International Journal of Advanced and Applied Sciences, 5(10) 2018, Pages: 76-86

Contents lists available at Science-Gate

International Journal of Advanced and Applied Sciences

Journal homepage: http://www.science-gate.com/IJAAS.html

Numerical simulation of groundwater rising due to rainfall at far field in triggering landslide

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ARTICLE INFO

Article history:
Received 5 March 2018
Received in revised form
2 July 2018
Accepted 22 August 2018

Keywords:
Landslide
Slope stability
Rainfall intensity
Groundwater table
Soil properties

ABSTRACT

Landslide is a major issue in tropical countries. The intensive rainfall is the main triggering factor for a landslide that causes a loss in lives and properties. Landslide's triggering factors are several such as rain infiltration, earthquake, and human activities and so on. Those factors are very common. In this paper, the effect of rising of groundwater table in triggering landslide with respect to soil type, soil permeability and rain intensity in a regional scale were studied by running coupled seepage-slope analysis using SOILWORKS software. The results indicate that soil slopes with high permeability coefficient are prone to fail during rainstorm due to the high infiltration of rainwater and the quick rise of the groundwater table, which increases the pore-water pressure. The highest rain infiltration occurs during the first rainfall event and declines at the second and third rainfall due to the saturation of soil at the top layer and the development of a perched water table. It was noticed that the negative pore water pressure increased above the groundwater table and reached its max at the crest of the slope due to the absence of wetting front and the movement of voids with the advancement of the groundwater table. Both high and low rainfall intensities have the same effect on the deep groundwater table. Sandy-silt soil slope was highly affected by rainfall infiltration in comparison with Sandy-clay and Silty-clay slope due to the difference in soil suction where it rose up -60 kpa with Sandy-silt slope after 8 hours of the rainfall which allows more rainwater to infiltrate comparing to other soil slopes which rose up to -21 and -17 kpa for Sandy-clay and Silty-clay slopes respectively. The groundwater table rises above the toe level of the slope causing the factor of safety to drop from 1.312 to 0.93 at the end of the third day. The study indicates that the rainfall at far field of the slope could trigger landslide due to the rise of the groundwater table.

1. Introduction

Slope failures one of the most frequent natural disasters and rainfall is one of the triggering factors (De Vita et al., 1998). The permeability of soil affects significantly rainfall infiltration within the unsaturated soil slope (Li et al., 2013; Tsaparas et al., 2002), soil with higher permeability allow more rainwater to infiltrate and flow into the soil slope resulting in a quick change of pore-water pressure from negative to positive (Rahardjo et al., 2009). Rainwater infiltration results in an increase in water content and reduces the matric suction in the soil (Qi and Vanapalli, 2015; Ng and Shi, 1998; Chae et al., 2015; Ali et al., 2014). During rainfall, soil suction dissipates due to saturation of the soil and failure would happen because of the development of positive pore-water pressure (Orense, 2004). The factor of safety increases with the increase of matric suction (Uchaipichat, 2013; Ishak et al., 2016). The rainfall intensity greater than the soil permeability (ks) infiltrate initially in higher infiltration rate than ks by as much as 3.5 times, and then it decline over time towards the steady state conditions (Gasmo et al., 2000). When the rainfall intensity is less than ks, the initial infiltration is low at the crest of the slope and then rise gradually towards the steady state conditions (Gasmo et al., 2000). Low-intensity rainfall for long duration are likely more dangerous than intense rain in inducing failure of the soil surface due to the low suction in the first 20-50 cm of the soil (Galeandro et al., 2014). Heavy and prolonged rainfall decreases the seepage rate (Tiwari and Caballero, 2015). A study was conducted

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https://doi.org/10.21833/ijaas.2018.10.011
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on the mechanism of 13-h duration rainfall induced landslide in Shenzhen, due to the prolonged rainfall, the highly permeable outcrops with good storability of the weathered granite, the rainwater continue to seep to the overlying fill layer even after the rainfall had ceased, and the groundwater table rose eventually triggered the landslide (Li et al., 2016).

During rainstorm, the ground water table rises and results in shallow landslide due to perched water table (Li et al., 2013; Tsuchida et al., 2014). Heavy rainstorm resulted in developing a perched water table and ground water table rose significantly (Ng and Shi, 1998; Leung et al., 2011; Bordoni et al., 2015). Shallow landslide were associated with the advance of wetting front in the unsaturated soils due to rainfall infiltration (Chae et al., 2015), and the critical factor of safety appeared to be the same depth as the wetting front (Qi and Vanapalli, 2015). Slope which have a friction angel less than the slope angel are prone to have failures induced by wetting front (Li et al., 2013).

Seepage forces that are directly proportional with the void ratio and the rainfall intensity, has a significant effect on seepage velocity in soil compacted at lower density (Tiwari et al., 2016). A reservoir landslide located in Sichuan provinces, China is associated with the reservoir water level drops. The landslide occurs due to the seepage forces caused by the difference between the groundwater level in the slope and water level of the reservoir (Han et al., 2014). Because of 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.

An experimental study on rainfall induced gully-type debris flow indicated that rainfall infiltration rate and soil water content are inversely proportional to the rainfall intensity (Ni, 2015). Hydraulic-type debris flow is induced by heavy rainfall while the soil-hydraulic-type debris flow is subjected to low rainfall intensity. The low rainfall intensity may induce liquefaction of soil mass and the subsequent landslide is the primary initiation mechanism of debris flow. Another experimental study revealed that when the flashfloods arrives on almost dry soil, the infiltration rate is much lower, thus debris flow would be developed starting with the initiation of a gully. Runoff water over high permeability soil would infiltrate and trigger landslide while the fragmentized mixed with the external runoff water could develop debris flow. Internal erosion in high porosity soil may also contribute to landslide by washing out fines and reducing shear strength (Hu et al., 2015). An experimental study conducted to examine the influence of rainfall, pore-water pressure and moisture content on flowslide indicated initial soil density is the most important factor in triggering flowslide failure, while rainfall intensity has a significant effect on increasing the pore-water pressure, moisture content and movement of flowslide (Hakro and Harahap, 2015). Pore-water pressure was found to be not reliable for early warning system due to the fact that the flowslide can occur before fully development of pore-water pressure.

The matric suction and degree of saturation can be assumed as indicators of the safety condition of the slope. the matric suction and volumetric water content can be affected by single rainfall event at the top part of the soil cover, however, the deeper part of the soil were affected by seasonal trend and unaffected by a single rainfall event (Pirone et al., 2015). Slope failure in a dry and permeable soil slope happen due to the increase of moisture content, advancement of wetting front and the development of perched water table. However, the failure of wet and less permeable soil slope is due to the increase of volumetric moisture content with the advancement of saturated wetting (Tohari et al., 2007).

