Effectiveness of Horizontal Sub-drain to Increase Slope Stability with Vertical Cracks and Weathering Soil in Areas with High Rainfall Intensity

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Research Article

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Abstract

A landslide occurred a few meters from the foot of the power plant tower in a hilly area in the Tulakan District, Pacitan, East Java Province, Indonesia. This incidence occurred after the area was flooded with a cumulative intensity of more than 1000 mm in one month and a maximum daily rainfall above 300 mm. Previous reports considered horizontal sub-drain cost-effective to reduce the groundwater level and the impact of rainwater seepage into the soil on slope stability. Therefore, this study aims to determine the effectiveness of horizontal sub-drain as an alternative for managing groundwater and rainwater that seeps into the soil to increase the slope factor of safety. The effect of real-time rainfall for 30 days before the landslide, hydraulic conductivity, changes in soil parameters due to cracking and weathering, and the existing groundwater level are also considered. The analyses were carried out using the coupled program SEEP/W for transient seepage and SLOPE/W with finite element method and limit equilibrium. The result showed that horizontal sub-drain increases the slope factor of safety from critical limit to more than 1.1 in 30 days of rainfall in high ground water level condition. The hydraulic conductivity parameters of the soil, the location of the horizontal sub-drain, as well as the cracked and weathered conditions in the soil also affect the effectiveness. In low-level ground water conditions, the duration of the rain and the intensity of the rain also greatly affect the effectiveness of the horizontal sub-drain as well as the number of cracks. In this condition, the safety factor on the slope with the horizontal sub-drain can increase the safety factor from less than one to more than one thus the slope becomes more stable. The results of this study also show that the effectiveness of the horizontal sub-drain is very sensitive to many things, therefore in its planning it is necessary to review many aspects more carefully.

1. Introduction

Slope failures are common phenomena worldwide, where large masses of soil move downslope by gravity. It occurs when the shear stress exceeds the shear strength of the slope (Kristo, Rahardjo and Satyanaga, 2017). Several studies were carried out to determine the main causes of landslides which are increasing in many areas on slopes of 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. This phenomenon is usually caused by changes in rain behavior that affect the hydrogeological, fluctuating parameters, and fracture conditions of the soil, which are mostly influenced by rain and the topography of the area.

The rainfall conditions that have led to landslides in the past can change over long periods or vary in the future due to environmental and climatic changes, including variation in intensity and frequency, and in the pattern of the meteorological triggering events (Gariano, Petrucci and Guzzetti, 2015). The variations in the frequency and intensity of the rainfall events will affect the prevalence of rainfall-induced landslides (Luigi and Guzzetti, 2016). Several investigations were carried out to determine a relationship between climate change which leads to variation in rain behavior and an increase in the number of landslides in the world (Gariano, Petrucci and Guzzetti, 2015). (Strauch et al., 2015) predicted a rise in temperatures as well as a more intense and less frequent rainfall due to climate change, thereby increasing landslide events. Based on a study in Hawaii, it was suggested that a decrease in mean annual rainfall is correlated with the increase in the intensity and number of dry days without rain. Changes in the patterns can also alter the flux boundary conditions such as infiltration and evapotranspiration, affecting the water pressure in the soil. As rainfall infiltrates through the soil pores, the water content of the soil will increase, and the groundwater table is elevated. This occurs specifically in soils with seepage coefficients greater than the intensity of the rain. Furthermore, it causes an increase in pore-water pressure and a decrease in effective stress, which reduces the shear strength of the soil to sustain loadings. 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 (Chen, Lee and Law, 2004).

Several studies including (Arezoo Rahimi, Rahardjo and Leong, 2011) showed that antecedent rainfall is the cause of landslides, which affects the stability of low-conductivity slopes more than high-conductivity slopes. It was discovered that different rainfall patterns affect various 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. Meanwhile, low-conductivity slopes achieved a minimum factor of safety under advanced rainfall patterns, where the intensity is high at the beginning and decreases with time (Rahardjo et al., 2010). Crosta and Dal Negro (2003), Fiorillo and Wilson (2004), and Mancarella and Simeone (2012) reported that these extreme instability phenomena occurred after several days of not intense rainfall, but continuously. Another study was also carried out to determine the landslides by comparing their prevalence during the rainy and dry seasons (Ciabatta et al., 2016). The results showed that most landslides occur during the rainy season.

The geological conditions are among the factors that affect the occurrence of landslides. Fu et al., (2011) identified soil thickness and rock fragment cover as key factors, which contribute to the soil's hydrological and landslide behaviors. This showed that thinner soils exhibit higher infiltration capacity and lower erosion rates across various rainfall events. The moisture content parameter is also considered to affect the stability of the slope. The study by (Zhang, Tao and Morvant, 2005) on cohesive soils showed that the high moisture content in the slope is due to surface water infiltration from rains. Moreover, a soil with moisture content near its liquid limit is expected to behave more similar with a liquid than a solid and have 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. Therefore, most slope surface failures occur when their soils become saturated (Gregory 1998; Gregory and Chill, 1998).

(Nyakundi et al., 2016) conducted a study on the effect of rain on groundwater levels that affect slope stability. The results showed that the rainfall played a significant role among the factors influencing groundwater levels, while others include the infiltration rate and land cover. The infiltration rate in the area can also be low because of the geological formation, indicating it takes more time for the rainfall to be reflected. Furthermore, (Jan and Chen, 2007) 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 to the influence of the population development in an area. The changes in the slope factor of safety due to variation in rainfall were also discussed by (Alsubal, Sapari and Harahap, 2018). It was discovered that the slope factor of safety with high soil permeability drops from 1.312 to 1.292 and 1.093 after the third rainfall event for the slope with and without pumping groundwater, respectively. For soil slope with moderate permeability, the factor of safety deteriorates from 1.314 to 1.157 at the end of the third day, while it remains stable with pumping groundwater. 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 influences the decrease of the safety factor, while the wetting process did not cause a significant reduction. Similarly, an investigation on the effect of groundwater levels has also been carried out by (Ibeh, 2020) and (Taib et al., 2017).

Based on previous reports, cracks in the soil are also one of the causes of landslides. This is because they provide preferential pathways for water flow, which significantly increases the hydraulic conductivity and the pore-water pressures in the soil mass (Wang, Xu and Liu, 2018). The case studies of landslides that occur in the field showed that the prevalence of deep landslide areas is due to rainfall on cracked slopes and weak soil layers ((Hu Shang, 2000); (Ping et al., 2005); (Wang, Zhang and Zhang, 2010). According to (N. W. Rogers and M. J. Selby, 1980), landslides that occurred in New Zealand were caused by pore pressure in soil cracks after previous rains. Moreover, a weak soil layer also shows high permeability and compressibility, which significantly affects the behavior of slope damage through changes in infiltration and deformation responses during rain. Therefore, (Wang, Zhang and Zhang, 2010) stated that the effect of the weak layer needs to be analyzed with a focus on the infiltration-deformation-slope failure relationship. (Ping et al., 2005), (Kodikara and Costa, 2013), (Suryo, 2013), and (Alexsander, Mochtar and Utama, 2017) also obtained the same results, where landslides are caused by cracks in the soil which will further increase slope instability during rain.

This showed that the main cause of many landslides in the world is rainwater or changes in groundwater levels. 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 (Tang, Tang and Wei Liu, 2011), a horizontal sub-drain is very effective in lowering the groundwater level. Similarly, (Cai et al., 1998) stated that it increases slope stability during rainfall, specifically for dangerous slopes and embankments. (Santi, Elifrits and Liljegren, 2003), (Cook, Santi and Higgins, 2008), and (Rahardjo, 2012) showed that the method is the most economical available approach due to its effectiveness. The summary of Sari (2022) on previous reports identified the effectiveness of horizontal drains to reduce the groundwater level while searching for an increase in the slope factor of safety by decreasing the water level due to the horizontal drain. This is in line with the discoveries of (Kenney and K.C.Lau, 1982), (Kopeckr, Ondrasi and Antolova, 2013), (Ahmed et al., 2012b), (Lin et al., 2016), (Pfeiffer, 2014) and (Amatya and Mori, 2018).

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. It also identifies the effectiveness of the horizontal sub-drain which was analyzed numerically as an alternative for handling landslides at the location. Furthermore, the changes in groundwater levels due to rainfall with and without horizontal drain are also discussed. To analyze the effectiveness of the horizontal drain, modeling with 2 dimensional using coupled program slope/w and slope/W was carried out to determine the effect of seepage and soil hydrological conditions on the slope stability.

2. Case Study: Landslide In Tulakan

In early December, after heavy rains over the previous few days, a natural landslide occurred in Tulakan Village, Pacitan, East Java, Indonesia. Pacitan Regency is located at the southwest tip of East Java Province. Its territory is bordered by Ponorogo and Wonogiri Regencies (Central Java) in the north, Trenggalek and Ponorogo Regencies in the east, the Indian Ocean in the south, and Wonogiri in the west. Most of the area is karst, which is part of the Sewu Mountains chain and is not suitable for agriculture because it is barren and dry with low groundwater levels. Moreover, the landslide occurred in Tulakan Village with hilly contours. Based on data from the ministry of energy and the mineral resources of the geological agency, most of these areas have a medium to the high status of landslides (Fig. 1).

The landslide occurred a few meters below the high-voltage power source tower (Fig. 2), causing a horizontal shift in the foundation of the electricity tower. When there was no immediate anticipation of subsequent landslides, it will have an impact on the electricity supply to several areas in East Java. This is an uninhabited hilly area with several shallow landslides in various locations. However, the small landslide that has occurred before has no impact on humans and did not need to be treated. In this study, new handling was carried out because the landslide that occurred was deep and close to the main power source in East Java.

Before the landslide, Pacitan area was flooded with very high intensity in almost all of its territory. From observations at 3 rain stations close to the location, the intensity of rain in November was more than 1000 mm with the highest value of 300 mm/day at the end of the month (Fig. 3). This heavy rainfall was assumed to be the main cause of the landslide, followed by weathered soil conditions and cracks on the surface.

Several field tests that were carried out to determine the cause of the landslides include N-SPT and geophysics (resistivity and induced polarization). The laboratory tests were also conducted to identify the soil parameters at the location. Furthermore, topographic measurements were carried out in several locations to determine the slope contours for current and long-term stability analysis. The layout of the test location, the topographic of the field, and the point of taking soil data are shown in Fig. 4.

Soil testing in the field was carried out at 4 points, of which 3 are located along section B and in exactly one line with the landslide. The soil conditions in the field, based on the results of the N-SPT test, were dominated by hard soil layers with very high N-SPT values (Fig. 5a). Hard cohesive soil layers were also discovered at shallow elevations to a depth of approximately 10 meters from the ground surface, while non-plastic and rocky layers are at later depths. Moreover, the condition of the soil layer at the landslide location was divided into 4 consisting silty clay, clay, rock on the surface, silty clay on the second, silty hard clay on the third, and rock on the fourth layer (Fig. 5b).

The handling of landslides at this location was carried out by using 2 methods. The first method is to lower the groundwater level to an elevation below – 15 meters from the surface for the slope to be stable with a factor of safety of more than one. This level is decreased by drilling wells and pumps to remove groundwater. Generally, pumping is carried out when the groundwater level increases during heavy rains. The diameters of drilling wells are recommended to be more than 15 cm using an installed PVC pipe wrapped with a non-woven geotextile which functions as a filter. The other approach is the use of ground anchors and geotextiles installed in areas damaged by landslides. This effort is made to restore the condition of the slope to its existing position and strengthen it to avoid another landslide in the future.

The recommendations were carried out in the field and did not experience further landslides in this location, other than that, very high intensity rain no longer occurs at this location. However, the first treatment, pumping to reduce the groundwater level, is less efficient because the process requires extra energy during the rainy season. In handling this case, an in-depth analysis has not been carried out on the effect of fluctuating rainfall intensity and hydraulic conductivity of the soil on slope stability. The previous evaluation only used the limit equilibrium method by assuming a high groundwater level during heavy rains. Similarly, the analysis using the finite element method to determine changes in groundwater level and the slope factor safety that occur due to rain with different durations and intensities has not been carried out. This will possibly lead to an increase in the cost of repairs and retrofitting to anticipate landslides and overestimated the need for reinforcement. Therefore, in this study, numerical analysis was carried out to determine other methods of managing water levels with horizontal sub-drain.

