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To cite this article: Shamsan Alsubal *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **513** 012009

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A review on mechanism of rainwater in triggering landslide

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Abstract. Landslide could be evaluated as a very serious issue in tropical countries due to its hazardous impact on lives and properties. One of the factors influencing the development of landslides is the rainfall infiltration which is considered as a major triggering factor. It decreases the matric suction, increases the pore-water pressure and causes the groundwater table to rise. This paper is reviewing the mechanism of rainfall induced slope failure, the effect of rainfall infiltration, soil suction and the rise of groundwater table on slope stability. The results show high rainfall intensity infiltrates initially in a higher rate than soil permeability and develops a perched water table which induces shallow landslide. While, low rainfall intensity for a longer period is more dangerous than heavy rain for a short period. It increases the saturation of the soil and causes the matric suction to dissipate and this triggers landslide. Moreover, the review reveals that the factor of safety increases when the initial soil suction at the ground surface is high. The rise of groundwater increases the pore-water pressure and softens the slope-forming material and leads to landslide.

1. Introduction

Landslide is defined by Gruden [1] as “a mass of rock, debris or earth moving or sliding down on a slope”. Werner [2] also defined landslide as a geological phenomena that includes a wide range of movement such as slope failure, rock falls, or debris flow, which occurs onshore or offshore. Meanwhile, unsaturated soil is described as the soil that is formed by solid particles, porewater, and air. The degree of saturation (S) that is defined as the volume of air to that of water is less than one; $S < 1$ [3, 4]. However, it is important to recognize the fourth phase namely, air-water interface or contractile skin [4]. Unsaturated soils have been of particular concern due to their complex behaviour resulted from their negative pore water pressures [4]. The soil can be described as saturated or unsaturated soil depending on the climate conditions that plays an important role. The evaporation processes is responsible for the removal of water from the soil or through evapotranspiration by the vegetation cover. The soil is dried by grass, plants and trees by enforcing a tension to the pore-water, most of the trees are able to apply about 1 to 2 Mpa of tension and the tension will be acting in all direction [5, 6]. The areas with annual evaporation from the ground surface more than annual precipitation are known as arid zones [4]. The areas are classified as extremely arid, arid and semi arid zones and they usually have high water table. The climatic changes highly affect the water content of the soil. During precipitation, the porewater pressure increases toward positive values. Therefore, changes occur in the volume and shear strength of the soil [4]. The soil zone above the groundwater



table is called Vadose zone, while the zone that is located immediately after the groundwater table and ranged from less than 1 m to approximately 10 m thickness is called capillary fringe and it is almost saturated [5].