An experimental study on factors that initiate slope failure indicated that failure would occur when the moisture content in a region near the toe of the slope becomes almost fully saturated even the other parts remain partially saturated. The loose soil slope fails faster than dense soil slope because of the high strength and low permeability of the dense slope. Furthermore, rainwater infiltration was not enough to trigger slope failure, rather generation of pore-water pressure from increase in moisture content associated with the rise of ground water table is the one that create an unstable zone. The degree of saturation at the crest of the slope increases with rainfall and decreases after the rainfall due to the rainwater drain out. The degree of saturation depends on the slope steepness where it was less in steeper slopes (Tiwari and Lewis, 2012). The slope failure occurs at different periods of rainfall due to the increase of pore-water pressure and the decrease in shear strength. The increase in pore-water pressure is according to the permeability of soil at the locations of the slope and the rate of increase is related to the degree of inclination of the slope (Tiwari and Caballero, 2015).

To conclude that, the rainfall plays a major role in triggering landslide. It infiltrates the soil causing the matric suction to dissipate and increases the pore-water pressure. Low rainfall intensity for long time is more dangerous than intensive rainfall for short time. Rainfall infiltrates in a higher rate of 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 significantly.

The objectives of this paper are to study the influence of various rainfall intensities and soil characteristics such as soil permeability on the rise of groundwater table in a regional scale (1 km) and to simulate the influence of the rise of groundwater table in triggering landslide. This is to get an idea on how the rise of the groundwater table by indirect rainfall could trigger landslide and enables engineers to avoid its risk. It helps researchers studying early warning system to know how the slope stability could be affected by the topography of the region. This paper looks into the effect of far field rain on slope stability due to the rise of groundwater level by running coupled seepage and slope stability analysis. It gives detailed study of water infiltration to the groundwater infiltration, development of perched water table with varied soil permeability and rain intensities, changes of matric suction at the far field of raining zone, and stability for slope located at far field of the raining zone.

2. Methodology

This paper focuses on the effect of rainfall induced landslide in which, the rise of ground water table, the rainfall intensity and permeability of the soil are identified. The rain is applied at far field from the area having potential slope failure with different rainfall intensities. This study is based on numerical analysis in which a coupled seepage-slope stability analysis was carried out by Soilworks software using finite element method.

2.1. Soil properties

Three types of soil textures are studied in homogeneous soil slopes; the soil properties are shown in Table 1. The soil properties are taken from the lab experiments for soil case studies located in Malaysia and reported by Kassim et al. (2012) at University Technology Malaysia, Skudai Campus, namely Bukit Cerapan and Babangida et al. (2014).

Table 1: Soil properties

Soil Texture	Cohesion Kn/m²	Friction Angel	γ (kn/m³)	γ_{sat} (kn/m³)
Sandy Silt	7.6	32°	18	19
Sandy Clay	6	35°	18.5	20
Silty Clay	9	34°	19	21

The fitting parameters for prediction hydraulic conductivity functions of soils using Van Genuchten method are as shown in Table 2.

Table 2: Fitting parameters for predicting hydraulic conductivity function of the soil

Soil Texture	α	n	θ_r	θ_s
Sandy Silt	0.178	1.966	33	45
Sandy Clay	0.225	1.318	0.279	0.424
Silty Clay	0.205	1.264	0.184	0.521

A homogeneous soil slope model is designed, with 1.00 Km long, 0.200 Km height and 45° slope angel. A ground water table is specified which is 5 m deep at the toe of the slope. The slope model is underlined with impermeable layer as shown Fig. 1. The raining zone is assumed to be limited at Zone 1 (300 m) and the slope stability check is allocated at Zone 3. This design enables us to study the effect of surrounding topography on slope stability and to study the infiltration of rainwater through long and deep distance as well as the effect of rain intensity on the rise of deep groundwater table.

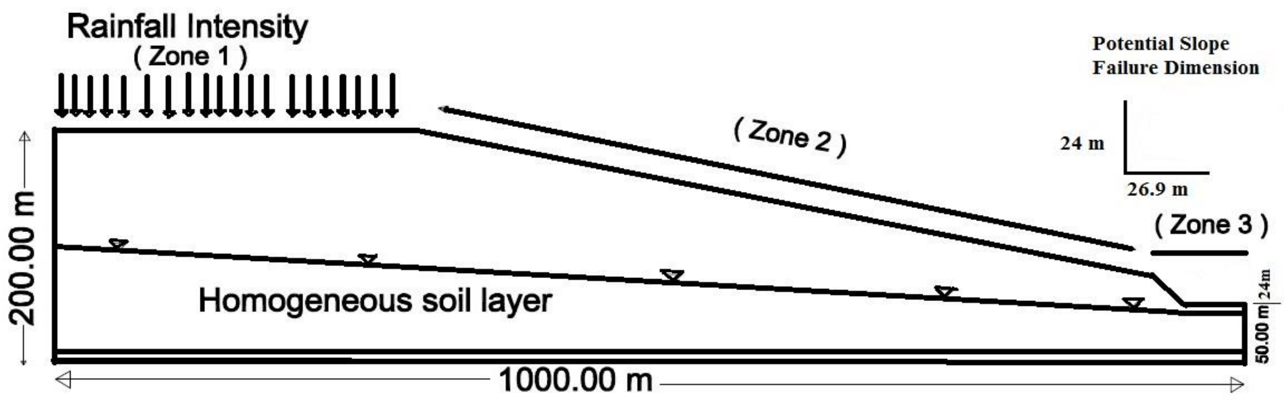


Fig. 1: Prototype cross section of soil slope

2.2. Rainfall boundary and intensity

The rainfall is applied at Zone 1 along 300 m of the slope model. The rainfall intensity varies from low intensity of 0.2 m/day to high intensity of 0.6 m/day with different soil permeability ranging from very permeable soil with ks = 10-5 to low permeable soil with ks = 10-7. The time stages of rainfall continue for three days in a rainfall period of 6 hrs/day (Table 3), which is sufficient for the study of the variation of groundwater level; Fig. 1 illustrates the distribution of rain along a homogeneous slope. The maximum negative pore water pressure in the slope model is 20 KN/m². Table 3 shows the rainfall functions for rainfall intensity within the rainfall period for low, moderate, and high intensities.