3. Theoretical Consideration

This study which concerned slope stability under the rainfall was carried out using 2 analyses. This includes the seepage analysis, which was conducted using commercially available software SEEP/W to compute the pore-water pressures. Secondly, the slope factor of safety was calculated using SLOPE/W to assess the stability of soil slope. The water-flow governing equation used in the software for solving 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 is the slope of the soil-water characteristic curve, γ_w is the unit weight of water, h_w is the hydraulic head or total head, t is time, k_{wx} and k_{wy} are the coefficients of permeability to water as a function of matric suction in the x- and y-direction, respectively, and q is 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 is based on (Fredlund and Xing, 1994) equation, as stated below:

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

Where τ is the shear strength of unsaturated soil, c' is the effective cohesion, $(\sigma_n - u_w)$ is net normal stress, σ_n is the total normal stress, u_a is the pore-air pressure, u_w is pore-water pressure, ϕ' is the effective angle of internal friction, $(u_a - u_w)$ is the matric suction, and ϕ^b is the angle indicating the rate of increase in shear strength relative to the matric suction. To compute the slope safety factor, Bishop's simplified method was used. Based on the previous study, this method has less computational effort, time required for analysis, and is more accurate compared to others (Rahimi, Rahardjo and Leong, 2010)

4. Methodology

The numerical model of the slope profile was established according to the existing condition on the field such as the topography, sub-surface layer, and hydrology condition in the landslide location. Rainfall-induced seepage and slope stability analyses with and without horizontal drain, with and without considering surface crack and weathered soil layer were carried out using the finite element method (FEM) and limit equilibrium method (LEM). The FEM seepage analysis involves calculating the pore-water pressure field coupled with LEM analysis along the potential sliding surface to estimate the factor of safety. The evaluation of horizontal drain effectiveness was analyzed by two-dimensional (2-D) numerical models to lower the groundwater levels and promote the factor of safety of the landslide. Since this study was carried out to show the method of integrating transient seepage modeling into the stability analysis of intricate landslides, the analysis was concentrated on transient seepage modeling. The effect of rainfall-induced seepage and effectiveness of horizontal drain is influenced by variations of groundwater levels due to rainfall and soil hydraulic conductivity, volumetric water content, and factor of safety of the potential sliding bodies. The flow chart of the working procedure for this study is shown in Fig. 6.

5. Numerical Model

5.1. Slope properties and boundary conditions

Figure 7 shows the existing slope geometry and boundary condition to be analyzed. The slope geometry such as angle and height influence the stability and factor of safety. Based on (Rahardjo et al., 2007) and (Rahimi, Rahardjo and Leong, 2011), the initial depth of the water table was also discovered to influence the stability of soil slope since it mainly affects the initial value of the slope factor of safety. Therefore, in this analysis, the determination of the slope geometry according to the conditions in the field and groundwater level in the existing conditions is carried out carefully.

The daily observations of groundwater level fluctuations before and after the landslide were not carried out during the rainy season. The groundwater level was determined only based on the results of observations during the boring test in the field with all its limitations. Several assumptions about the groundwater level during initial conditions were also carried out to determine the effect of the existing water level on slope stability during rain with different intensities over 30 days (Fig. 8). The shear strength properties of the soil used were based on laboratory testing. An effective cohesion range in each layer, c'= 0–90 kPa, the effective angle of internal friction, ϕ'= 1–40°, and unit weight of soil, γ = 17–19 kN/m^3, were used in the slope stability analyses. According to (Lin et al., 2016), shear strength parameters of soil were also kept constants for all cases. This was to ensure that the changes in the stability of the slope were only due to pore-water pressure (or matric suction) changes in the soil.

In this study, the boundary conditions were determined based on previous investigations conducted by (Rahimi, Rahardjo and Leong, 2010), (Rahimi, Rahardjo and Leong, 2011), (Suryo, 2013), (Lin et al., 2016), and many others. Meanwhile, the boundary conditions used for the transient seepage analysis are shown in Fig. 7. A boundary flux, q, equal to rainfall intensity, I_r, was applied to the surface of the slope. The nodal flux, Q, equal to zero was applied along the sides of the slope above the water table and along the bottom of the slope to simulate a no-flow zone. A boundary condition equal to total head, hw, was applied along the sides of the slope below the water table line. The left and right total heads are different and affected by the groundwater level. The determination of boundary conditions for horizontal drains is carried out based on (Lin et al., 2016), which assumed Q (potential seepage face review) is equal to 0 and the water rate is constant with a value of zero.

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 Fig. 9, which indicated that there is a layer with a low resistivity value. Moreover, one of the soil zones with low resistivity values is located under the electric tower, which is an area affected by landslides. Castelblanco et al (2012) stated that the changes in resistivity were related to the variations in the degree of saturation and growth of the crack. McCarter (1984) showed that at low water contents, the resistivity rapidly decreases with increased water content. (Ghazali et al., 2013) stated that high-water content and weak zones can be determined as low resistivity regions by the methods used in this study. The report by (Ghazali et al., 2013) was also conducted to determine the debris flow in the soil using Geoelectrical Resistivity Surveys.

Based on the resistivity results in Fig. 9, it was discovered that there are zones below the surface with low resistivity values. This indicates that the location has a higher water content compared to the zone with a greater resistivity value ((Ismail, Ng and Abustan, 2017), (Alexsander, Mochtar and Utama, 2017)). The area with high water content is assumed to be a weak layer which can be in form of cracks or weathering of the soil. Meanwhile, several theories stated that a weak layer existing as a crack in the soil is initiated by a surface crack. (Gofar et al., 2006), (Wang and Li, 2011), (Zhang, Tao and Morvant, 2005), (Suryo, 2013), and (Alexsander, Mochtar and Utama, 2017) showed that there are main cracks from the surface propagating into deep ones and a surrounding weak zone. According to (Gofar et al., 2006) dan (Wang and Li, 2011), cracks cause 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. (Suryo, 2013) also modeled a weak layer as a silty soil surface disturbed by direct rainwater infiltration through the soil's deep crack.

The weak layer below the soil surface which is the impact of the cracks infiltrated by rainwater causes changes in soil parameters. According to (Zhang, Tao and Morvant, 2005), increasing the moisture content from 13.5–30% can decrease a shear strength to 80% from the initial value. These results have also been applied by (Gofar et al., 2006), (Wang and Li, 2011), and (Suryo, 2013). Moreover, (Gofar et al., 2006) and (Wang and Li, 2011) suggested that the shear strength of the crack material has a zero value to represent the 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 crack material was assigned 10 cm/sec for the hydraulic conductivity parameter and assumed by (Suryo, 2013) to be porous as gravel. Due to the existence of deep cracks, the K_{sat} of the weak material can be assumed as those with high permeability such as coarse or fine sand (Gofar et al., 2006). The crack parameters in unsaturated soil conditions have also been developed by (Wang and Li, 2011) through the determination of the SWCC graph and crack soil hydraulic conductivity for random aperture. (Zhang et al., 2021) used the permeability ratio (Ky/Kx) applying 3 various data: 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 results of the resistivity test which shows the presence of a weak layer in the subsurface, several modeling that was carried out include:

• ES condition (Existing Slope condition).

This analysis was carried out based on the results of soil observations with N-SPT and laboratory testing. There were no detailed results obtained for the presence of weak layers, weathering, or cracks in the soil. This showed that the soil parameters in the location are strong and consist of stiff clay. The hydraulic conductivity testing was also not carried out in the laboratory. Therefore, it is assumed that the value of hydraulic conductivity in the soil is very small, and rainfall does not affect the stability of the slope. Landslides also occurred after this area was flooded with very heavy rain.

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

This analysis was carried out based on observations from resistivity testing. The results showed that there is a zone with a low value with a high-water content based on the existing report. The high-water content in the deep zone is believed to originate from surface cracks that allow rainwater to seep into deeper soil, causing an increase in water content. Therefore, the VC condition is analyzed to determine whether the slope stability can be affected at the beginning of the presence of a weak layer. The parameters used for VC are based on (Suryo, 2013) with γ = 15 KN/m^3, C'=0, φ '= 0, K_{sat}=0.01 m/s; n = 0.8.

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

This analysis was carried out based on observations from resistivity testing. The vertical cracks are considered to be the beginning of a weak layer in the soil. The weak layer was soil with greater water content, causing a change in the parameters of the existing condition. The parameters used for the weak layer in this analysis were adapted from a study by (Zhang, Tao and Morvant, 2005) and (Suryo, 2013), namely γ = 15 KN/m3, C'=5.4 Kpa, φ'= 17.5^o, Ksat = 0.001 m/s, n = 0.43.

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

5.2. Rainfall data

The rainfall parameters were obtained from observations of rain at 3 stations in Pacitan in 2017. Figure 3 shows that the highest rainfall intensity, 1027 mm occurred in November at the Kebon Agung rain station. This station is closer to the study location compared to others, therefore, its data were used in numerical analysis. Since the landslide occurred in early December, the data used were obtained for 30 days in November and the intensity of rain per day is shown in Fig. 11a. From these results, the highest rainfall intensity occurred on 27–28 November 2017 and significantly decreased the next day. Although there were no definite data from the relevant institutions on the duration of the rain that occurs daily, it was discovered that the rain with the greatest intensity occurs for a maximum of 6 hours/day. Furthermore, the duration of rain was analyzed with 3 rain scenarios, namely 1 hour/day, 3 hours/day, and 6 hours/day rain. The duration will be applied uniformly daily for 30 days in November which is analyzed. Figure 11b shows the rainfall intensity in m/s in each rain duration scenario used in this study.

6. Result And Discussion

The results of the analysis are divided into several discussions, namely the effect of the elevations of the existing groundwater level on slope stability, horizontal sub-drain on slope stability with the different water levels, vertical crack and weak layer on slope stability, and the effectiveness of horizontal drain with variations in soil conditions and groundwater level. This was carried out to determine the mechanism of the landslide at the study location, the effect of cracks and weak layers. It also makes horizontal sub-drain an effort to mitigate landslides by managing rainwater and understanding its effectiveness to increase the factor of safety.

In ES conditions, the elevation of the existing groundwater greatly affects the value of the safety factor on the slope. This indicates the lower the elevation of the existing groundwater level, the greater the value of the slope factor of safety. The daily factor of safety with real-time rain conditions has decreased (Fig. 12a) due to the absence of significant changes in the water level which can affect the factor of safety. Soil conditions that have a hydraulic conductivity value are much smaller than the intensity of the rain, causing most of the rainwater to become surface runoff, and not many seeps into the soil, which does not affect slope stability. This is in line with (Galeandro et al., 2013) which stated that when the rainfall intensity exceeds the infiltration capacity of the soil matrix, a certain amount of water is not able to infiltrate into the matrix. In this condition, the horizontal sub-drain (HD) does not have much effect to increase slope stability. At groundwater level conditions 1, 2, and 3, and in the installation of horizontal drains at sub-drain locations 1, 2, and 3, the factor of safety is the same as the slope without a horizontal drain (Figs. 12b and c). These results indicate that when the hydraulic conductivity is very small compared to the intensity, 30 days of rain does not significantly affect the stability of the slope. The selection of landslide handling with a horizontal drain in this condition is also very ineffective. in this condition, the installed horizontal sub-drain must be longer until it reaches the ground water level position.

Most of ES conditions obtained a factor of safety greater than 1.1 during the 30 days of rain in November, which had the highest intensity and is safe because it is above the critical slide limit (SF = 1). In this analysis, the soil parameters used are based on conventional tests, namely N-SPT and laboratory that do not capture the weathering conditions or the presence of other weaker layers below the soil surface. The conventional test was only carried out at several 3 points in a very large landslide area to avoid its representation of real conditions in the field. Therefore, the results of the analysis of slope stability gave a factor of safety that is safe against landslides when landslides occur. More in-depth observations were made on the geophysical data. The resistivity test also showed several zones which are crack soil and weak layers. The results of geophysical observations are interpreted under VC and VCWL conditions.

This is similar to the results of the analysis of ES conditions, where the elevation of the groundwater level in the VC condition also affected the factor of safety. This indicated that the higher the groundwater level, the lower the factor of safety, however, different results were obtained when a horizontal drain was used. Under the ES conditions, the horizontal drain did not effectively elevate slope stability but increased the factor of safety under VC conditions (Fig. 13), which tends to be higher after the 27th day of rain. Meanwhile, a significant decrease can also be caused by the rainfall that had accumulated from the previous day. According to (Suryo, 2013), a change in the factor of safety in vertical cracked conditions only began to occur after experiencing more than 70 days of rain. This decrease is influenced by the value of the hydraulic conductivity in the soil, the intensity of rain, number, position, and the dimension of cracks. The study also conducted a comparison of the factor of safety value with the presence of vertical cracks with variations in the position of the crack to decrease the safety value.

The location of the horizontal drain placement also affects its effectiveness. HD 1, which is in a lower position, improves the slope stability compared to HD 3, which is in the top position (Fig. 13a, b, and c). This result is only valid when the groundwater level is high (GWL 3). Meanwhile, different results were obtained in GWL 1 and 2, where horizontal drain did not increase slope stability (Fig. 13d). This occurred due to the presence of vertical surface cracks that did not increase the amount of rainwater that enters the soil, therefore, it does not affect the groundwater level at deep elevations. The results obtained will be different if there are more surface cracks and longer cracks on the slope. The effect of the horizontal position of the sub-drain, where HD is at a low elevation with a higher level of effectiveness, was also confirmed by (Rahardjo et al., 2003) and (Rahardjo, 2012) in their parametric study and field validation. (Ismail, Ng and Abustan, 2017) also obtained the same results on the relationship between the horizontal position of the sub-drain and its effectiveness.