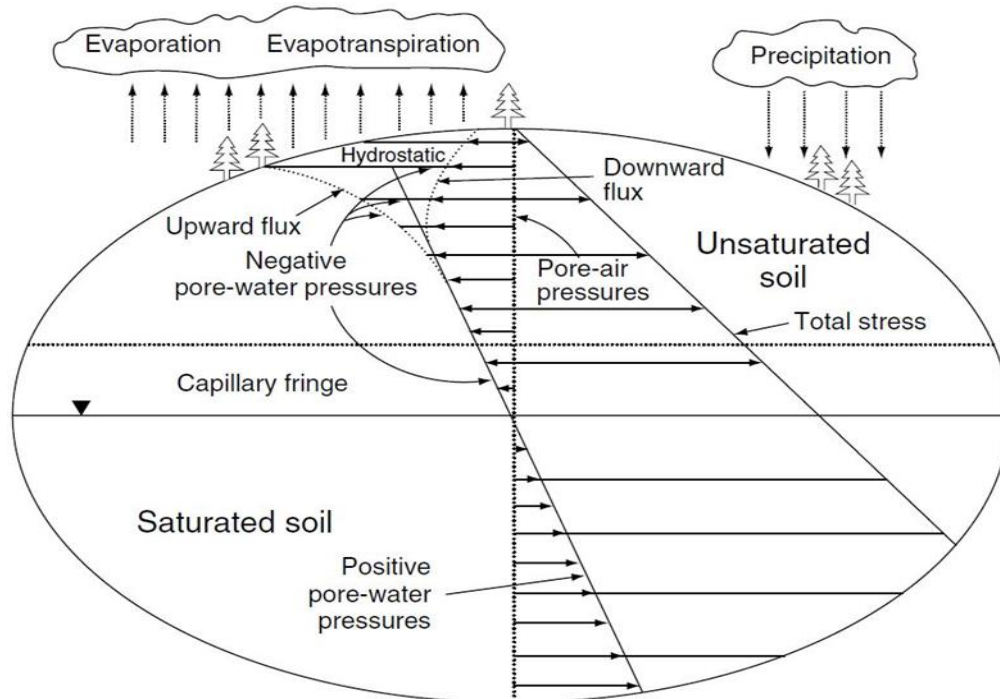


Figure 1. A visualization of saturated/unsaturated soil mechanics based on the nature of the fluid phases [5].

There are many influencing factors prompting the stability of slopes such as the slope forming materials, location of water table, and soil suction. The slope fails due to weakness of the slope forming material that can initially be triggered by the changes in the soil properties [7]. Rainfall is one of the main triggers which makes several variations in the soil properties. It increases the porewater pressure and weaken the strength of the soil. Besides, the saturation of the soil at the first 0.3 to 0.4 m results in the dissipation of soil suction and induces shallow landslide [8]. Rainfall with low intensity for longer period increases the groundwater table and results in a deep-seated landslide, usually after several rainfall events [9].

To the authors best of knowledge, there is no detailed review on the landslide triggering factors in relation to rainfall infiltration, soil suction, and rise of ground water table. Hence, this paper is reviewing those factors and providing a detailed mechanism that explains the landslide failure.

2. Rainfall infiltration

Rock and soil slopes are considered as natural hazardous phenomenon happening frequently all over the globe and the event of rainfall may considered as one of the generating factors [10]. Rainfall infiltration within slope formed by unsaturated soil slope is affected significantly by the permeability of soil [11, 12]. More amounts of rainfall water is infiltrating into the soils forming the slope that are characterized with high permeability causes a reduction in the matric suction of the soil due to saturation [13].

The infiltration of the rainwater into the soil with high permeability is considered higher than the soil permeability at the beginning by as much as 3.5 times and then start to degrade toward the steady state conditions [14]. On the other hand, when the intensity of the rainfall is low, the infiltration is low at the crest of the slope and then rise gradually towards the steady state conditions [14]. For a long period of time, low intensity rain is perhaps more unsafe than the heavy rain happening shortly in

causing slope failure due to the reduction of soil suction in the first 20 to 50 cm of the soil [15]. Heavy rainfall for a long period reduces the seepage rate within the soil slope [16]. According to a study performed to show the extend of heavy rain in triggering landslide in Shenzhen, China. The landslide occurred after 13h of the rainfall event because of prolonged rainfall. The high permeability outcrops allowed more rainwater to infiltrate to the granite stone. The rainfall water continued seeping through the fill layer even after the rainfall had stopped, and the ground water table rose eventually inducing the landslide [17].

Furthermore, an experimental study was conducted on the rain infiltration in silty sand soil compacted with different water content and connected to a constant water head of 20 mm. The results showed that the soil compacted with lower water content (8 %) has the highest infiltration rate of 3.25 mm/min while it was 2.15 mm/min and 1.21 mm/min with water content of 15.5% and 24.3%, respectively as shown in Fig. 2 [18]. The infiltration decreased with time towards the steady state conditions (k_s value).