2.3. Rainfall Intensity, soil permeability, and soil texture scenarios

Twenty-seven scenarios are simulated; the scenarios divide into three types of soil textures. The first nine scenarios are Sandy-silt soil slope and differ from each other in rainfall intensity, which range from 0.2 m/day to 0.6 m/day and soil permeability, which range from 1E-5 m/sec to 1E-7 m/sec. Likewise, for Sandy-clay and silty-clay soil slopes. Table 4 shows the scenarios for the homogenous slope. The evaporation rate is 0.005 m/day (Ali et al., 2000).

2.4. Coupled seepage-slope stability analysis

The slope model contains a total number of 46737 mesh elements, which range from 10 m long to 0.3 m at Zone 3 of the slope to ensure an accurate seepage analysis result using FE Methods as shown in Fig. 2.

Table 3: Rainfall functions

Low Rain Intensity		Moderate Rain intensity		High Rain Intensity	
Day	Value m/day	Day	Value m/day	Day	Value m/day
0.00000	0.2	1.00E-05	0.4	1.00E-05	0.6
0.25000	0.2	0.25000	0.4	0.25000	0.6
0.25001	0	0.25001	0	0.25001	0
1.00000	0	1.00000	0	1.00000	0
1.00001	0.2	1.00001	0.4	1.00001	0.6
1.25000	0.2	1.25000	0.4	1.25000	0.6
1.25001	0	1.25001	0	1.25001	0
2.00000	0	2.00000	0	2.00000	0
2.00001	0.2	2.00001	0.4	2.00001	0.6
2.25000	0.2	2.25000	0.4	2.25000	0.6
2.25001	0	2.25001	0	2.25001	0
3.00000	0	3.00000	0	3.00000	0

Table 4: Rainfall intensity, soil permeability, and pumping rate scenarios

No	Soil texture	Rain intensity	Coefficient of permeability
1		0.2	Ks = 10-5
2		0.2	Ks = 10-6
3		0.2	Ks = 10-7
4		0.4	Ks = 10-5
5	Sandy Silt	0.4	Ks = 10-6
6		0.4	Ks = 10-7
7		0.6	Ks = 10-5
8		0.6	Ks = 10-6
9		0.6	Ks = 10-7
10		0.2	Ks = 10-5
11		0.2	Ks = 10-6
12		0.2	Ks = 10-7
13		0.4	Ks = 10-5
14	Sandy Clay	0.4	Ks = 10-6
15		0.4	Ks = 10-7
16		0.6	Ks = 10-5
17		0.6	Ks = 10-6
18		0.6	Ks = 10-7
19		0.2	Ks = 10-5
20		0.2	Ks = 10-6
21		0.2	Ks = 10-7
22		0.4	Ks = 10-5
23	Silty Clay	0.4	Ks = 10-6
24		0.4	Ks = 10-7
25		0.6	Ks = 10-5
26		0.6	Ks = 10-6
27		0.6	Ks = 10-7

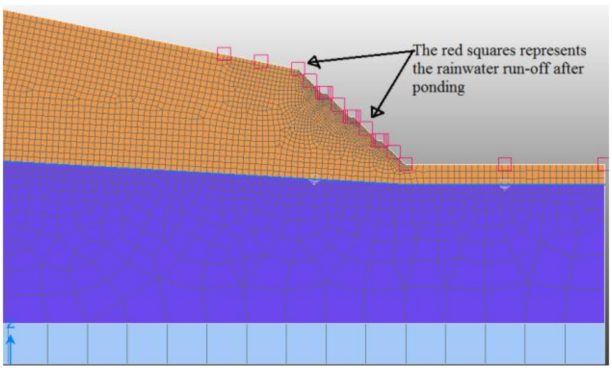


Fig. 2: Mesh elements of the slope

3. Result and discussions

The groundwater table increases rapidly with Sandy-silt soil texture as it is compared to other soil textures followed by Sandy-clay and then Silty-clay. All rain intensities have the same effect on the main groundwater but differ in the development of perched water table at the raining Zone. High rainfall intensity and moderate rain intensities develops a large perched water table at Zone 1 whereas low rain intensity drains out during the rain event, similar findings were reported by Ng and Shi (1998), Leung et al. (2011), and Bordoni et al. (2015). The perched water tables dissipate after 6 hours of the rain event in high soil permeability slope while it remained until the end of the third day in low permeability soil slope.

Soil suction dissipates during the rainfall at Zone 1 and rises at the dry zones. For sandy-silt soil slope, the pore water pressure drops slightly after the first rainfall event and rises rapidly at the end of the first day due to the fast drainage of rainwater. For Sandy-clay soil slope, the matric suction at the ground surface is almost zero after each rain event and the soil is saturated due to the large perched water table developed at the ground surface. The matric suction rises after the rain event and reaches up to 22 kN/m2 at the end of the day. For Silty-clay soil slope, the matric suction dissipates and the soil is almost saturated at the ground surface after each rain event. It rises after the rain to 18 kN/m2.

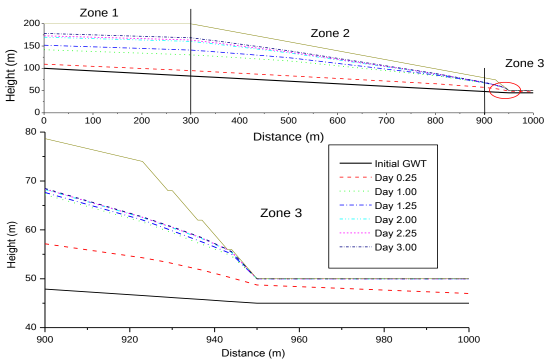
The rainfall infiltration starts higher than the soil permeability at the first rainfall event and declines at the second and third rain event to a value close to the soil permeability, similar phenomena was reported by Gasmo et al. (2000). The infiltration declines with the depth and only a small quantity reaches the groundwater table. The developed perched water table continues to drain to the main groundwater table for hours with high soil permeability and for days with low soil permeability soil after the rainfall event.