VCWL obtained almost the same results as ES and VC in some conditions. Figure 15a shows that the higher the groundwater level, the lower the factor of safety. The same results were also obtained in the ES and VC conditions, which indicated that the elevation of the existing groundwater level is also very influential on the stability of the slope. The horizontal sub-drain did not increase the slope factor of safety at a low level. This is because the position of the weak layer is far above the level at low elevation and the horizontal sub-drain does not touch the groundwater. Meanwhile, the very small Ks condition of the soil restricted the rainwater from reaching the weak layer position and the horizontal drain to becomes ineffective. The increase in the factor of safety is observed only when it rains for 6 hours after experiencing 28 days of rain (Fig. 14c). This shows that the location of the horizontal sub-drain installation and the duration of one day of rain also affect the effectiveness of the sub-drain. From Fig. 13b, the HD 3 which is in the top position has the same factor of safety as the slope without horizontal drain. This occurred because the position of HD 3 is only in a small part of the weak layer. Therefore, the area and the location of the weak layer also affect the horizontal placement of the sub-drain when used in landslide mitigation. This result is almost the same as the study by (Martin, 2013), where the water from the Horizontal sub-drain is installed at the same elevation but various points have different discharges in a view location. (Ahmed et al., 2012a) also stated that horizontal sub-drain which emits the largest water discharge is only at certain points in this study area with a small resistivity value, this is also in line with the results of (Ismail, Ng and Abustan, 2017).

The effect of vertical crack and weak layer with no horizontal sub-drain condition was also observed in this study. Figure 15 shows the changes in the factor of safety in 30 days of rain with variations in groundwater level and soil parameters. In GWL 1 and 2 (Fig. 15a and b), the factor of safety under VCWL conditions is the highest, specifically at the beginning of the rain, but significantly decreases to the lowest for ES and VC conditions. However, in GWL 3 (Fig. 15c), which is the highest groundwater level, the factor of safety for VCWL is much lower compared to the ES and VC conditions. This indicates that at high groundwater levels, the presence of cracks and weak layers significantly reduces the stability of a slope. Meanwhile, at lower groundwater levels, the decrease in the factor of safety in VCWL conditions only occurred after several days of rain. These results showed that the stability of a slope that experiences rain with different intensities daily is influenced by soil conditions such as the presence or absence of cracks and weak layers as in this case, the elevation of the existing groundwater level, and contour topography.

Another experiment was carried out by adding the number of vertical cracks under VCWL conditions. The number of surface cracks previously was 6 pieces and was added to 18 pieces to determine the effect of rain when the ground water level is low. In Fig. 16a it can be seen that the more the number of cracks on the surface, the smaller the safety factor that occurs. In addition, the horizontal sub-drain in this condition also becomes effective during heavy rains on day 27 (Fig. 16b). This condition also shows that rain can affect the effectiveness of the horizontal drain. The presence of high intensity and duration of rain is proven to also affect the effectiveness of the horizontal drain. In Fig. 17a it can be seen that the horizontal sub-drain can be more effective in increasing the safety factor to reach 11.5% in rain with a higher intensity, which is between $1.41x10^{-05}$ – $1.85x\ 10^{-07}$ and occurs throughout the day for 14 days. At a lower rain intensity, namely $3.52x\ 16^{-06}$-$1.16x10^{-08}$ and occurs throughout the day for 30 days, the horizontal sub-drain will be able to increase the safety factor when it rains with a higher intensity, namely on days 27–28 (Fig. 17b). These results indicate that the number of cracks, the intensity of the rain and the duration of the rain can affect the effectiveness of the horizontal sub-drain to increase the safety factor slope.

Furthermore, a slight oddity occurred in the VCWL conditions in GWL 2 and 3, where there was a slight increase in the factor of safety at the beginning of the rain. This occurred due to the changes in groundwater levels during rain. The changes in groundwater level in this condition are very different from the ES and VC because there is a weak zone with a larger Ks parameter. According to Vucovic (1997) and (Mattei et al., 2020), the differences in hydraulic conductivity parameters have a major effect on groundwater level fluctuations. This is because of an increase in the factor of safety caused by fluctuations in the groundwater level that occur. The increase in the value at the beginning of the rain does not occur when the existing groundwater level is very low.

Investigation on the effectiveness of horizontal drain during the rain was also carried out with a higher hydraulic conductivity value. (Tang, Tang and Wei Liu, 2011) discovered that the presence of a horizontal drain can increase the factor of safety by up to 25% when monitoring is carried out 48 hours after 60 mm/hour of rain for 9 hours. This study was conducted on soil with Ks = $9.2\ x\ 10^{-6}$ m/s. According to (Rahardjo, 2012), the presence of a horizontal drain increased the SF from 1,193 to 1,303 with Ks = 2.1 x 10 – 7 m/s. Meanwhile, the horizontal drains were installed at the foot of the slope with a length of 12–18 meters in Rahardjo's study and 25–30 meters in (Tang, Tang and Wei Liu, 2011). In the previous report by (Lin et al., 2016), increasing the factor of safety with horizontal drain combined with sub-surface drainage increased the value for slope from 1,098 to 1,228.

The position and length of the horizontal drain also affect its effectiveness. In this study, the installed horizontal drain for some conditions has not reached the location of the groundwater level. Based on (Cook, Santi and Higgins, 2008) summaries, drains need to extend far enough into the slope to achieve the desired water level drawdown throughout the slope. Since water needs to be removed from the slip zone, drains are installed to penetrate through this zone. Apart from the minimum length limit, the effectiveness of the horizontal drain can also be affected by its maximum length. (Royster, 1972) stated that drains must not extend more than 3–5 meters past the slip surface. Meanwhile, (Lau and Kenney, 1983) stated that no additional benefits can be achieved by installing drains that extend beyond where the critical slip surface intersects the top of the slope. This result was supported by (Nakamura, 1988) which showed that the maximum reduction in subsurface water is not affected by changes in drain length beyond a critical length. Furthermore, (Cai et al., 1998) stated that the increase in the factor of safety became smaller when the drains extend beyond a critical length. This showed that installing drains that significantly exceed the slip surface is uneconomical and can cause more water to be conveyed into the failure zone (Royster, 1972).

In this landslide case, the soil at the study location has the dominant parameters of hard clay and rock with high shear strength, but there are weathered layers in several zones below the soil surface. This showed that there is a slight decrease in the factor of safety due to rainfall with and without horizontal drain installation. From the results of numerical analysis, the decrease in the value of the factor of safety under ES conditions is between 0.01–0.03 without and with horizontal drain, while VC is between 0.02–0.035. However, the decrease in the safety value in the VCWL condition is slightly higher, namely 0.11. The presence of a horizontal drain also increases the slope factor of safety. Based on the results, the increase due to horizontal sub-drain installation ranges from 0.02 to 0.083 in 30 days of rain. This increase in the factor of safety is slightly smaller than the study by (Rahardjo, 2012). Meanwhile, the result is due to the Ks parameter on the slope, which is much smaller than the rainfall intensity causing the value of the increase in the factor of safety. The soil shear parameters and the horizontal sub-drain length also affect the effectiveness of the horizontal drain.

Gambar 17. 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; a) Effect of horizontal sub-drain due to 30 days of rain and occurs throughout the day with lower intensity

(Ismail, Ng and Abustan, 2017) conducted a study to determine the effectiveness of horizontal drain on cutting slopes with high GWL by varying the length. The result showed that a horizontal drain with a minimum length of 22.5 meters is the most effective way of increasing safety. In this case, the value of the factor of safety increased from 1,021 without a horizontal drain to 1,456 with a horizontal drain of 25 meters. This investigation was conducted on a cutting slope with lower shear strength and Ks parameters compared to this case study. The increase in factor of safety after a horizontal drain was installed in the report by Ismail was greater than the results of this study, (Rahardjo, 2012), and (Lin et al., 2016) but almost the same as (Tang, Tang and Wei Liu, 2011). Therefore, the effectiveness of the horizontal drain is very sensitive and is influenced by many factors, namely soil parameters, topography slope, groundwater level conditions, rainfall intensity and duration, length, and horizontal position of the drain. When the horizontal drain is installed in a suitable location, its effective length can significantly increase the factor of safety by lowering the groundwater level and reducing the effect of rain on slope stability.

Based on the landslide case, the results showed that the condition of the subsurface soil is very heterogeneous and affects its stability. Soil parameters obtained from conventional testing in form of boring, CPTU, N-SPT, and laboratory tests are not sufficient to explain the real conditions for all layers below the soil surface. Therefore, the soil parameters from the conventional test are stable, making it impossible for landslides to occur. There are weathered soil and surface cracks that are not known from the test. A geophysical test that obtains a resistivity value can help identify subsurface zones with a higher water content, which is believed to be a weak layer due to soil weathering. This causes the differences in soil parameters that occur where the shear parameter becomes lower (Zhang, Tao and

Morvant, 2005) and hydraulic conductivity is greater ((Gofar et al., 2006), (Wang and Li, 2011) and (Suryo, 2013)).

In this study, the landslide occurred due to heavy rain and seeped into the ground through vertical cracks. The continuous ingress of rainwater through vertical cracks is suspected to have caused two things, namely, first, crack propagation until it reaches the weathered deep layers. The second is weathering of hard soils, a decrease in soil shear parameters, and an increase in hydraulic conductivity parameters. When this condition is accompanied by continuous rain, it causes a decrease in soil parameters leading to slope instability and landslides. The horizontal drain will be effective in increasing slope stability when it is installed in a good position in the weak layer zone and locations with high rainfall intensity as well as a fairly long duration of rain such as in tropical countries. This will lead to an increase in the groundwater level due to rainwater infiltration which can be removed through the horizontal drain.

7. Conclusion

The landslide that occurred at the study location was caused by the presence of a weak layer below the surface and vertical cracks on the soil due to heavy rain. In the absence of weak layers and vertical cracks, the soil parameters at this location are very good and landslides will not occur. The existence of a weak zone is not readable from conventional soil testing and was discovered from geophysical examination using resistivity parameters. The subsurface with low resistivity is an area with high water content, which causes a decrease in soil shear stress parameters and slope stability. The weak zone in the subsurface layer is caused by vertical cracks on the surface that allow rainwater to seep into the ground. Cracked soil conditions and weak layers have greater hydraulic conductivity parameters compared to slope soils. Therefore, it affects the groundwater level condition on the soil and slope stability. The use of horizontal sub-drain was also considered effective to increase the slope factor of safety. The increase in safety factor after horizontal sub-drain installation can reach more than 10% under certain conditions. The percentage increase in the safety factor slope after horizontal sub-drain installation is influenced by many factors where there are cracks and weak layers, seepage parameters, intensity and duration of rain are very important factors. Therefore, it is also important to balance the determination of horizontal sub-drain installation with the existence of complete subsurface data such as geophysics to determine the real condition of the soil as well as important parameters that can increase the role of horizontal sub-drain as a landslide disaster mitigation.

Declarations

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Authors contributions

PTKS collects secondary data from several related agencies and processes the data for analysis. This author performed a numerical analysis with SEEP/W and SLOPE/W and wrote a draft for publication. IBM Analyzed the results of numerical modeling and proofread the manuscript so that it was ready for publication. SC provides recommendations on various aspects that must be reviewed in performing numerical analysis. All authors read and approved the final manuscript

Competing interests

The authors declare that they have no competing interests.

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References

1. Ahmed, J. et al. (2012a) 'Effectiveness of horizontal drains in improving slope stability: A case study of landslide event in Putra Jaya Precinct 9, Malaysia', in Unsaturated Soils: Theory and Practice 2011.
2. Ahmed, J. et al. (2012b) 'Effectiveness of horizontal drains in improving slope stability: A case study of landslide event in Putra Jaya Precinct 9, Malaysia Effectiveness of Horizontal Drains in Improving Slope Stability : A Case Study of Landslide Event in drains Putra in Jaya', in Unsaturated Soils: Theory and Practice 2011, pp. 753–758.
3. Alexsander, S., Mochtar, I. B. and 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.
4. Alsubal, S., Sapari, N. and Harahap, I. S. H. (2018) 'The Rise of Groundwater Due to Rainfall and the Control of Landslide by Zero-Energy Groundwater Withdrawal System', International Journal of Engineering & Technology, 7(2.29), pp. 921–926.
5. Amatya, S. C. and 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', Journal of Nepal Geological Society, 55, pp. 109–122.
6. Arezoo Rahimi, Rahardjo, H. and Leong, E.-C. (2011) 'Effect of Antecedent Rainfall Patterns on Rainfall-Induced Slope Failure', JOURNAL OF GEOTECHNICAL AND GEOENVIRONMENTAL ENGINEERING, 137(May), pp. 483–491. doi: 10.1061/(ASCE)GT.
7. 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)', Journal of The Civil Engineering Forum, 5(2), pp. 149–160.