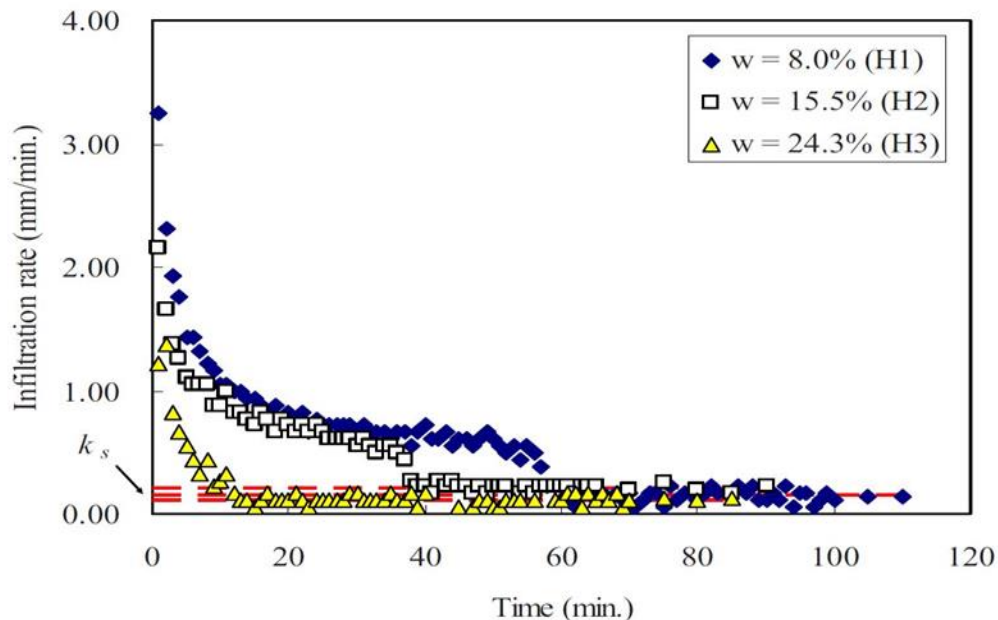


Figure 2. Curves of infiltration for samples exposed to a constant water pressure and compacted at different moisture [18].

The experiment was conducted with soil compacted at similar water content ($w = 11.7\%$) and exposed to different rain intensity ranging between maximum infiltration (I_{max}) and soil permeability (k_s). The result indicated that before bonding, the infiltration was as high as the rain intensity and it declined towards the steady state value (k_s value) but the time taken to ponding was faster with high rain intensity than it was with low rain intensity due to the fast saturation of the soil specimen [18]. Figure 3 shows the infiltration rate with time.

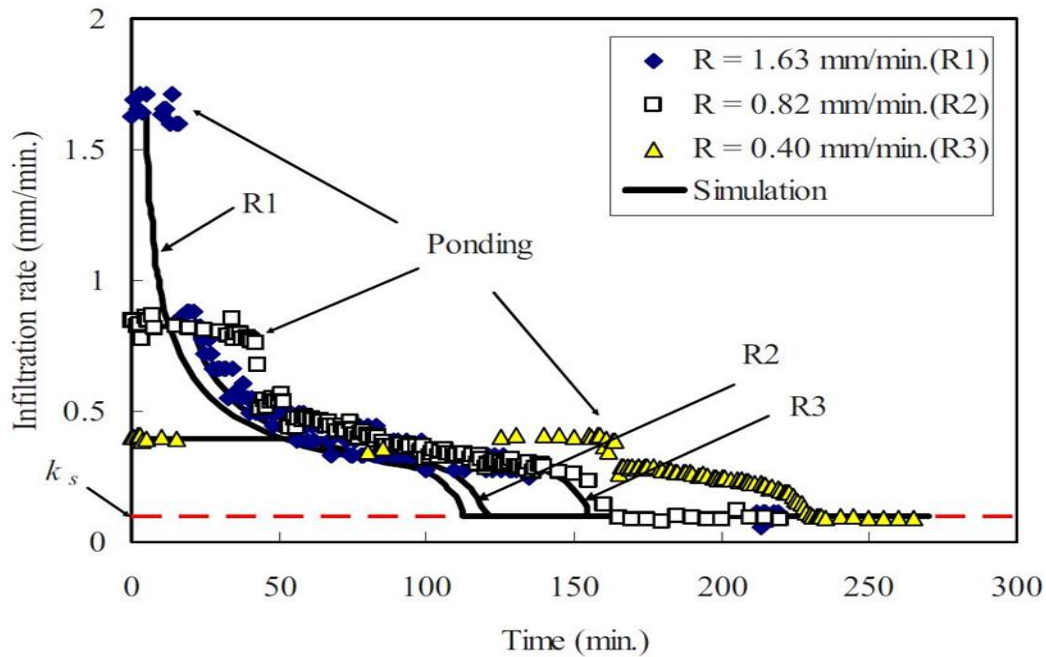


Figure 3. Curves represents infiltration for samples with similar compaction moisture content ($w=11.7\%$) [18].