3.1. The rise of groundwater table

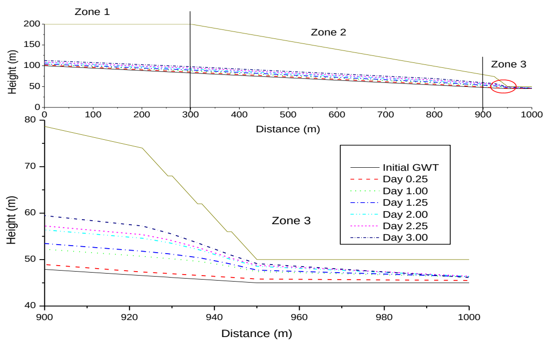
The groundwater table increases rapidly with Sandy Silt soil texture comparing with other soil texture following by Sandy Clay and then Silty Clay. All rain intensities have the same effect on the main groundwater but differ in the developed perched water table at the raining Zone. High rainfall intensity and moderate rain intensities develops a large perched water table at Zone 1 whereas low rain intensity drains out during the rain event. The perched water table dissipates after 6 hours of the rain event in high soil permeability slope while it remained until the end of the third day in low permeability soil slope.

3.1.1. Sandy silt

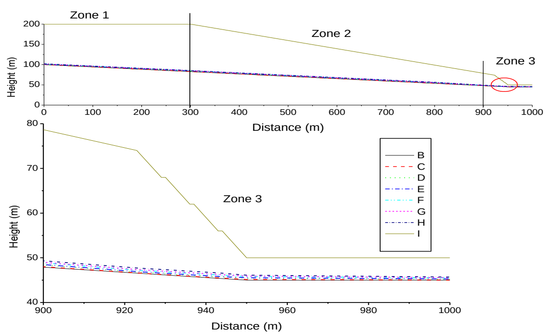
Rainfall intensity with high (1E-5 m/sec) soil permeability results in a rise in the ground water table to almost two thirds of the slope height at Zone 1 in the first day of the rainfall and slightly rises in the second and third day as shown in Fig. 3a.



a) High permeability soil



b) Moderate permeability soil



c) Low permeability soil

Fig. 3: The rise of GWT after 0.2, 0.4 and 0.6 m/day rainfall intensity in soil of (a) high (b) moderate (c) low soil permeability

When the soil permeability is low (1E-7 m/sec), the effect of rainfall declines and the rise of ground water table is less than one meter in the first day and slightly rises to almost one meter above the initial ground water table in the third day as shown in Fig. 3c. When the soil permeability is moderate (1E-6 m/sec) the groundwater table rises almost one meter after the first rainfall event and four meters at the end of the day as shown in Fig. 3b. Low permeability soil slope model develops a perched water table with low, moderate, and high rainfall intensities. Those perched water tables appear at the end of the rainfall period, dissipate after 6 hours with low rain intensities, and remain until the end of the day with high and moderate rain intensities. High rain intensity develops perched water table in low, moderate and high permeability soil slope. Moderate rain intensity develops a perched water table in low and moderate permeability soil slopes. Low rain intensity develops a perched water table in low rain intensities. The deepest developed perched water table is 38.2 with high rain intensity and low soil permeability while it is 20.8 m and 3 m with moderate and low rain intensities respectively as shown in Fig. 4.

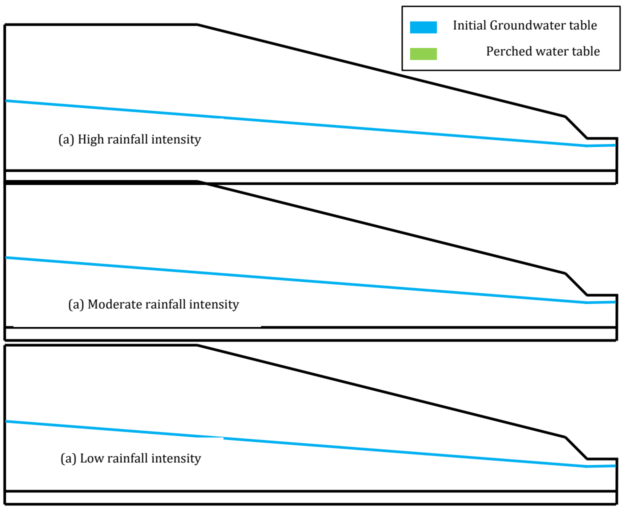


Fig. 4: The rise of groundwater table and perched water table for high permeability soil slope at the end of the third rainfall event with (a) high, (b) moderate and (c) low rain intensity

The groundwater table rises identically in all cases except at Zone 1 with high soil permeability at the third day where it is noticed to be higher with high rain intensity than it is with low and moderate rain intensities. The ground water continues to rise after the rainfall has stopped because of the time taken for the rainfall infiltration to reach the groundwater table and for the groundwater to flow from Zone 1 to Zone 3.

3.1.2. Sandy clay

Groundwater table in sandy clay soil rises gradually to its highest level, 10 meters above the initial one on the third day at Zone 3 with soil permeability of 0.864 m/day as shown in Fig. 5a. A huge perched water table appears at Zone 1 after the rainfall event and dissipates after 6 hours of the rainfall event. Rainfall slightly affects slope with moderate soil permeability and the groundwater table slightly increases as shown in Fig. 5b.

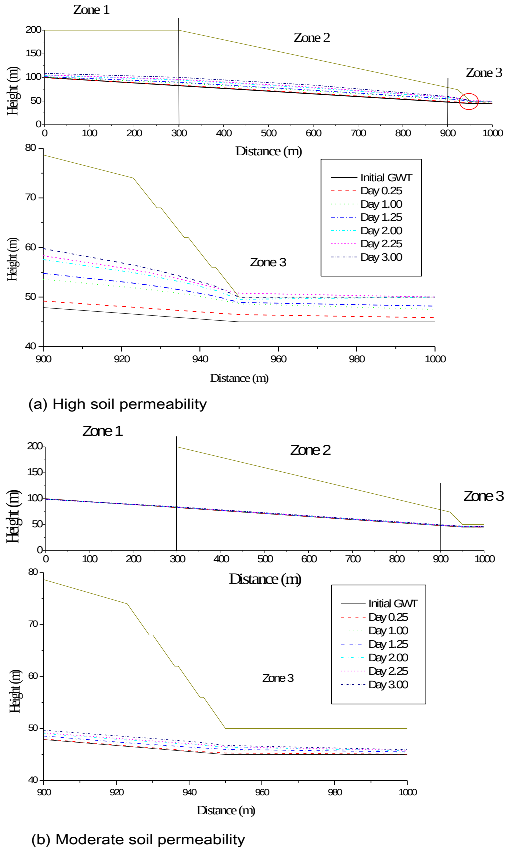


Fig. 5: The rise of GWT after 0.2, 0.4 and 0.6 m/day rainfall intensity in soil of (a) high (b) moderate permeability

It rises to almost 2 meters at the end of the third day. For high soil permeability, a large perched water table develops at Zone 1 with moderate and high rainfall intensities, which expends to almost 10 m and 20 m deep at the end of the third rainfall event respectively as shown in Fig. 6.