8. Cai, F. et al. (1998) ‘Effects of horizonal drains on slope stability under rainfall bt three-dimensional finite element analysis’, Computers and Geotechnics, 23(December 1998). doi: 10.1016/S0266-352X(98)00021-4.
9. Chen, H., Lee, C. F. and Law, K. T. (2004) ‘Causative Mechanisms of Rainfall-Induced Fill Slope Failures’, JOURNAL OF GEOTECHNICAL AND GEOENVIRONMENTAL ENGINEERING, 130(6), pp. 593–602.
10. Cook, D. I., Santi, P. M. and Higgins, J. D. (2008) ‘Horizontal Landslide Drain Design: State of the Art and Suggested Improvements’, The Geological Soiety of America, XIV(4), pp. 241–250.
11. Fredlund, D.. and Xing, A. (1994) ‘Equations for the soil-water characteristic ’ curve ”, Can Geotech Journal, 31.
12. Galeandro, A. et al. (2013) ‘Analysis of rainfall infiltration effects on the stability of pyroclastic soil veneer affected by vertical drying shrinkage fractures’, Bull Eng Geol Environ, 72(July), pp. 447–455. doi: 10.1007/s10064-013-0492-5.
13. Gariano, S. L., Petrucci, O. and Guzzetti, F. (2015) ‘Changes in the occurrence of rainfall-induced landslides in Calabria, southern Italy, in the 20th century’, (October). doi: 10.5194/nhess-15-2313-2015.
14. Ghazali, M. A. et al. (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’, Journal of Geological Research. doi: 10.1155/2013/721260.
15. Gofar, N. et al. (2006) ‘TRANSIENT SEEPAGE AND SLOPE STABILITY ANALYSIS FOR RAINFALL-INDUCED LANDSLIDE: A CASE STUDY R AINFALL -I NDUCED L ANDSLIDE : A C ASE S TUDY’, Malaysian Journal of Civil Engineering, 18(1), pp. 1–13.
16. Hu Shang (2000) Reliability of Slope Stability Considering Infiltration Through Surface Cracks. Hong Kong University of Science and Technology.
17. Hutagamissufardal, Mochtar, I. B. and Mochtar, N. E. B. (2018) ‘The Effect of Soil Cracks on Cohesion and Internal Friction Angle at Landslide’, Journal of Applied Environmental and Biological Sciences, 8(3), pp. 1–5.
18. Ibeh, C. U. (2020) ‘Effect of changing groundwater level on shallow landslide at the basin scale: a case study in the Odo basin of South Eastern Nigeria’, Journal of African Earth Sciences. Elsevier Ltd, p. 103773. doi: 10.1016/j.jafrearsci.2020.103773.
19. Ismail, M. A. M., Ng, S. M. and Abustan, I. (2017) ‘Parametric Study of Horizontal Drains for Slope Stability Measure: A Case Study in Putrajaya, Malaysia’, KSCE Journal of Civil Engineering, 21, pp. 2162–2167. doi: 10.1007/s12205-016-1084-2.
20. Jan, C. and Chen, T. (2007) ‘Effect of rainfall intensity and distribution on groundwater level fluctuations’, JOURNAL OF HYDROLOGY, pp. 348–360. doi: 10.1016/j.jhydrol.2006.07.010.
21. Kenney, T. C. and K.C.Lau (1982) Horizontal deep drains to stabilize clay slopes.
22. Kodikara, J. and Costa, S. (2013) ‘Desiccation Cracking in Clayey Soils: Mechanisms and Modelling Desiccation Cracking in Clayey Soils ’:, (January). doi: 10.1007/978-3-642-32492-5.

23. Kopeckr, M., Ondrasi, M. and Antolova, D. (2013) ‘Horizontal Drains as Effective Measure for Landslide Remediation’, Studia Geotehnia et Mehania, XXXV(March), pp. 129–141. doi: 10.2478/sgem-2013-0011.
24. Kristo, C., Rahardjo, H. and Satyanaga, A. (2017) ‘International Soil and Water Conservation Research Effect of variations in rainfall intensity on slope stability in Singapore’, International Soil and Water Conservation Research. Elsevier B.V., pp. 1–7. doi: 10.1016/j.iswcr.2017.07.001.
25. Lau, K. C. and Kenney, T. C. (1983) ‘Horizontal drains to stabilize clay slopes’, Can. Geotech. J, 21, pp. 241–249.
26. Li, H. et al. (2020) ‘Seasonal and Inter-Annual Variability of Groundwater and Their Responses to Climate Change and Human Activities in Arid and Desert Areas ’:, Water, 12(303). doi: 10.3390/w12010303.
27. Lin, D. et al. (2016) ‘Evaluating the Efficiency of Subsurface Drainages for Li-Shan Landslide in Taiwan’, Nat. Hazards Earth Syst. Sci. Discuss, 1(January), pp. 1–22. doi: 10.5194/nhess-2015-309.
28. Luigi, S. and Guzzetti, F. (2016) ‘Earth-Science Reviews Landslides in a changing climate’, Earth Science Reviews. The Authors, 162(October 2017), pp. 227–252. doi: 10.1016/j.earscirev.2016.08.011.
29. Martin, R. (2013) ‘Use of Horizontal Drains for Slope Stabilisation in Hong Kong’, HKIE Transactions, 3(April 2015), pp. 37–41. doi: 10.1080/1023697X.1996.10667700.
30. Mattei, A. et al. (2020) ‘Can Soil Hydraulic Parameters be Estimated from the Stable Isotope Composition of Pore Water from a Single Soil Profile ?’, Water, 12(393), pp. 1–19.
31. N. W. Rogers and M. J. Selby (1980) ‘Mechanisms of Shallow Translational Landsliding during Summer Rainstorms: North Island, New Zealand’, Geografiska Annaler. Series A, Physical Geography, 62(1/2), pp. 11–21. doi: 10.2307/520448.
32. Nakamura (1988) ‘Landslide control works by horizontal drainage works’, in Landslides: Proceedings of the 5th Symposium: Lausanne, Switzerland Vol. 2, pp. 893–896.
33. Nyakundi, R. M. et al. (2016) ‘Impact of rainfall variability on groundwater levels in Ruiru municipality, Kenya’, African Journal of Science, Technology, Innovation and Development, 1338(April). doi: 10.1080/20421338.2015.1085157.
34. Pfeiffer, T. J. (2014) ‘Practical Considerations for the Design and Construction of Landslide Mitigation using Horizontal Drains’, in 65TH HIGHWAY GEOLOGY SYMPOSIUM.
35. Ping, F. A. N. et al. (2005) ‘Numerical analysis of rainfall infiltration in the slope with a fracture’, Science in China Ser. E Engineering & Materials Science, 48, pp. 107–120.
36. Rahardjo, H. et al. (2003) ‘Effectiveness of horizontal drains for slope stability’, Engineering Geology, 69, pp. 295–308. doi: 10.1016/S0013-7952(02)00288-0.
37. Rahardjo, H. et al. (2007) ‘Factors Controlling Instability of Homogeneous Soil Slopes under Rainfall’, JOURNAL OF GEOTECHNICAL AND GEOENVIRONMENTAL ENGINEERING, (December), pp. 1532–1543.

38. Rahardjo, H. et al. (2010) ‘Effects of Groundwater Table Position and Soil Properties’, JOURNAL OF GEOTECHNICAL AND GEOENVIRONMENTAL ENGINEERING, 136(November), pp. 1555–1564.
39. Rahardjo, H. (2012) ‘Performance of horizontal drains in residual soil slopes’, SOILS AND FOUNDATIONS, 51(3), pp. 437–447.
40. Rahimi, A., Rahardjo, H. and Leong, E.-C. (2011) ‘Effect of antecedent rainfall patterns on rainfall – induced slope failure Effect of Antecedent Rainfall Patterns on Rainfall- Induced Slope Failure’, ASCE Journal of the Geotechnical Engineering Division, 137. doi: https://doi.org/10.1061/(ASCE)GT.1943–5606.0000451.
41. Rahimi, A., Rahardjo, H. and Leong, E. (2010) ‘Effect of hydraulic properties of soil on rainfall-induced slope failure’, Engineering Geology. Elsevier B.V., 114(3–4), pp. 135–143. doi: 10.1016/j.enggeo.2010.04.010.
42. Royster, D. L. (1972) ‘Horizontal Drains and Horizontal Drilling: An Overview’, TRANSPORTATION RESEARCH RECORD, pp. 16–20.
43. Santi, P. M., Elifrits, C. D. and Liljegren, J. A. (2003) ‘Design and Installation of Horizontal Wick Drains for Landslide Stabilization’, Transportation Research Record 1757, 2(01), pp. 58–66.
44. Strauch, A. M. et al. (2015) ‘Climate driven changes to rainfall and streamflow patterns in a model tropical island hydrological system’, JOURNAL OF HYDROLOGY. Elsevier B.V., 523, pp. 160–169. doi: 10.1016/j.jhydrol.2015.01.045.
45. Suryo, E. A. (2013) Real-time Prediction of Rainfall Induced Instability of Residual Soil Slopes Associated with Deep Cracks.
46. Taib, S. N. L. et al. (2017) ‘Landslide Susceptibility in Relation to Correlation of Groundwater Development and Ground Condition’, Hindawi Advances in Civil Engineering, pp. 1–7. doi: 10.1155/2017/4320340.
47. Tang, L., Tang, X. and Wei Liu (2011) ‘A Case Study of Effect of Horizontal Drains on Rainfall-induced Landslide’, Advanced Materials Research, 253, pp. 1834–1837. doi: 10.4028/www.scientific.net/AMR.250-253.1834.
48. Wang, R., Zhang, G. and Zhang, J. (2010) ‘Applied Clay Science Centrifuge modelling of clay slope with montmorillonite weak layer under rainfall conditions’, Applied Clay Science. Elsevier B.V., 50(3), pp. 386–394. doi: 10.1016/j.clay.2010.09.002.
49. Wang, S., Xu, W. and Liu, J. (2018) ‘Stability and Failure Mechanism Analyses of the Zhenggang Landslide in Southwestern China’, Hindawi Advances in Civil Engineering, 2018(October 2008).
50. Wang, Z. F. and Li, J. H. (2011) ‘Influence of Cracks on the Stability of a Cracked Soil Slope’, in Unsaturated Soils: Theory and Practice 2011, pp. 721–727.
51. Zhang, Z. et al. (2021) ‘Effect of Rainfall Pattern and Crack on the Stability of a Red Bed Slope: A Case Study in Yunnan Province’, Hindawi Advances in Civil Engineering, 2021.
52. Zhang, Z., Tao, M. and Morvant, M. (2005) ‘Cohesive Slope Surface Failure and Evaluation’, JOURNAL OF GEOTECHNICAL AND GEOENVIRONMENTAL ENGINEERING, 7(July), pp. 898–906.

Figures

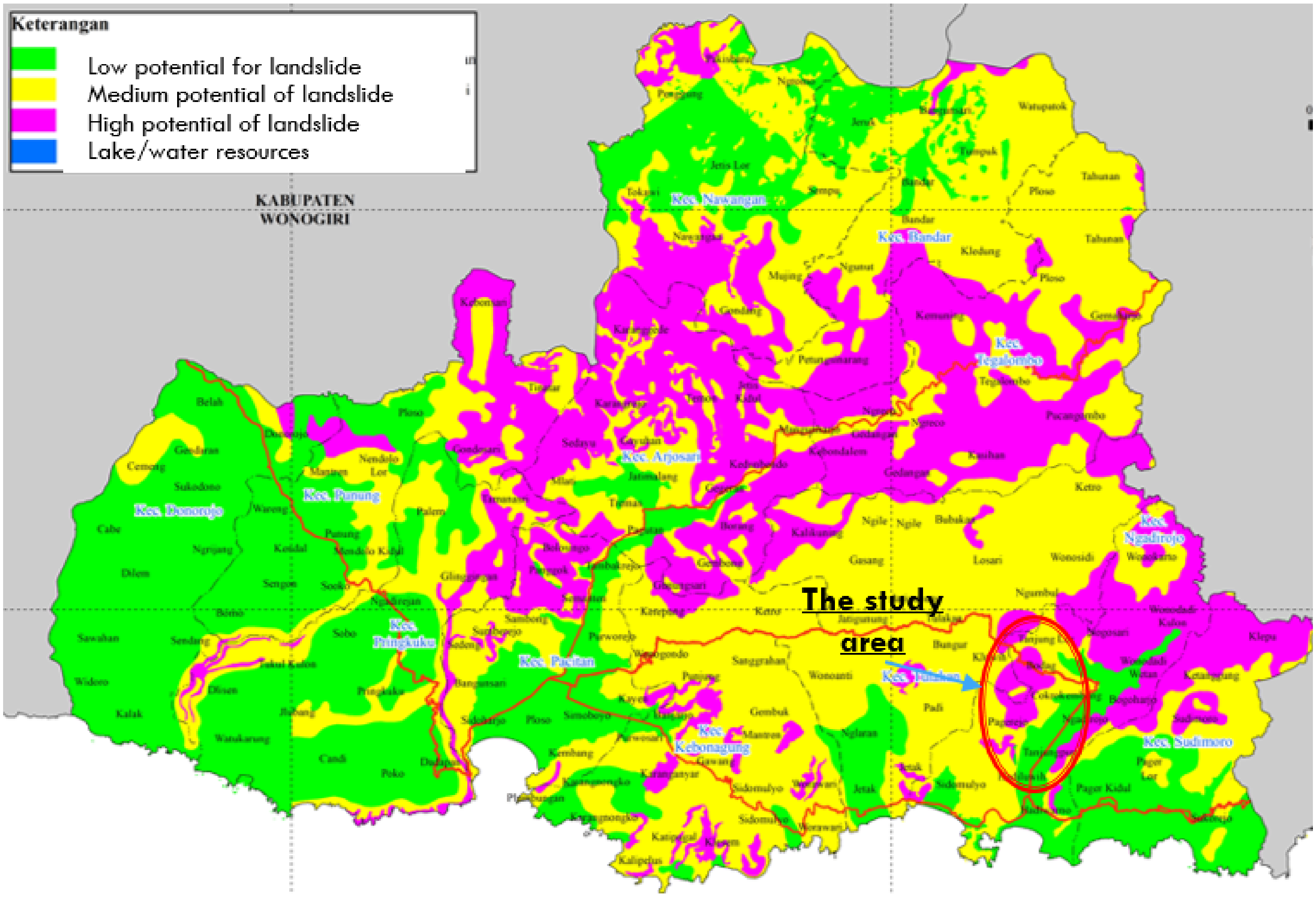

Figure 1

Pacitan landslide potential map from Indonesian ministry of energy and mineral resources of the geological agency