3. Soil suction

Suction can be described as the state of free energy of soil-water which can usually be measured using its partial vapor pressure. Kelvin's equation described the total suction as follow [5]:

$$\psi = -\frac{RT}{u_{w0}\omega_v} \ln\left(\frac{u_v}{u_{v0}}\right) \quad (1)$$

Where ψ is the total suction in kPa; T is the temperature (K); R is the universal gas constant (J/mol.K); u_{w0} is the specific volume of water (m^3/kg); u_{v0} is the saturation pressure of water vapor over a flat surface of pure water at the same temperature (kPa); ω_v is the molecular mass of water vapor (g/mol); u_v is the partial pressure of pore water vapor (kPa) [5]. In order to give a fixed relationship between relative vapor pressure and total suction, Equation 2 can also be written at 20°C as follows:

$$\psi = -135,022 \ln\left(\frac{u_v}{u_{v0}}\right) \quad (2)$$

The total suction can be evaluated by the following equation:

$$\psi = (u_a - u_w) + \pi \quad (3)$$

Where $(u_a - u_w)$ is the matric suction while (π) is the osmotic suction [5].

The field's matric suction can be measured, the typical air entry value of sandy soils is between 1 and 10 kPa [19]. The residual suction can be estimated to be between 10 and 100 kPa for sand soil [19]. Van Genuchten method can be used to compute the soil suction at field as shown in Equation 4, if the fitting parameters a , m , and n for the Van Genuchten equation of SWCC are known [20].

$$\psi = \frac{1}{a} \left(\left(\frac{w_s}{w} \right)^{1/m} - 1 \right)^{1/n} \quad (4)$$

This Equation is only applicable to evaluate the suction at a range between the residual suction and the air-entry value [19].

The safety condition of the slope can always be measured using the degree of saturation and matric suction that are considered as a significant indicator for safety. High stability can be seen for slopes with high matric suction, while low stability is found in slopes with low matric suction. A single rainfall event at the top part of the soil cover can extremely affect the matric suction and the

volumetric water content. However, the deeper parts of the soil will be affected by seasonal trend and unaffected by a single rainfall event [21]. An increase in water content may result in rainwater infiltration that reduces the matric suction in the soil [22-25]. The soil suction of soil dissipates due to its saturation during the rainfall events and the failure may result because of the initiation of the positive porewater pressure [8]. At the ground surface, the matric suction is first affected by the direct rainfall [26, 27]. A soil that has a cohesion of 2 kPa may equalize a suction of 7 kPa. Therefore, the factor of safety is 30% higher when the initial soil suction at the ground surface is 50 kPa [28]. Hossain [2010] performed an in-situ soil suction monitoring on a residual granite soil slope. It was found that the average soil suction at the ground surface was 30 kPa. The suction of 30 kPa was equivalent to a cohesion of 9.6 kPa. This is responsible of the increment in the factor of safety from 2.14 to 2.48 [27]. The factor of safety usually increases with the increase of matric suction [29, 30]. Figure 4 shows the increase of factor of safety by increasing the matric suction of the soil slope.