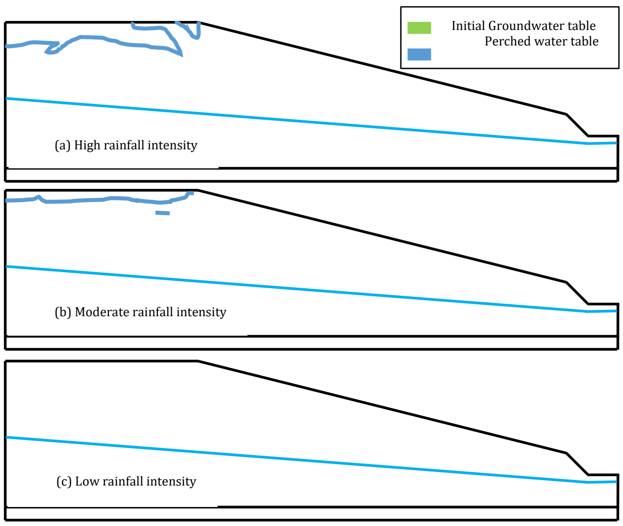


Fig. 6: Groundwater table and perched water table for high permeability soil slope at the end of the third rainfall event with (a) high, (b) moderate and (c) low rain intensity

The perched water table dissipates after 6 hours of the first rainfall event and 18 hours after the third rainfall event. A perched tater table appears with moderate soil permeability slope, which expands to 29.5 m deep at the end of the third rainfall event and dissipates after 18 hours of the precipitation. Moderate and low rainfall intensities develop discontinuous perched water tables that expand to almost 15 m and 1.3 m deep respectively after the third rainfall event. The rise of groundwater table with low soil permeability is very slight; it rises 0.13 m at the end of the third day. A large perched water table develops with high and moderate rainfall intensity, which expands to almost 31.5 m and 14.85 m deep respectively at the end of the third rainfall event and does not dissipate at the end of the day whereas it is 3 m deep with low rainfall intensity and dissipates at the end of the day as shown in Fig. 7. Figs. 5a and 5b show the rise of groundwater table for slope with high and moderate soil permeability slopes.

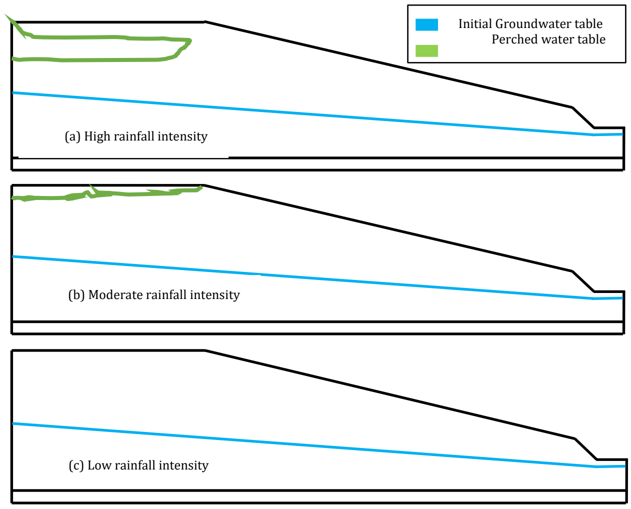


Fig. 7: Groundwater table and perched water table for low soil permeability slope at the end of the third day with (a) high, (b) moderate and (c) low rain intensity

3.1.3. Silty clay

Groundwater table in silty-clay soil slope slightly rises with rainfall comparing to the other soil types. It rises 6.78 m at the end of the third day for high soil permeability soil, 0.81 m for moderate soil permeability and 0.07 m for low soil permeability. For high soil permeability, a large perched water table develops with high rainfall intensity, which expands to 12 m deep after the second rainfall event and separates at the end of the third rainfall event into two-perched water table above each other and dissipates after 6 hours. A perched water table develops with moderate rainfall intensity that expands to 5.4 m deep at the end of the second rainfall event and divides into a number of small-perched water tables at Zone 1 after the third rainfall event. On the other hand, low rainfall intensity does not develop any perched water table as shown in Fig. 8. For soil slope with moderate soil permeability, a perched water table is noticed with high, moderate, and low rainfall intensity that expands to 19 m, 7.17 m and 1.1 m deep respectively. The perched water tables dissipate after 18 hours with high rainfall intensity and 6 hours with moderate and low rainfall intensity.

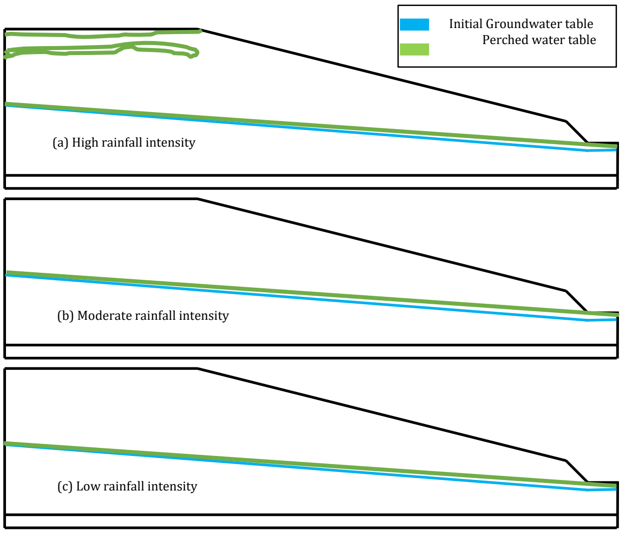


Fig. 8: The rise of groundwater table and perched water table for high permeability soil slope with (a) high, (b) moderate, and (c) low rain intensity at the end of the third rainfall event

For low soil permeability slope, large perched water tables develop and expand to 17.83 m, 7.76 m and 1.47 m with high, moderate, and low rain intensity at the end of the third rainfall event. Perched water tables remain until the end of the third day for high and moderate rain intensity and dissipate within 18 hours with low rain intensity. Fig. 9 shows the rise of the main groundwater table for slopes with high and moderate soil permeability.