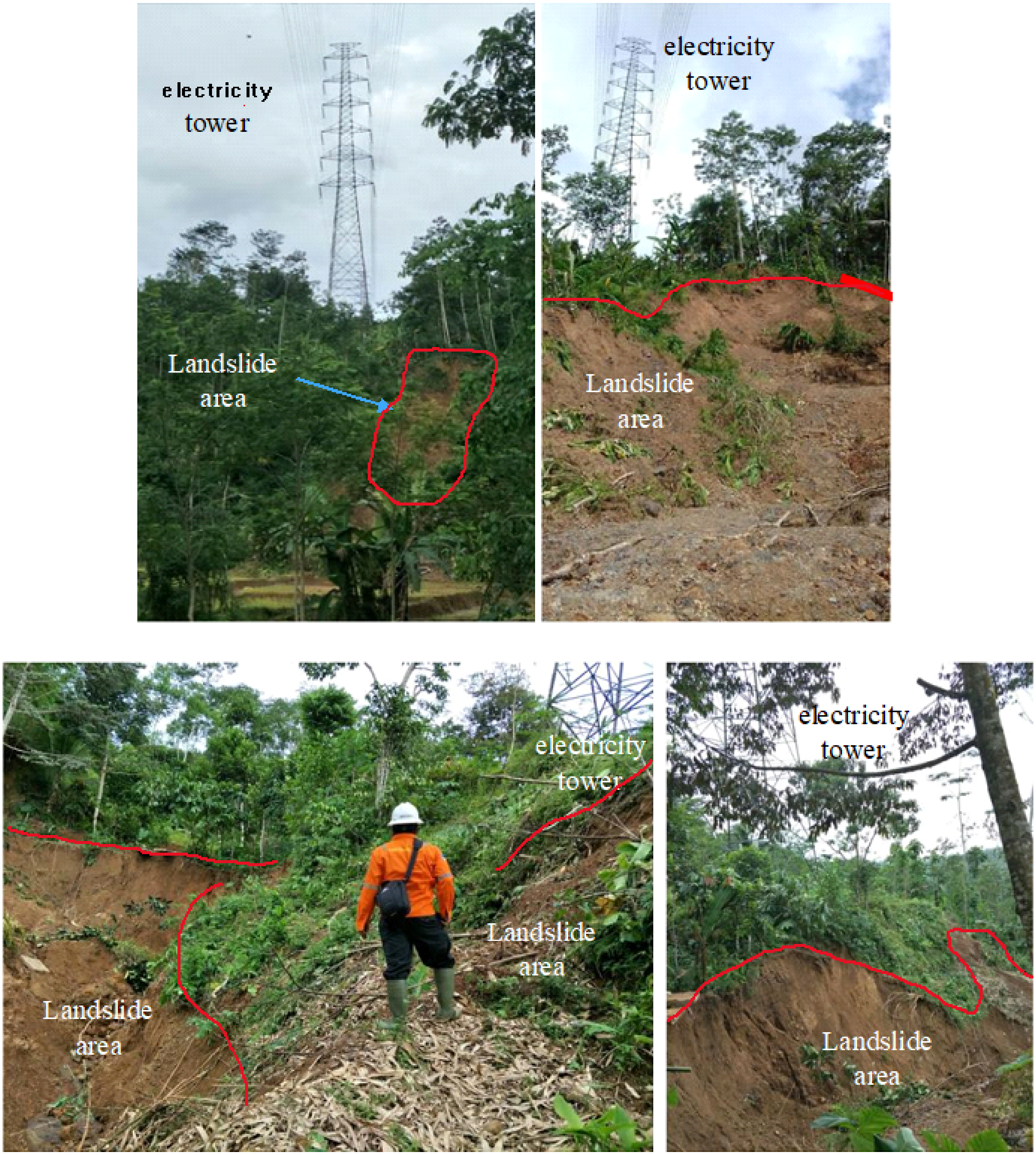

Figure 2

The landslide location in Tulakan Village as the study location

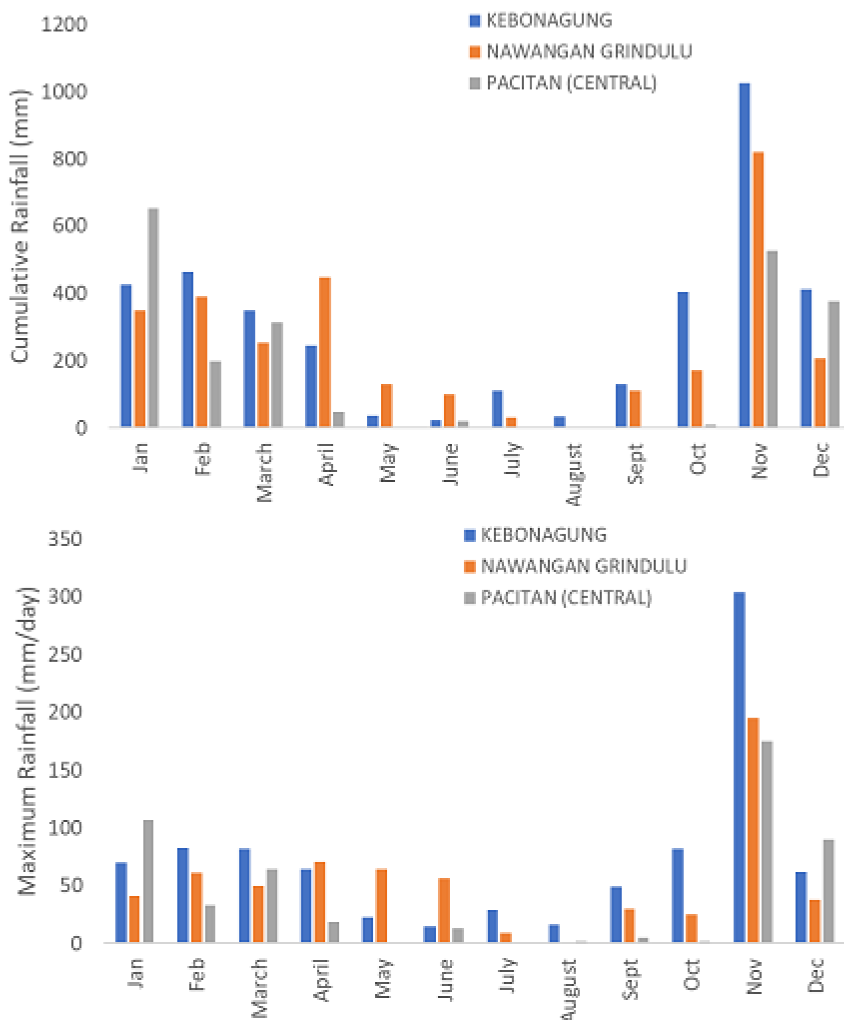

Figure 3

The Rainfall intensity in Pacitan based on 3 rainfall stations in 2017 (upper) Cumulative rainfall, (lower) Maximum rainfall

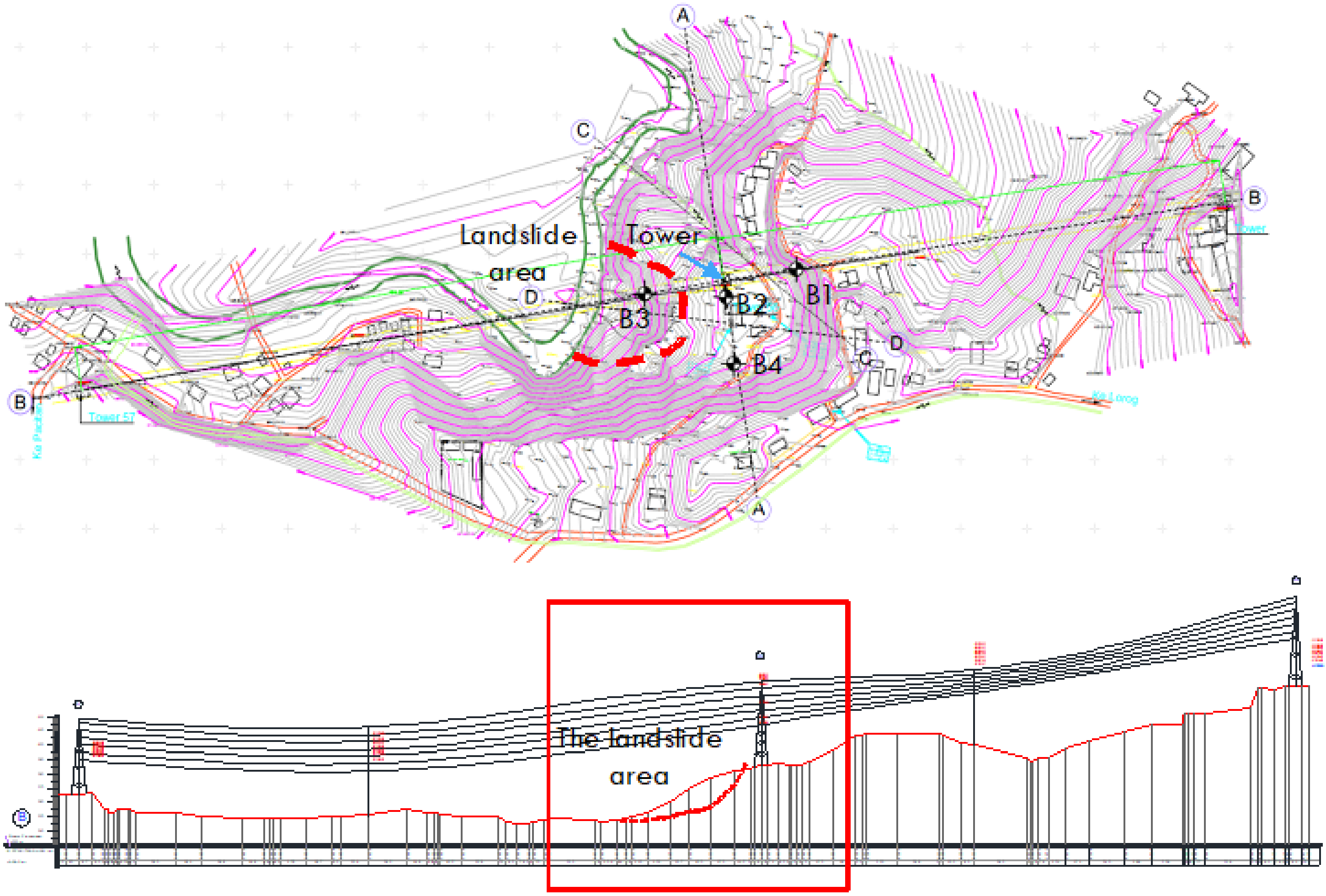

Figure 4

The layout of the test location and the topographic contour of the landslide area

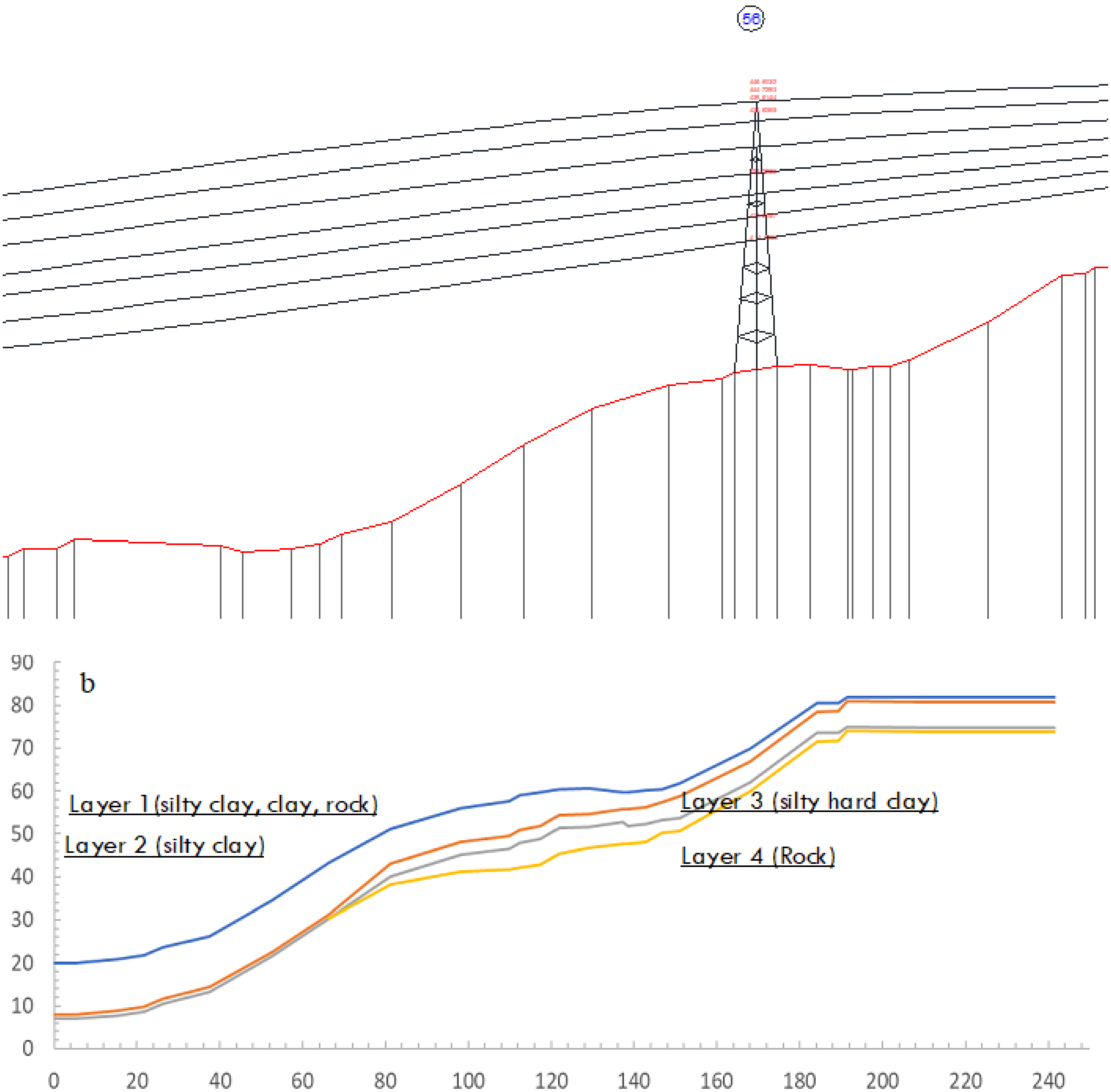

Figure 5

Soil surface condition. (a). N-SPT soil testing and testing location, (b). Soil layer under the landslide area