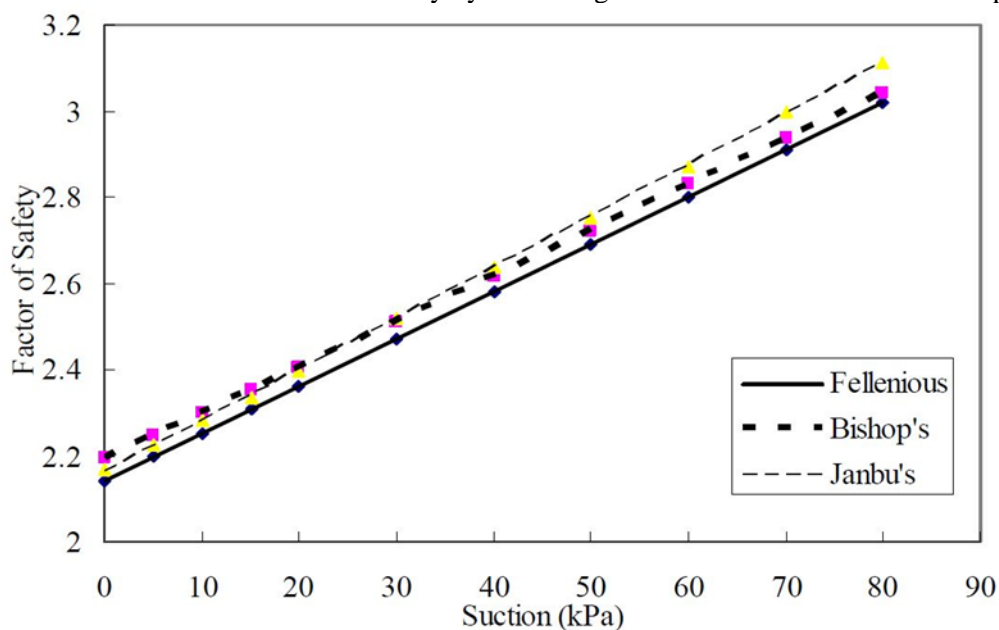


Figure 4. The FOS of a granite soil slope affected by matric suction [27].

Lim [26] conducted an experimental study on an in-situ suction measurement under three different surface conditions; canvas covered surface, grass surface and bare surface. It was found that there was some similarities in the characteristics of the in-situ matric suction variations; the maximum changes of the matric suction occurs near to the ground surface. The variation of the matric suction under the canvas covered section was less significant than that under the grass-covered and the bare sections. The matric suction in the bare slope decreased significantly immediately after the rain storm, while that for grass covered slope decreased immediately after the rainstorms as shown in Figure 5 [26].

