1–5
- Ibeh CU (2020) Effect of changing groundwater level on shallow landslide at the basin scale: a case study in the Odo basin of South Eastern Nigeria. *J African Earth Sci.* <https://doi.org/10.1016/j.jafrearsci.2020.103773>
- Ismail MAM, Ng SM, Abustan I (2017) Abustan I (2017) Parametric study of horizontal sub-drains for slope stability measure : a case study in Putrajaya, Malaysia. *KSCE J Civ Eng* 21:2162–2167. <https://doi.org/10.1007/s12205-016-1084-2>
- Jeong SW (2022) Determining the shear resistance in landslides with respect to shear displacement and shearing time in drainage-controlled ring shear tests. *Appl Sci* 2022(12):5295. <https://doi.org/10.3390/app12115295>
- Kodikara J, Costa S (2013) Desiccation Cracking in Clayey Soils : Mechanisms and Modelling Desiccation Cracking in Clayey Soils. In: Laloui L, Ferrari A (eds) Multiphysical Testing of Soils and Shales Springer Series in Geomechanics and Geoenvironment. Springer, Berlin
- Kopeckr M, Ondrasi M, Antolova D (2013) Horizontal sub-drains as effective measure for landslide remediation. *Stud Geotehnia Meh.* <https://doi.org/10.2478/sgem-2013-0011>
- Kowalczyk S, Maślakowski M, Tucholka P (2014) Determination of the correlation between the electrical resistivity of non-cohesive soils and the degree of compaction. *J Appl Geophys* 110:43–50. <https://doi.org/10.1016/j.jappgeo.2014.08.016>
- Kristo C, Rahardjo H, Satyanaga A (2017) Effect of variations in rainfall intensity on slope stability in Singapore". *Int Soil Water Conser Res* 5(2017):258–264. <https://doi.org/10.1016/j.iswcr.2017.07.001>
- 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* 18:3707–3714. <https://doi.org/10.1007/s10346-021-01724-3>
- Lakruwan M, Kamura A, Kazama M (2022a) Effect of 3D water table profile of horizontal drains on slope stability and idealization of 3D-FEM flow modeling to 2D-FEM flow modeling. *E3S Web Conf* 347:03002
- Lee J-U, Cho Y-C, Kim M, Jang S-J, Lee J, Kim S (2022) The effects of different geological conditions on landslide-triggering rainfall conditions in South Korea. *Water* 14:2051. <https://doi.org/10.3390/w14132051>
- Li H, Lu Y, Zheng C, Zhang X, Zhou B, Wu J (2020) Seasonal and inter-annual variability of groundwater and their responses to climate change and human activities in arid and desert areas. *Water.* <https://doi.org/10.3390/w12010303>
- Lin D, Hung S, Ku C, Chan H (2016) Evaluating the efficiency of subsurface drainages for Li-Shan landslide in Taiwan. *Nat Hazards Earth Syst Sci Discuss.* 1:1–22. <https://doi.org/10.5194/nhess-2015-309>
- Lin DG, Chang KC, Ku CY, Chou JC (2020) Three-dimensional numerical investigation on the efficiency of subsurface drainage for large-scale. *Appl Sci* 10(10):3346. <https://doi.org/10.3390/app10103346>
- Luigi S, Guzzetti F (2017) Earth-science reviews landslides in a changing climate. *Earth Sci Rev* 162(October):227–252. <https://doi.org/10.1016/j.earscirev.2016.08.011>
- Martin R (2013) Use of Horizontal sub-drains for Slope Stabilisation in Hong Kong. *HKIE Trans.* 3:37–41
- Mattei A, Goblet PF, Barbecot S, Guillon Y, Coquet WS (2020) Can soil hydraulic parameters be estimated from the stable isotope composition of pore water from a single soil profile. *Water* 12(393):1–19. <https://doi.org/10.3390/w12020393>
- Mukhlisin M (2018) Khiyon KN (2018) the effects of cracking on slope stability. *J Geol Soc India* 91:704–710. <https://doi.org/10.1007/s12594-018-0927-5>
- Mukhlisin M, Abd Aziz NAB (2016) Study of horizontal drain effect on slope stability. *J Geol Soc India* 87:483–490
- Nyakundi RM, Makokha M, Mwangi JK, Obiero C (2016) Impact of rainfall variability on groundwater levels in Ruiru municipality Kenya". *African J Sci Technol Innov Dev.* <https://doi.org/10.1080/20421338.2015.1085157>
- Pfeiffer TJ (2014) Practical Considerations for the Design and Construction of Landslide Mitigation using Horizontal sub-drains. in 65th Highway Geology Symposium.