Table 5 summarizes the rise of groundwater table and the resulted factor of safety at Zone 3. Scenarios 1, 4 and 7 are Sandy silt with high soil permeability; the groundwater table rises 10.09 m above the toe of the slope causing the slope to drop from 1.312 to 0.93 at the end of the third day. Scenarios 2, 5 and 8 are sandy silt with moderate soil permeability; the groundwater table rises 5.66 m above the toe level of the slope resulting in a decline in the factor of safety from 1.314 to 1.157. Scenarios 10, 13, and 16 are Sandy clay with high soil permeability; the groundwater table rises 4.91 m above the toe level of the slope, which results in a decline in the factor of safety from 1.411 to 1.233 at the end of the third day. Scenarios 19, 22 and 25 are silty clay with high permeability; the groundwater table rises 1.78 m above the toe of the slope causing the factor of safety to decrease from 1.415 to 1.346 at the end of the third day. The groundwater table in the remaining scenarios rises slightly to a level below the toe of the slope and the factor of safety remains stable.

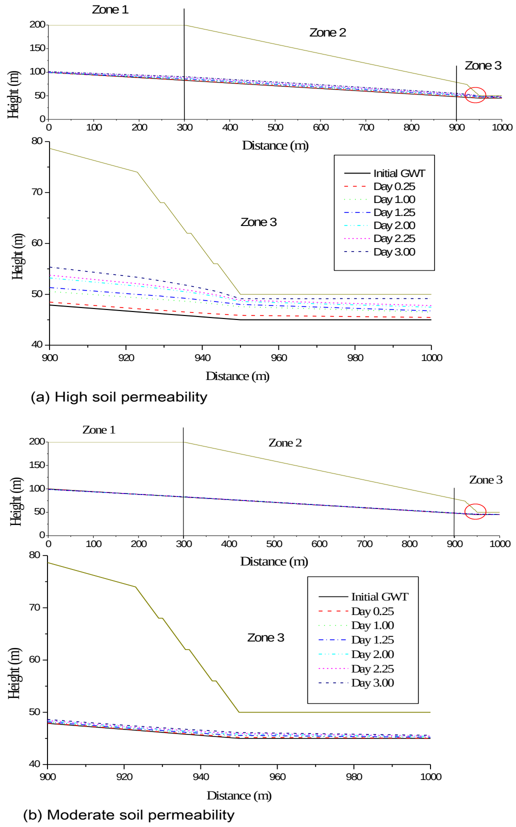


Fig. 9: The rise of GWT after 0.2, 0.4 and 0.6 m/day rainfall intensity in soil of (a) high (b) moderate permeability

Table 5: Summary of the groundwater table changes at Zone 3 and the resulted factor of safety at the beginning and the end of the third day for scenarios in which the groundwater table rises above the toe of the slope

Scenario No	Time	Description of groundwater table	FOS
1, 4 and 7 (Sandy silt)	0 day 3rd day	The groundwater table rises 16.09 m above the initial groundwater table and below the crest of the slope at the end of the third day	1.312 0.93
2, 5 and 8 (Sandy silt)	0 day 3rd day	The groundwater table rises 10.66 m above the initial groundwater table and below the crest of the slope at the end of the third day	1.314 1.157
10, 13 and 16 (Sandy clay)	0 day 3rd day	The groundwater table rises 9.91 m above the initial groundwater table and below the crest of the slope at the end of the third day	1.411 1.233
19, 22 and 25 (Silty clay)	0 day 3rd day	The groundwater table rises 6.78 m above the initial groundwater table and below the crest of the slope at the end of the third day	1.415 1.346

3.2. The changes of negative pore-water pressure

The negative pore water pressure raises almost double the initial negative pore water pressure during the first day in low permeability soil and continues to rise due to the movement of voids upward and the absence of wetting front at Zone 1. The matric suction decreases at the raining Zone during the rainfall and climbs back at the end of the day. The pore-water pressure changes to be positive as the groundwater table rises and all the voids are filled with water as shown in Figs. 10, 11, and 12 for slope model with soil permeability of 1E-6 m/sec and rainfall intensity of 0.4 m/day. Figs. 10, 11, and 12 show the increase of soil matric suction where higher matric suction is found to be at the crest of slope.

The negative pore water pressure dissipates at Zone 1 after the first rainfall event in sandy-clay and Silty-clay soil slopes because they are fully saturated by the perched water table developed at the raining Zone as shown in Figs. 11 and 12. It climbs at the end of the day to almost the same initial value and drops again after the second and third rainfall events to zero. The pore water pressure in Sandy-silt soil slope remains stable after the first rainfall event with moderate rainfall intensity as shown in Fig. 10 while it drops to -10 kn/m² with high rainfall intensity; it declines after each rainfall event and rises gradually to -55 kn/m² at the end of the third day. The matric suction at Zone 2 increases gradually with the rise of groundwater table to reach -66 kn/m² in sandy-silt, -63 kn/m2 in sandy-clay soil slopes and -44kn/m² in silty clay slope. Zone 3 records the highest matric suction at the crest of the slope. Figs. 10, 11, and 12 show the fluctuation of matric suction at the ground surface for soil slopes with moderate rainfall intensity and moderate soil permeability.

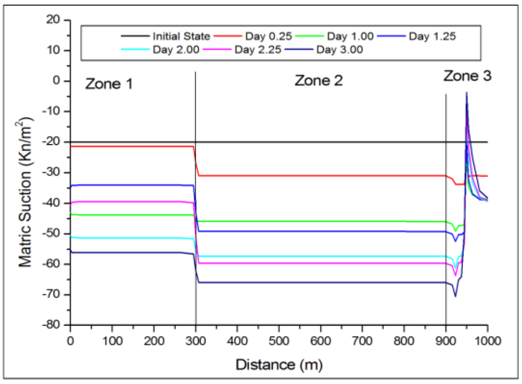


Fig. 10: Distribution of Pore-water pressure after 0.4 m/day rainfall intensity for 1E-6 m/sec soil permeability (Sandy silt)

3.3. Flow quantity

The highest rate of flow quantity occurs during the first day of rainfall, it declines in the second and third day, and this agree with the study of other researcher (Gasmo et al., 2000). It records Zero-flow quantity under the initial ground water table. The infiltration rate of rainwater at Zone 1 varies according to the rainfall intensity where the highest infiltration rate occurs at high rainfall intensity followed by moderate rainfall intensity and then low rain intensity. the infiltration starts very high at the ground surface but the infiltration rate does not continue in the same quantity to reach the groundwater table, it seeps bellow a few meters laterally as a negative flux to Zone 2 as shown in Fig. 13. Almost the same quantity of rainwater infiltration reaches the groundwater table regardless of rainfall intensities and this explains the similarity of the rise of groundwater table with different rainfall intensities.