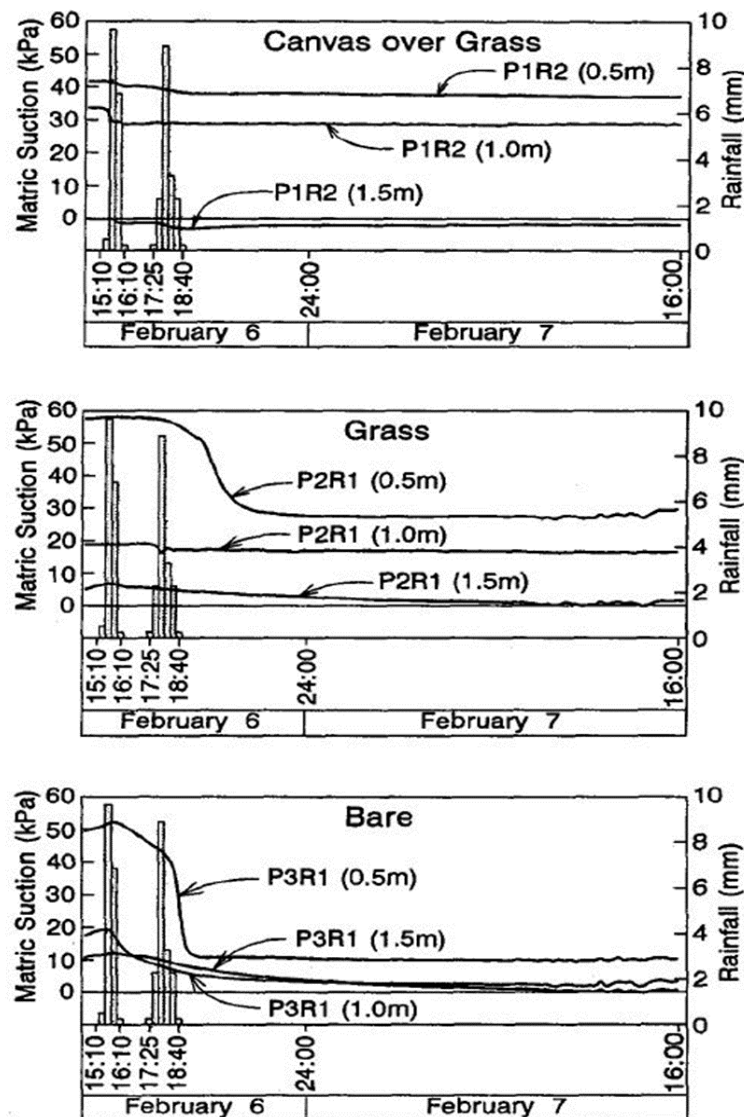


Figure 5. The reduction of matric suction during rainfall at different depth of the soil [26].

4. The rise of groundwater table

The sudden increases in the pore-water pressure of soils due to rainfall softens the slope's forming material and failure of slopes usually occurs [7]. The ground water table rises and results in shallow landslide due to perched water table [11, 31]. Perched water table and sudden increases in the ground water table are a result of the rainstorm [23, 32, 33]. Due to rainfall infiltration, landslides are commonly associated with the advancement of wetting front in the unsaturated soils [24], and the critical factor of safety seemed to be at the same depth as the wetting front [22]. Failure of slopes that have soil with a friction angle less than the slope angel are induced by wetting front [11].

Seepage forces in soils with a low compaction density have a significant effect on seepage velocity [34]. The seepage forces that are proportional to the rainfall intensity and void ratio may causes the formation of landslide. For instance, a reservoir landslide located in Sichuan provinces, China is associated with the reservoir water level drop. The landslide occurred due to the seepage forces caused by the differences between the groundwater level in the slope and the water level of the reservoir [9]. Due to the limitation of soil slope permeability, the drop of the reservoir water level is faster than the groundwater level at the slope. Therefore, the seepage pressure in the slope mass increases and the

deformation starts. It was stated that the rise of ground water table within the slope may lead to instability event. Hence, the degradation of the slope may be in a severe mode of failure [35, 36].

4.1. Vibo Valentia Southern Italy landslide

A large landslide occurred at Maierato that caused around 2300 people to be evacuated in addition to high economical losses. The landslide area was 0.3 km^2 with 1.2 km runout and about 10 Mm^3 volume of soil as shown in Fig. 6 [37]. The most possible triggering factor was the increase of pore water pressure due to the rise of groundwater table from the heavy rainfall and the prolonged rainfall one month prior to the landslide occurrence [37, 38]. The last two winters before the landslide were much rainy than the usual within the period from 1919 to 2010 [39]. Figure 7 shows the daily rainfall for the three months prior to the occurrence of the landslide. The cumulative rainfall of the twenty days preceded the landslide was more than 250 mm and around 35 mm the day before the landslide [40].



Figure 6. Post failure photograph of Maierato landslide [39].