- Phanjaya H, Parnadi WW, Santoso D (2022) Electrical resistivity survey for groundwater investigation in Padarang West Java. *IOP Conf Series Earth Environ Sci*

- 1031:012006. <https://doi.org/10.1088/1755-1315/1031/1/012006>
- Rahardjo H (2012) Performance of horizontal sub-drains in residual soil slopes". *SOILS Found* 51(3):437–447. <https://doi.org/10.3208/sandf.51.437>
- Rahimi A, Rahardjo H, Leong E-C (2011) Effect of antecedent rainfall patterns on rainfall-induced slope failure. *J. Geotech Geoenviron Eng.* 137:483–491. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0000451](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000451)
- Rogers NW, Selby MJ (1980) Mechanisms of shallow translational landsliding during summer rainstorms: North Island, New Zealand. *Geogr Ann Ser A Phys Geogr.* 62(1/2):11–21. <https://doi.org/10.1080/04353676.1980.11879995>
- Rønning JS, Ganerød GV, Dalsegg E (2014) Resistivity mapping as a tool for identification and characterisation of weakness zones in crystalline bedrock: definition and testing of an interpretational model. *Bull Eng Geol Environ* 73:1225–1244. <https://doi.org/10.1007/s10064-013-0555-7>
- Rupp S (2022) Effect of the antecedent precipitation on the occurrence of landslides: examples from the central uplands in Germany. *Z Geomorphol* 64(1):1–16
- Salmasi F, Dalir AH, Sarkarabad RN (2019) Investigation of the performance of horizontal drains in increasing slope stability in intense rainfall conditions by numerical simulation. *Amirkabir J Civil Eng* 51(3):153–156. <https://doi.org/10.22060/ceej.2018.13739.5468>
- Sari PTK (2023) The Performance of Horizontal sub-drain as a Landslide Mitigation Strategy," in The 5th International Conference on Rehabilitation and Maintenance in Civil Engineering. https://doi.org/10.1007/978-981-16-9348-9_39
- Stability Modeling with seep/W 2007 Version (2008) GEO-SLOPE International Ltd. Canada
- Stability Modeling with SLOPE/W 2007 Version, (2008) GEO-SLOPE International Ltd. Canada
- Suryo EA, Gallage C, Trigunarysah B (2015) A Method for Predicting Rain-induced Instability of an Individual Slope. The 9th Annual International Conference of the International Institute for Infrastructure Renewal and Reconstruction, 2013, no. May.
- Suryo EA (2013) Real-time Prediction of Rainfall Induced Instability of Residual Soil Slopes Associated with Deep Cracks. PhD thesis, Queensland University of Technology.
- Taib SNL, Selaman OS, Chen CL, Lim R, Ismail DSA (2017) Landslide susceptibility in relation to correlation of groundwater development and ground condition. *Hindawi Adv Civ Eng.* <https://doi.org/10.1155/2017/4320340>
- Vasudevan N, Ramanathan K (2016) Geological factors contributing to landslides: case studies of a few landslides in different regions of India. *IOP Conf Ser Earth Environ Sci.* <https://doi.org/10.1088/1755-1315/30/1/012011>
- Wang S, Xu W, Liu J (2018) Stability and failure mechanism analyses of the zhenggang landslide in southwestern China. *Hindawi Adv Civ Eng.* <https://doi.org/10.1155/2018/6128401>
- 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 MDPI. *Water.* <https://doi.org/10.3390/w14071123>
- Zeng L, Xiao LY, Zhang JH (2020) Effect of the characteristics of surface cracks on the transient saturated zones in colluvial soil slopes during rainfall. *Bull Eng Geol Environ* 79:699–709. <https://doi.org/10.1007/s10064-019-01584-1>
- Zhang GR, Qian YJ, Wang ZC, Zhao B (2014) Analysis of rainfall infiltration law in unsaturated soil slope. *Sci World J* 2014:7. <https://doi.org/10.1155/2014/567250>
- Zhang Z, Fu X, Sheng Q, Yin D, Zhou Y, Huang J (2021) Effect of rainfall pattern and crack on the stability of a red bed slope: a case study in yunnan province. *Hindawi Adv Civ Eng* 6658211:1–21. <https://doi.org/10.1155/2021/6658211>

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