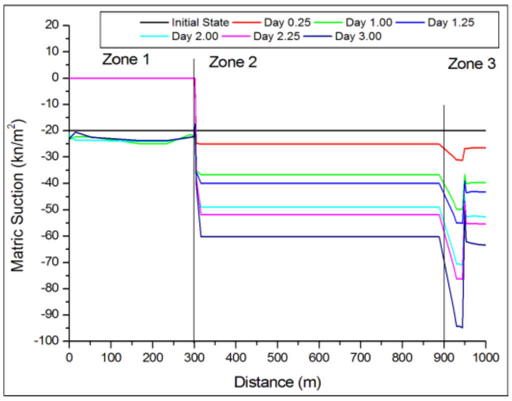


Fig. 11: Distribution of Pore-water pressure after 0.4 m/day rainfall intensity for 1E-6 m/sec soil permeability (Sandy clay)

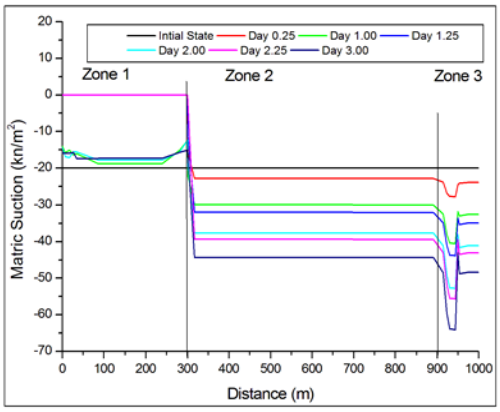


Fig. 12: Distribution of Pore-water pressure after 0.4 m/day rainfall intensity for 1E-6 m/sec soil permeability (Silty clay)

Fig. 13a shows the infiltration of the rainwater at the end of the first rainfall event (day; 0.25) with different soil permeability. In general, the infiltration rate depends on the soil permeability. The highest infiltration rate occurs at the raining zone (Zone 1) and declines along Zone 2. It is obvious that the infiltration is high at the ground surface with positive value and then gradually declines to reach a constant value until it reaches the groundwater table. While the groundwater table rises, some of the water seeps to Zone 2 and 1. The positive value of the curve indicates influx as it is seen near the ground surface while, the negative value of the curve indicates an out-flux as it is noticed within the groundwater table. Zone 2 has low infiltration at the ground surface and it increases below a few meters due to the out-flux from Zone 1 after that it declines again. Similarly in Figs. 13b and 13c, the infiltration continues but in very low rate and reaches zero infiltration below 15 m and 10 m of the ground surface with moderate and low soil permeability respectively. Zone 1 has zero infiltration at the ground surface but it is an out-flux area.

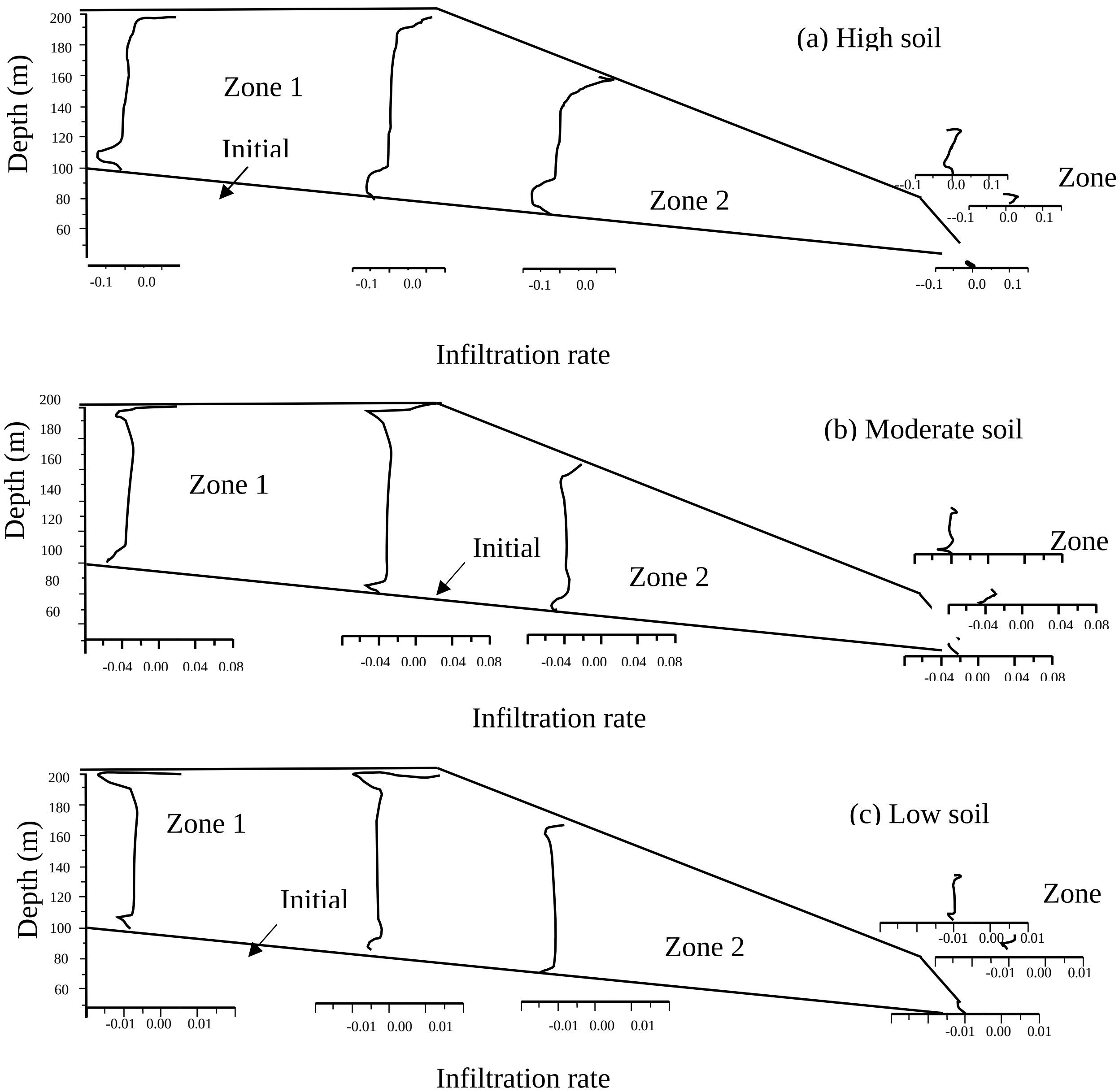


Fig. 13: Distribution of rainfall infiltration at the end of the first rainfall event with (a) high permeability of soil (b) moderate permeability of soil (c) Low permeability of soil