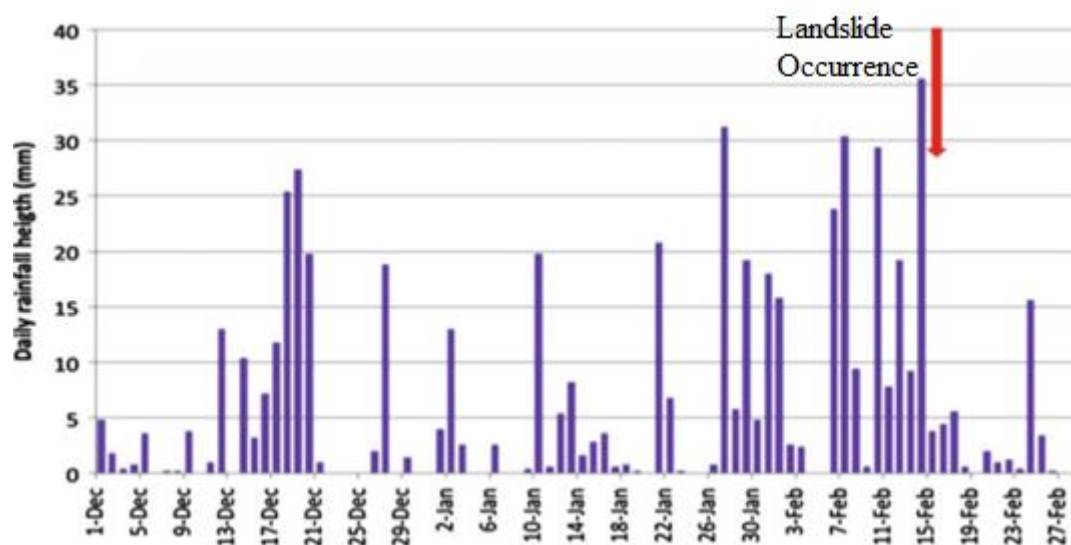


Figure 7. The daily rainfall heights three months prior to the landslide. The red arrow points to the day of landslide [39].

The sliding mass was initiated within Miocene sandstone at a depth of 60 -70 m. The landslide was preceded by a sequence of failures at the toe [39]. The presence of weak and permeable rocks allowed the rain to feed the deep groundwater tables [37, 38]. The rise of groundwater created a high groundwater pressure head, and decreased the effective stresses at the toe, thus inducing failure [40].

A slope stability analysis was performed using finite element method for the calculation of FOS along cross-section A-A' (Figure 8). The modeling was carried out using different groundwater levels to recognize the conditions that induced landslide. The result indicated that the factor of safety during the dry conditions was more than three. By using the observed groundwater, the factor of safety decreased by 20%. A further decline of around 20 % is approached considering a rise in groundwater levels of 10 - 15 m. In these ground conditions, the limit equilibrium of the slope stability ($F_s = 1$) can be achieved when the friction angle of the sandstone is decreased by 50 to 60 % [38].

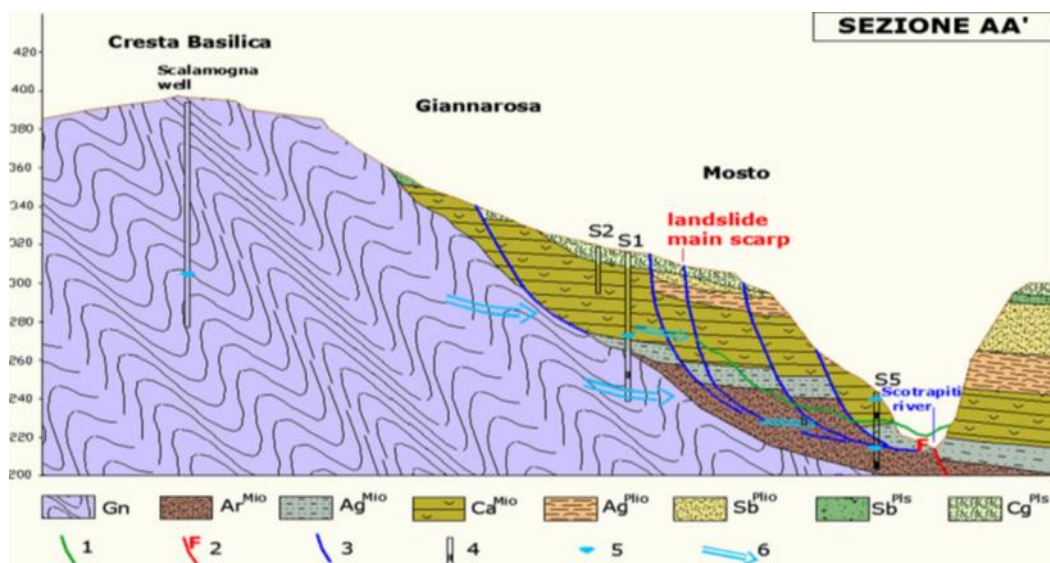


Figure 8. Geological cross-section of the study area before the landslide [38].