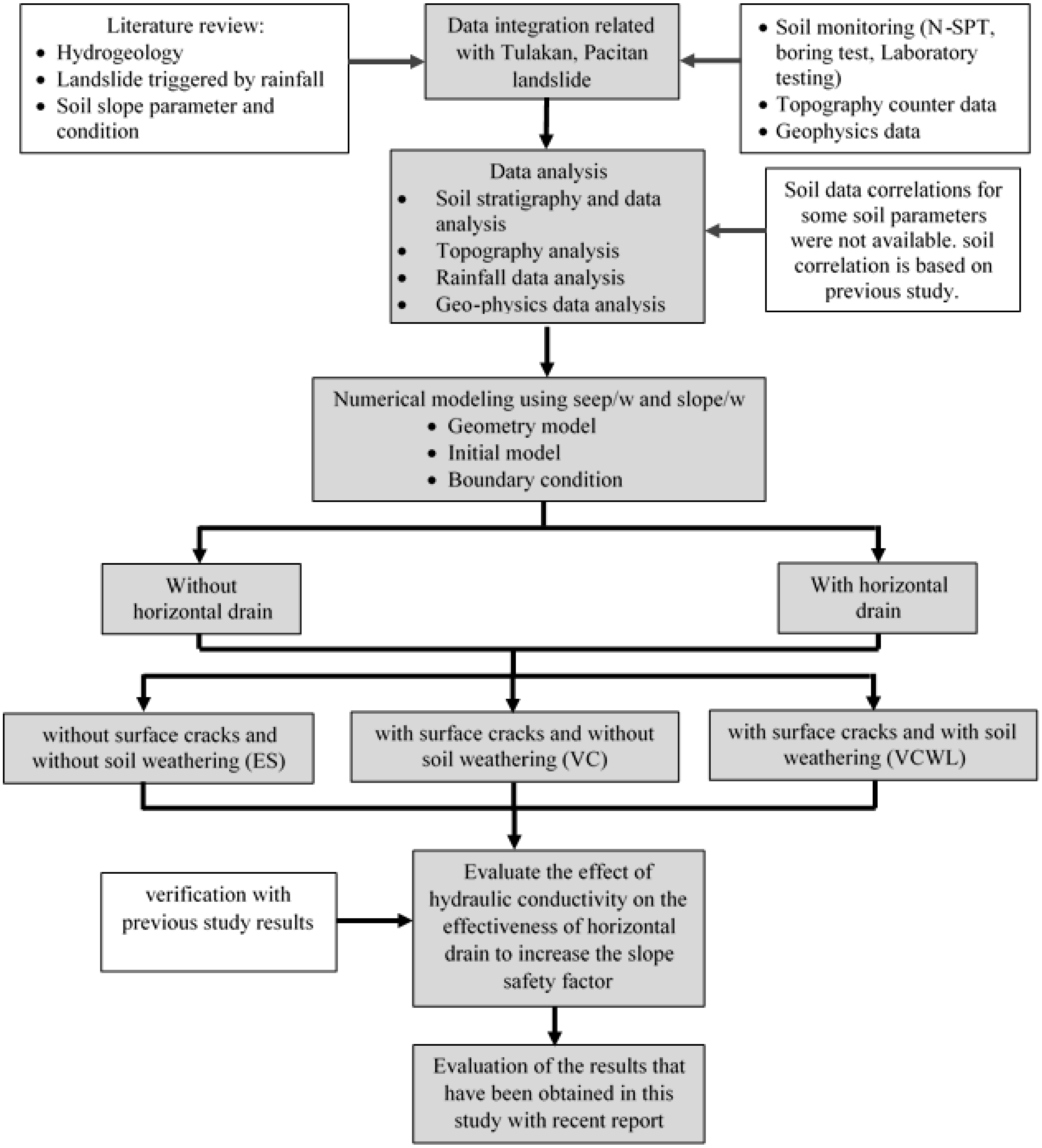

Figure 6

Fow chart of a working procedure for this study

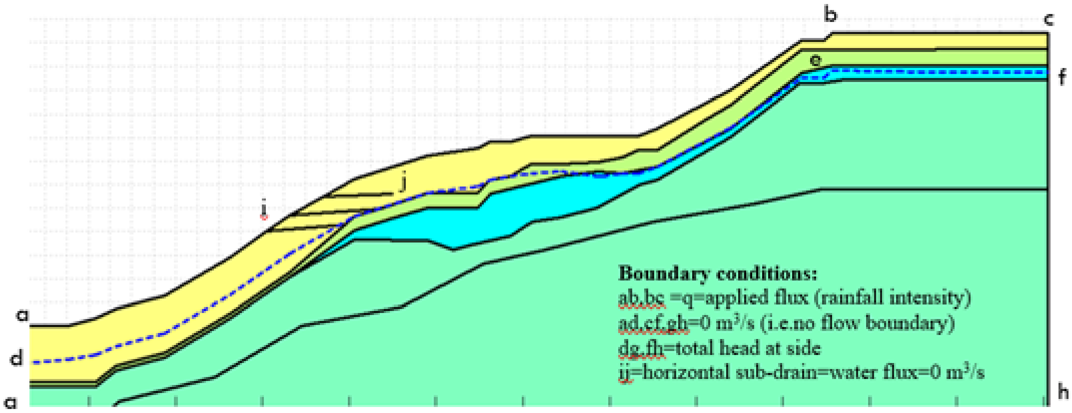

Figure 7

The existing slope geometry and boundary condition

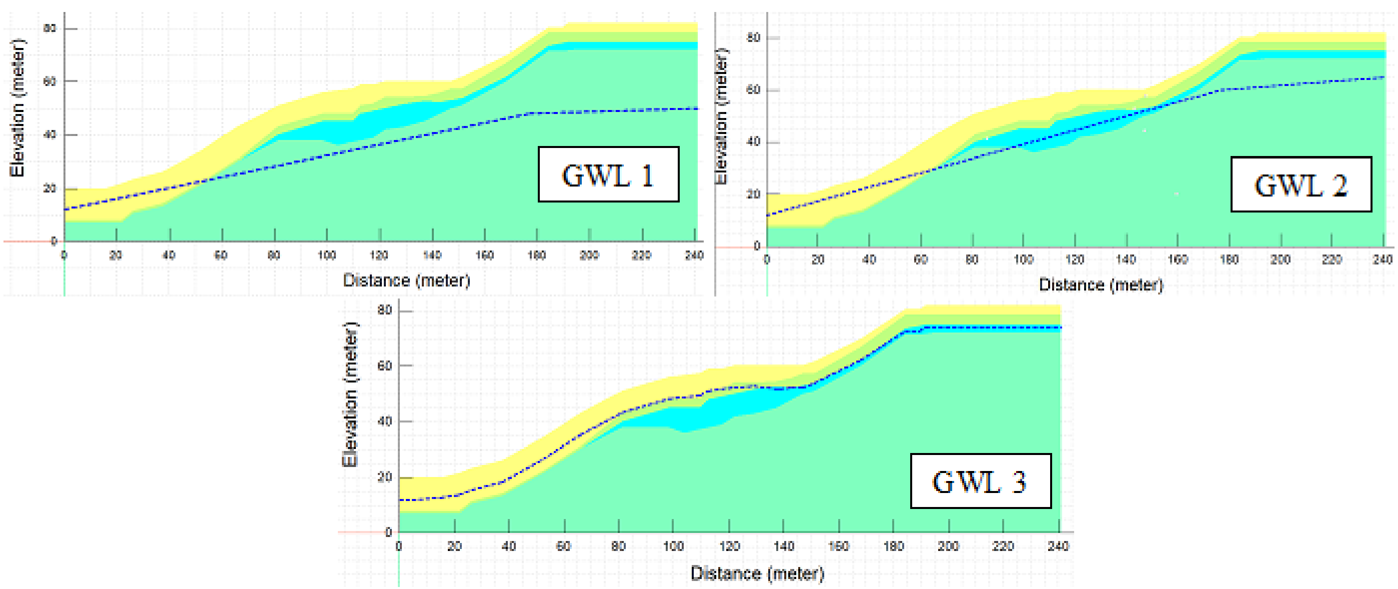

Figure 8

Groundwater level variations

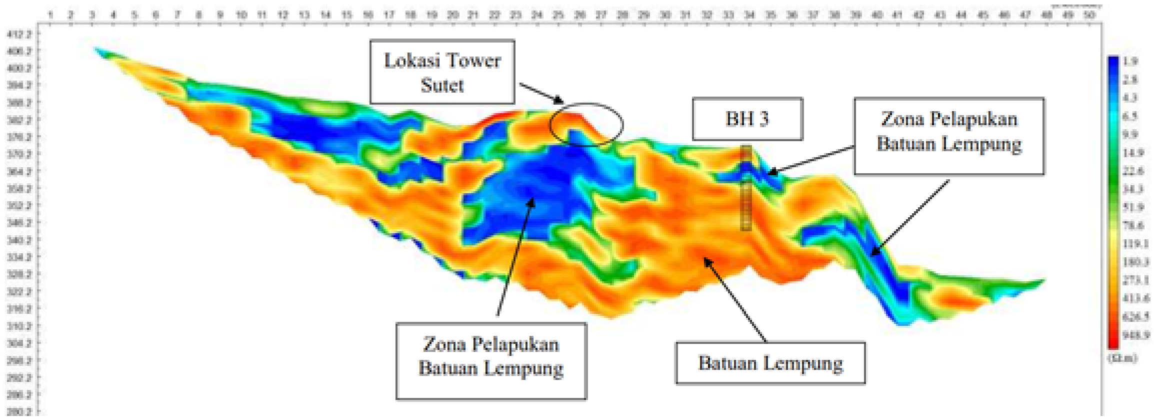

Figure 9

Resistivity test results at the landslide site

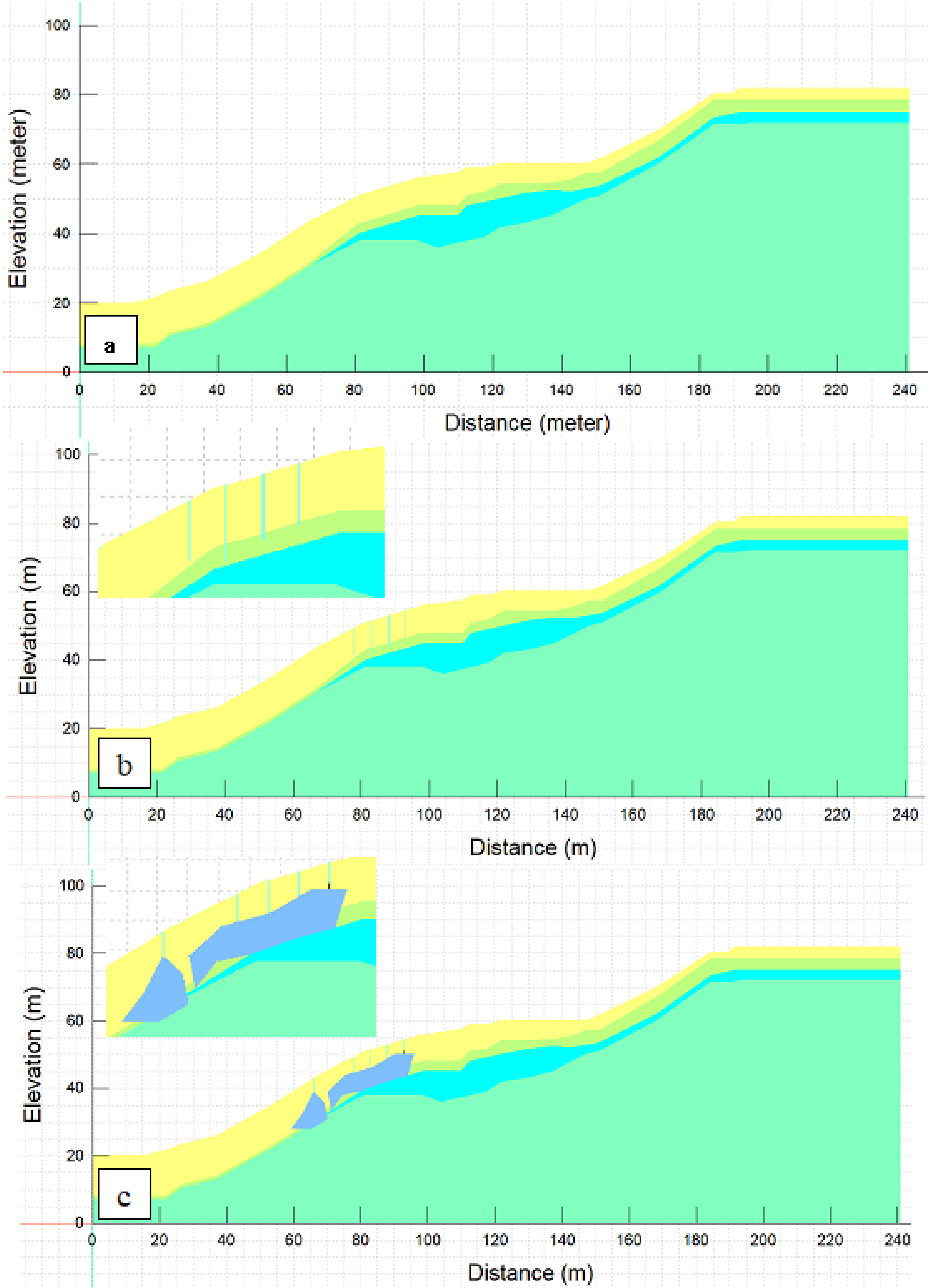

Figure 10

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)