3.4. The effect of the rise of the groundwater table on slope stability

The rise of ground water table has a great effect on slope stability due to the increase in the pore water pressure. For the slope with a high permeability soil (ks = 1E-5 m/sec), the ground water table rises rapidly and the factor of safety drops from 1.312 to 0.95 at the end of the first day for Sandy silt soil slope. The factor of safety for Sandy-clay soil slope drops gradually from 1.425 to 1.242 at the end of the third day. The rise of the groundwater table slightly affects silty clay slope where the factor of safety drops from 1.420 to 1.345 at the end of the third day, Fig. 14 shows the decreases of FOS for three types of soil slope after each rainfall event and at the end of the day. As the soil permeability decreases, the rise of the water table is slight above the initial groundwater table; hence, the slope stability decreases slightly in sandy silt soil slope and remains stable in sandy clay and silty clay soil slopes. For Sandy silt slope with 0.0864 m/day soil permeability, the factor of safety drops gradually from 1.314 to 1.158 at the end of the third day as shown in Fig. 15 and remains constant with 0.00864 m/day soil permeability because the groundwater table rises slightly and does not reach the slip surface. The factor of safety remains constant in Sandy-clay and Silty-clay soil slope with moderate and low soil permeability because the rise of groundwater is slight and below the toe of the slope.

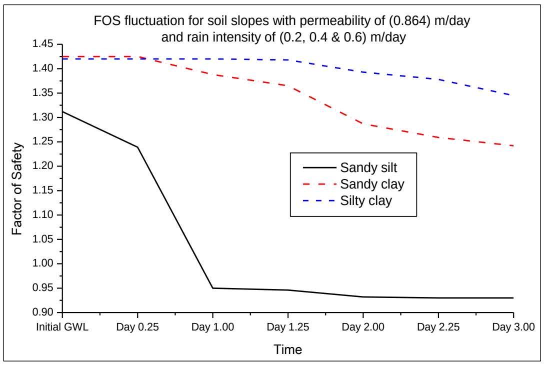


Fig. 14: The factor of safety for soil slopes of high soil permeability with rain intensity of 0.2, 0.4 and 0.6 m/day

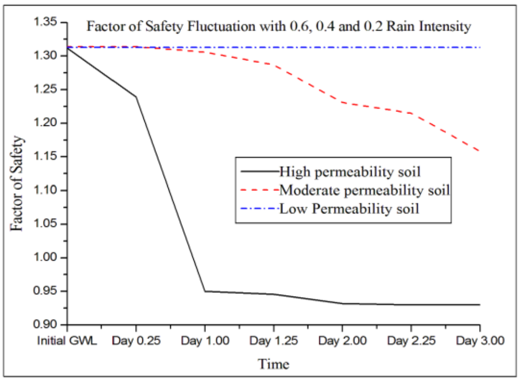


Fig. 15: The factor of safety for soil slopes of high moderate and low soil permeability with rain intensity of 0.2, 0.4 and 0.6 m/day

It is noticed that the worst case is in Sandy-silt soil slope where the factor of safety drops from 1.309 to 0.952 at the end of the first day due to the rise of groundwater table. The factor of safety for Sandy-clay soil slope is only decreased with high permeability soil and it declines from 1.414 to 1.233 at the end of the third day. Likewise, in Silty-clay soil slope where the factor of safety declines from 1.415 to 1.346 at the end of the third rainfall event with high permeability soil slope.

4. Conclusion

Coupled seepage-slope stability analysis is an efficient way to find out the effect of intensive rainfall on slope stability and to compare it with soil properties and geometry features of slope. The groundwater table rises due to the rainwater infiltration. The high permeable soil allows much rainwater to reach the groundwater table and cause a quick rise of groundwater level. The quick rise of groundwater may trigger a landslide even though the rain occurs at far field from the slope. The rise of groundwater may induce landslide just after a few hours of the rain event. Slopes with moderate or low soil permeability may fail due to the rise of groundwater table after one or two days of the rain event because of the time taken for the rainwater to infiltrate and the developed perched water tables to drain to the main groundwater table.

Sandy-silt soil slope with high permeability was highly affected by the rainfall due to the rise of the groundwater table. It caused the factor of safety to drop from 1.309 to 0.93. The rainfall has less influence on Sandy-clay and Silty-clay soil slopes. although the groundwater table rises above the toe of the slope, the factor of safety only drop from 1.414 to 1.233 in Sandy-clay slope and from 1.415 to 1.346 in Silty-clay. This difference between soil types is due to the suction at the ground surface where it reached up to -60 kpa after 18 hours of the rainfall for Sandy-silt soil that allows more rainwater to infiltrate and drain faster than other soil types. In comparison with Sandy-clay and Silty-clay, it was -21 kpa and -17 kpa after 18 hours of the rainfall event that prevent the majority of the future rainfall events to infiltrate and the perched water table takes more than one day to dissipate. All slope models have identical reaction to different rainfall intensities in terms of the rise of groundwater table and flow quantity at Zone 1, where the factor of safety dropped in a similar manner in all rainfall intensity cases. The rise of the groundwater at Zones 2 and 3 is highly affected by the rise of groundwater at Zone 1, which seeps in a quantity higher than the infiltration of runoff water. The infiltration of rainwater at the ground surface does not continue with the same quantity to reach the groundwater table, it seeps laterally and almost at the same quantity the rain intensities varies. The matric suction of the soil drops at the raining Zone after the rainfall event and rises at the end of the day at Zone 1 whereas it increases gradually at Zone 2 and 3. The highest matric suction is to be at the ground surface of Zone 3 due to the rise of groundwater table below the toe of the slope and the absence of wetting front at the crest of the slope. A large perched water table is developed in low permeability soil slopes that does not dissipates at the end of the third day and this makes the groundwater table continue to rise for days after rainfall event. The rise of groundwater table is more dangerous than perched water table since the groundwater table includes all the slip surface and drain out at the toe of the slope and this will weaken the shear strength due to the seepage forces.

Acknowledgement

The authors are thankful to The Malaysian Ministry of Higher Education (MOHE), for Supporting the Research through Fundamental Research Grant Scheme (FRGS- 0153AB-L33), and to Universiti Teknologi PETRONAS (UTP) for Providing Favorable Research Environment and Facilities.

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