4.2. Putrajaya Landslide

A landslide occurred in Precinct 9, Putrajaya, Malaysia caused an evacuation of about 1200 people and buried 27 cars [41]. The failure happened on the western side of a fifty meter hill with a built water tank located at the top. The distance of the tank to the edge of the slope where it failed is 25 m. The area is underlain by graphitic quartz mica schist from Kajang Formation [42]. Figure 9 shows the location of the slope failure.



Figure 9. The location of the landslide failure at Putrajaya [42].

A heavy rainfall was recorded in Putrajaya since for two days before the landslide which occurred after the one day of the rainfall [43] and this agrees with the study reported by [44, 45]. Rain gauge located at Precinct 2 recorded a heavy rainfall of 140 mm two days before the landslide as shown in figure 10. The rainfall intensity on the day of the slide was 10 mm. Soil investigation was conducted just after the failure of the slope with a total number of seventeen boreholes. Ismail [2016] also conducted back analysis based on the information obtained from site investigation to identify the causes of landslide. The result indicated that fluctuations in the groundwater due to rainwater infiltration was the main triggering factor of the landslide. The rise of groundwater increased the pore-water pressure at the toe of the slope and reduced the shear strength of the soil. As a result, failure was initiated. It was found that existing groundwater table was high. Based on the measurements of groundwater from boreholes, the groundwater level was at the ground surface at the toe of the slope and 1 m deep at the mid-slope [42].

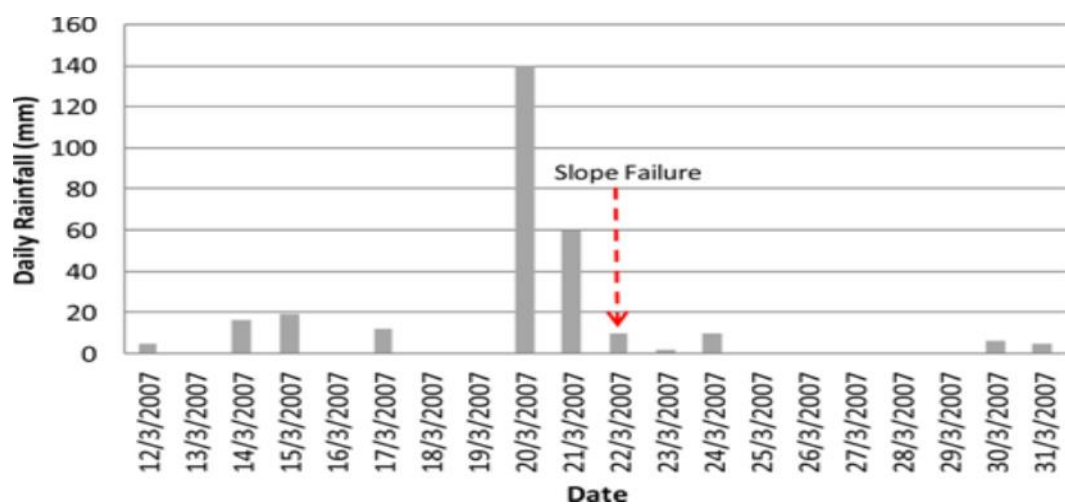


Figure 10. The rain intensity data [42].

5. Conclusion

It can be summarized that the rainfall intensity is one of the factors contributing in triggering hazardous landslides. It seep through the soil resulting the dissipation of the matric suction, increasing the pore-water pressure and reducing the overall strength of the soil. Low rainfall intensity for long time are more hazardous than intensive rainfall for short time. Rainfall infiltrates in a higher rate than

soil permeability at the beginning of the rainfall event and drops over time toward the steady state conditions. Heavy rainfall develops a perched water table and the groundwater table rises extensively. The rise of groundwater table is critical once it touches the slip surface of the slope, it causes a deep-seated landslide even though the other part of the slope still dry. Slope failure due to the rise of groundwater table takes one day or more to trigger landslide which is the time taken for the water to infiltrate from the ground surface and the developed perched water tables.

Acknowledgments

The authors are thankful to the Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS and would like to extend their gratitude to UTP for the generous supports and the provided facilities.

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