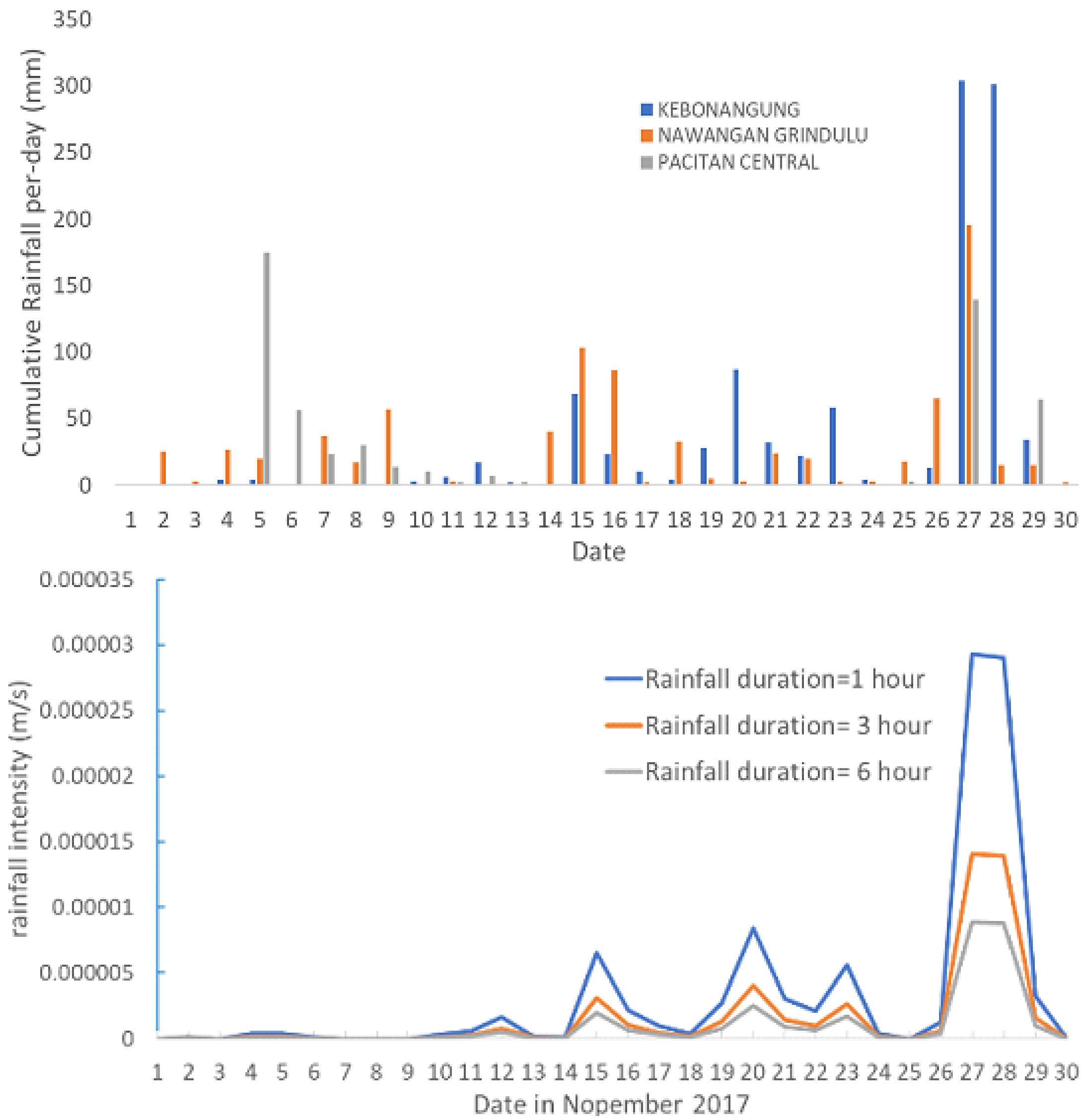

Figure 11

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

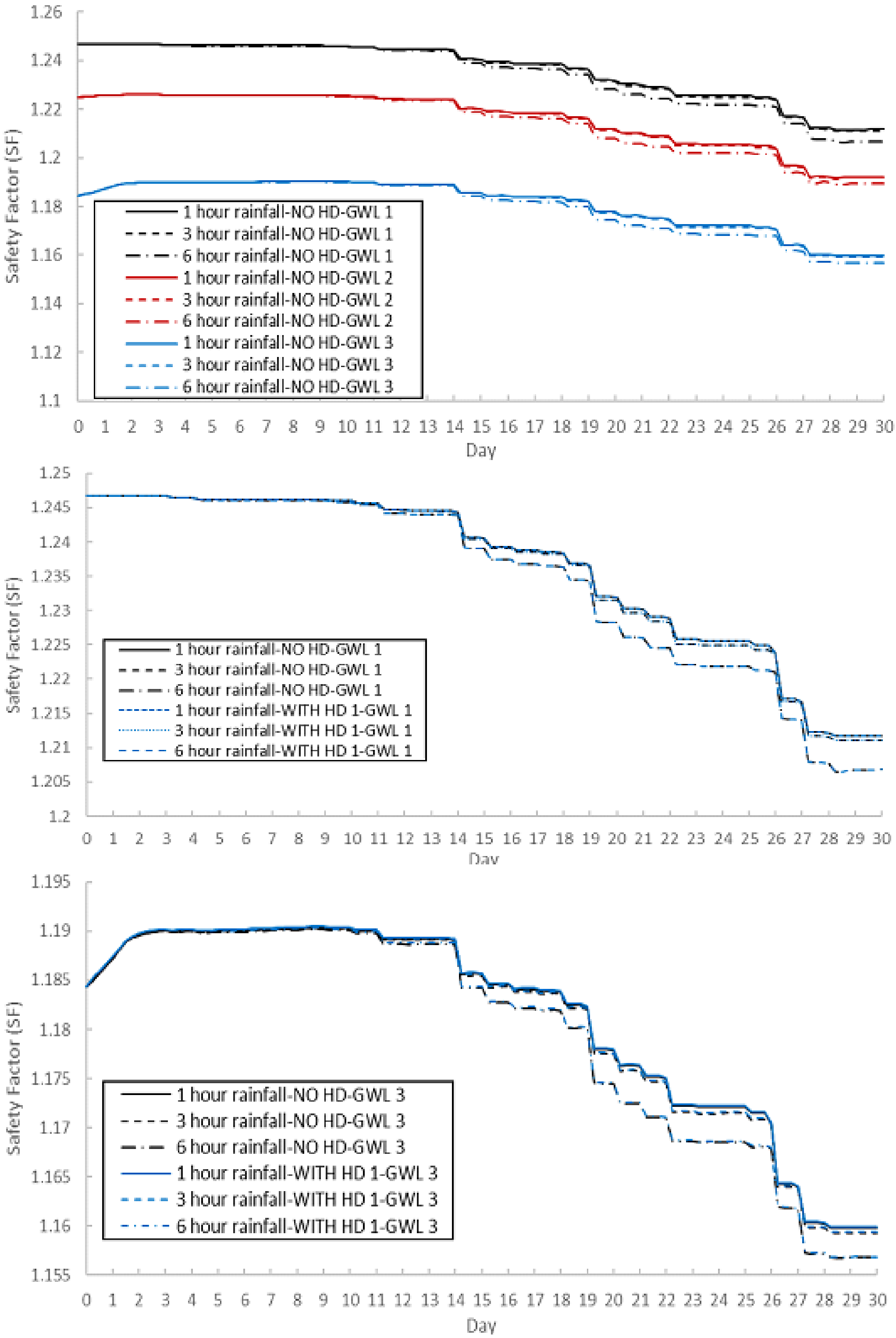

Figure 12

Changes in factor of safety due to 30 days of rain in ES conditions

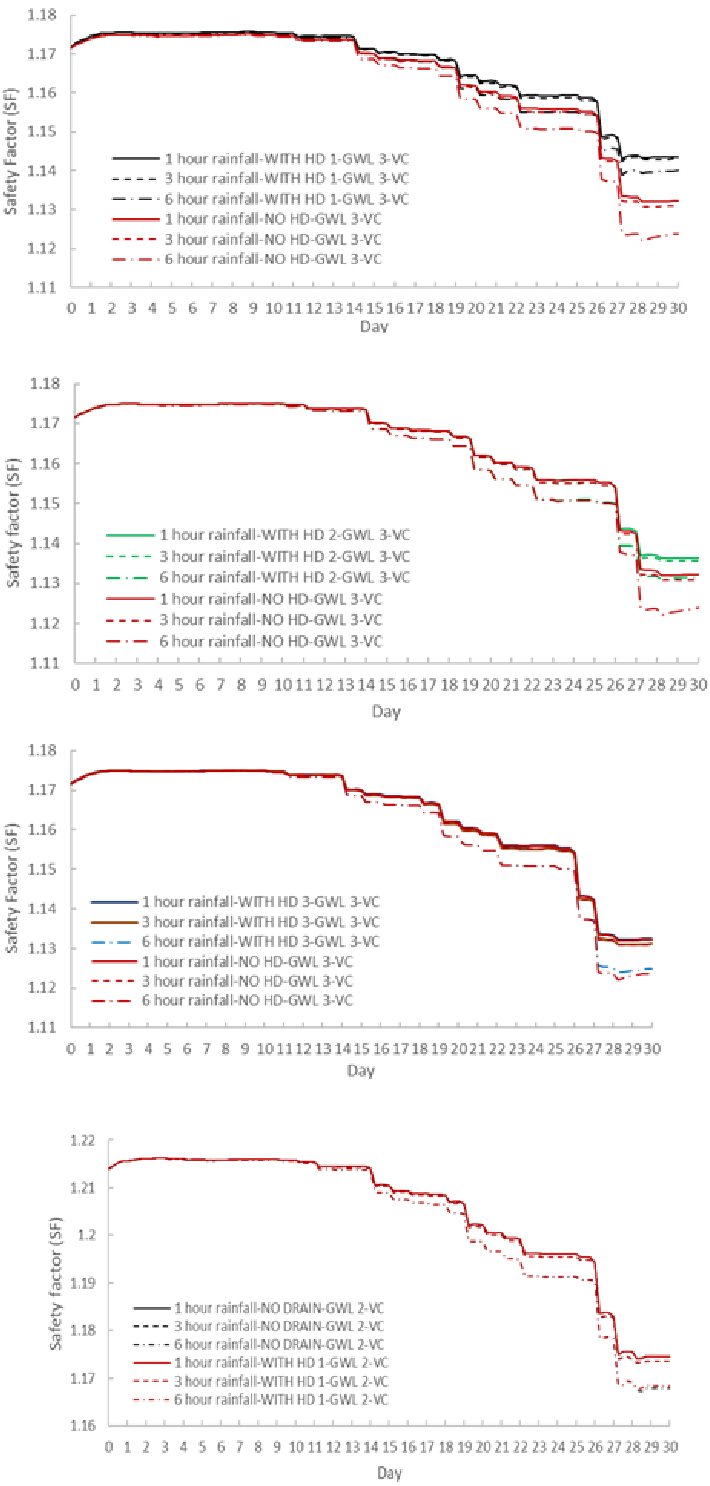

Figure 13

Changes in factor of safety due to 30 days of rain in VC conditions

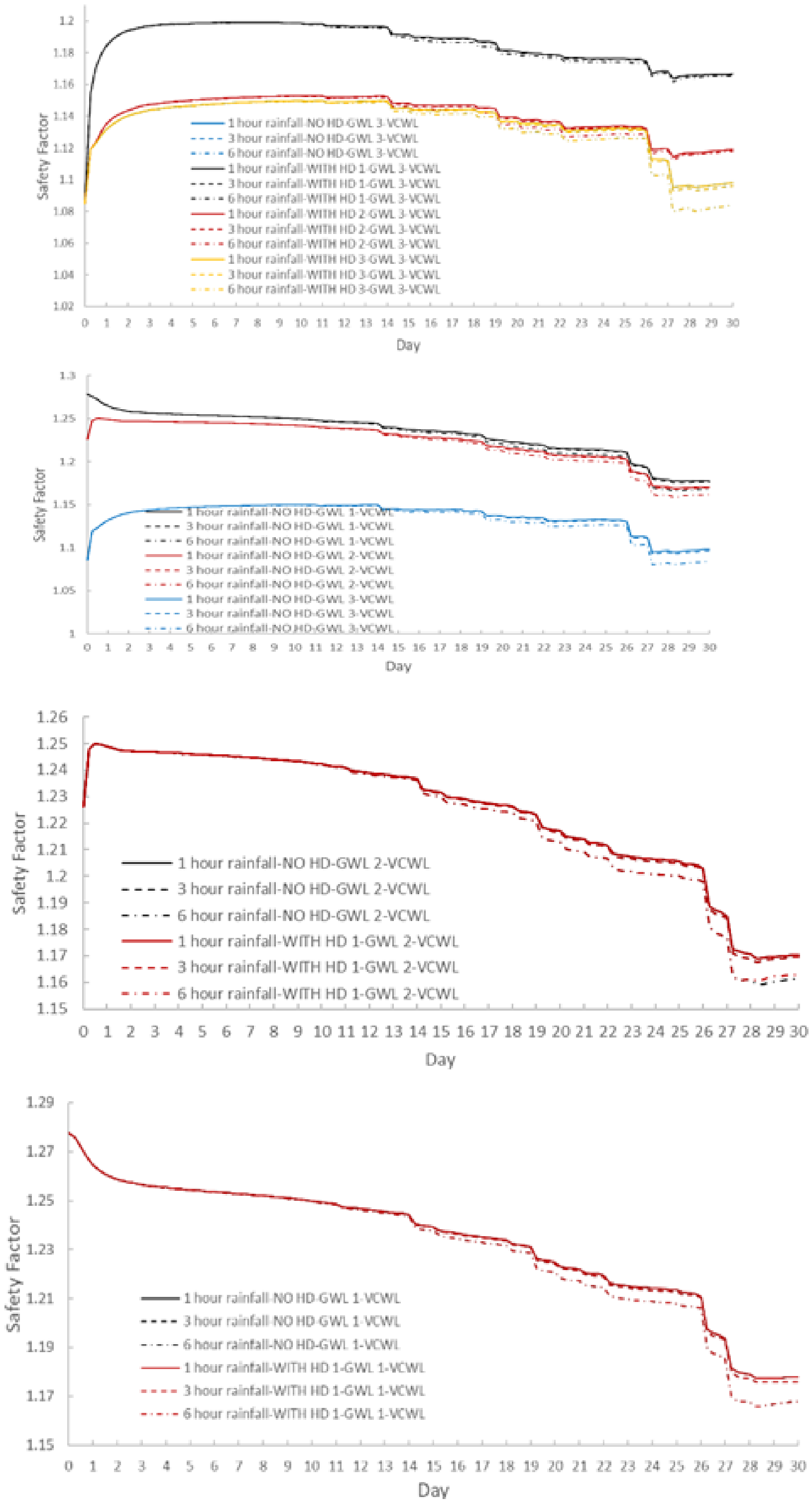

Figure 14

Changes in factor of safety due to 30 days of rain in VCWL conditions

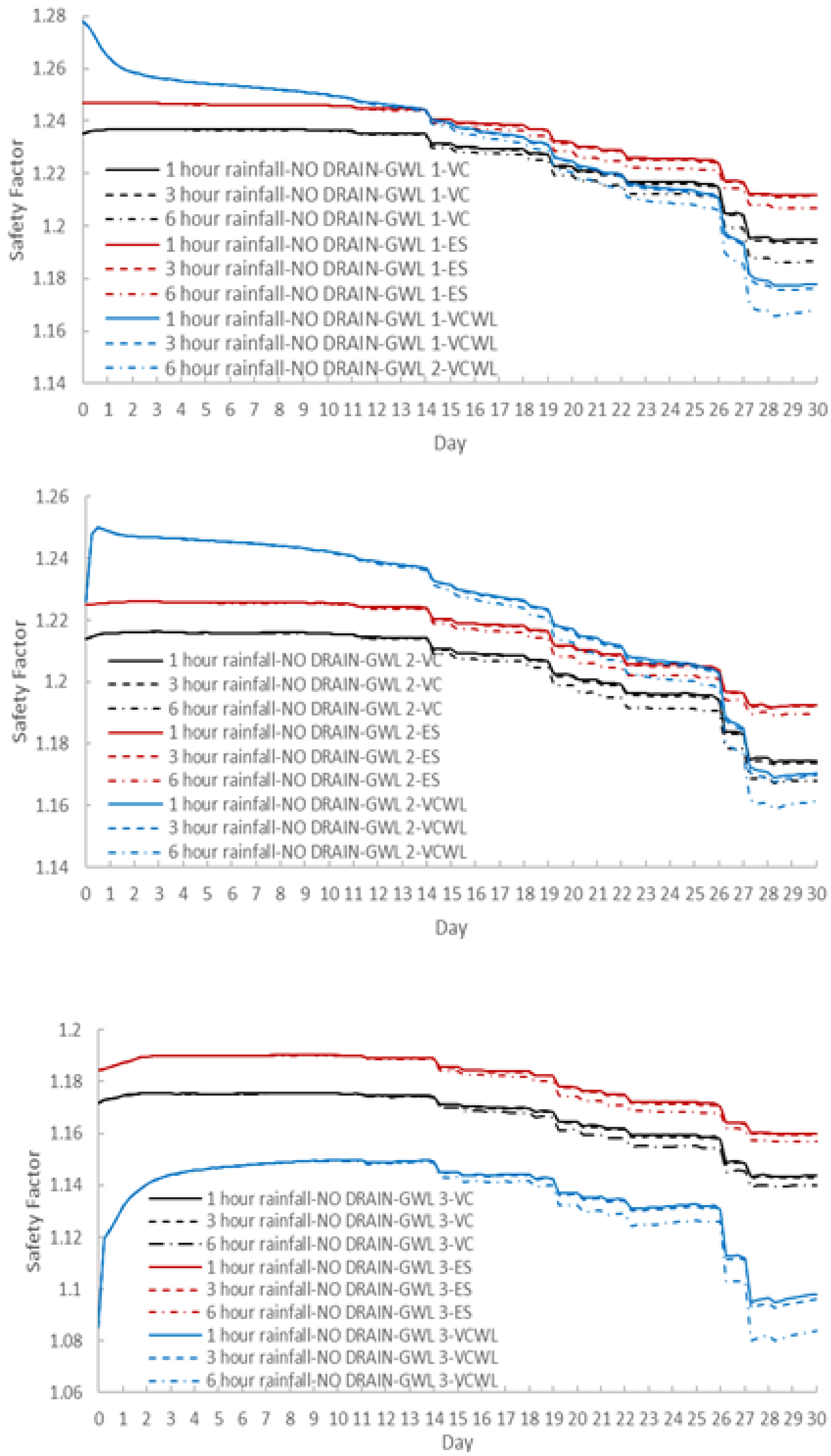

Figure 15

Effect of vertical crack and weak layer without horizontal sub-drain condition was also observed in this study

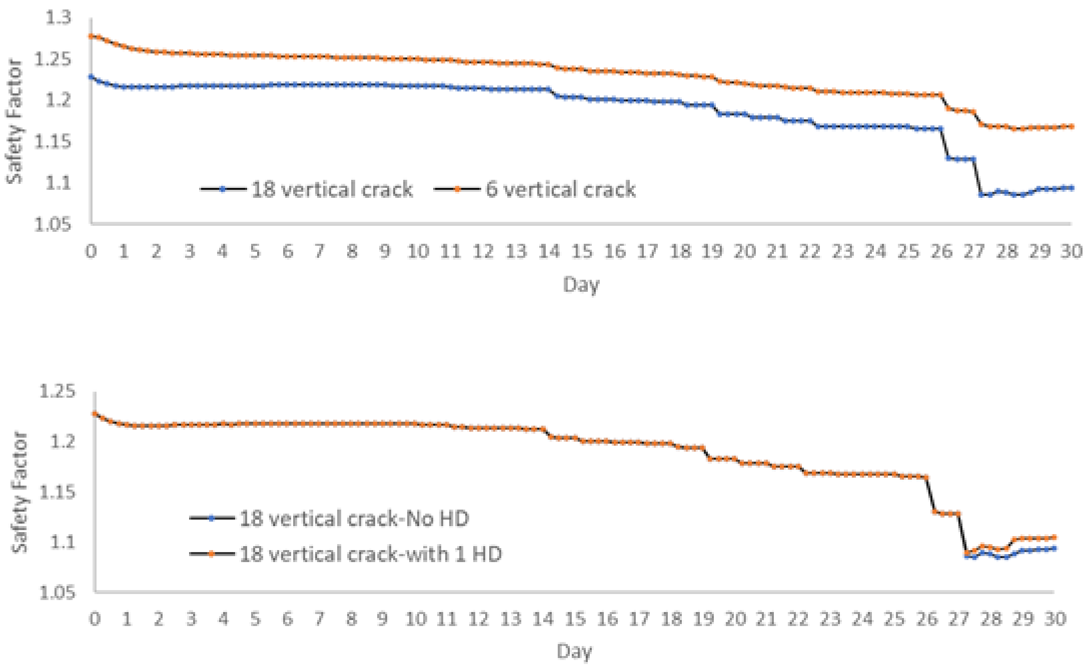

Figure 16

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.

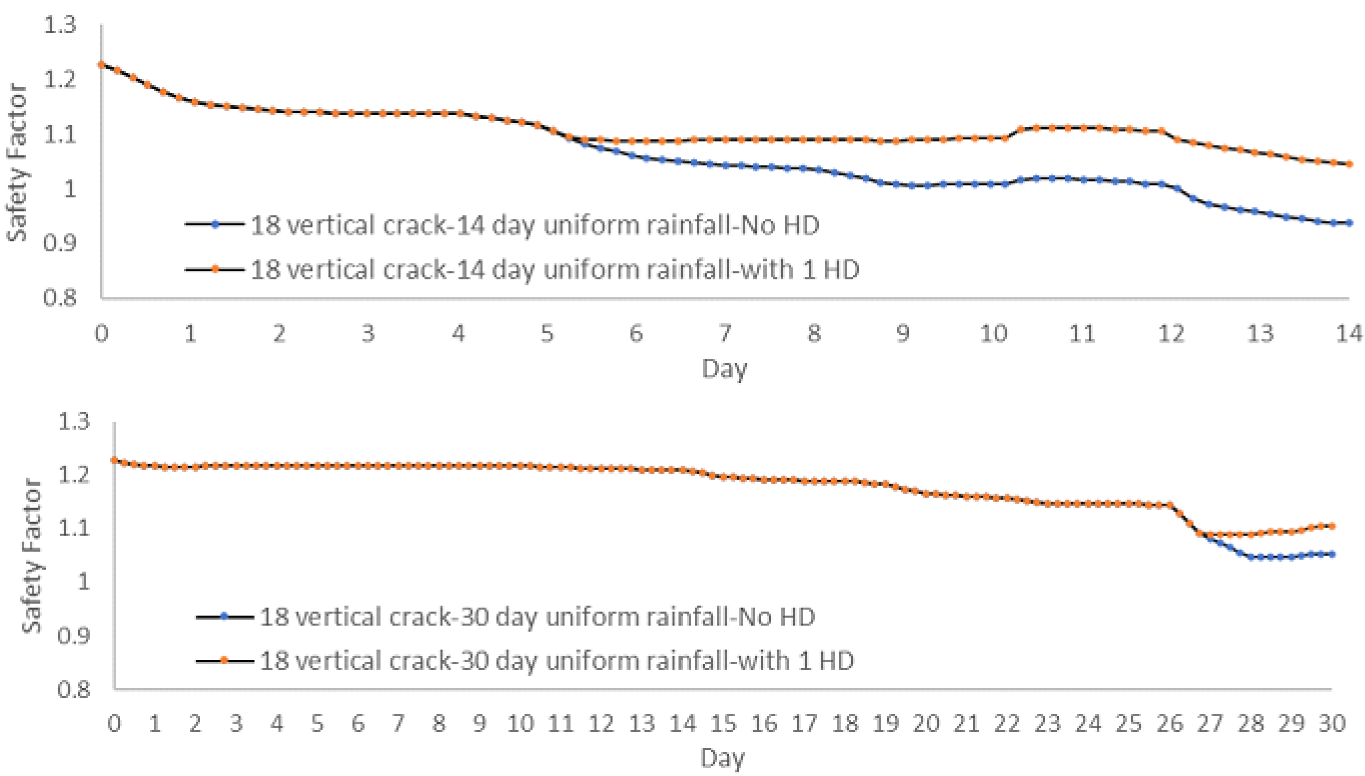

Figure 17

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; a) Effect of horizontal sub-drain due to 30 days of rain and occurs throughout the day with lower intensity