EFFECT OF NEAR SURFACE HETEROGENEITY ON THE PORE WATER PRESSURE DISTRIBUTION AND SLOPE STABILITY

Nurly Gofar, Ega Nanda Pangestika, Yudi Harianto

Universitas Bina Darma Palembang

nurly_gofar@binadarma.ac.id

ABSTRACT

Seepage is an important problem analyzed in geotechnical engineering. Conventionally, the analysis is performed in conditions where the soil is intact. However, near-surface soil is subjected to various conditions which lead to heterogeneity for example, the presence of desiccated cracks in clay, the presence of relics in weathered rock, the root of vegetation, etc. The presence of cracks and other forms of heterogeneity on the near-surface layer increases the rainfall infiltration in the slope and decreases the suction accordingly. Water infiltration increases the pore water pressure and groundwater level and decreases the matrix suction of unsaturated soils - which is a critical factor for the stability of slopes. This study aims to evaluate the effect of varying permeability of near-surface soil on the rainwater infiltration to slope, and subsequently the factor of safety. In this case, the near-surface soil is modeled as a layer with higher permeability. Numerical analysis performed in this using SEEP/W and SLOPE/W indicated that considering this condition results in a higher factor of safety of the slope because the higher permeability resulting from heterogeneity helps dissipate pore water pressure which is critical in maintaining the slope stability during heavy rainfall.

INTRODUCTION

Rainfall-induced slope failure is prevalent geohazard in tropical countries that are covered with residual soils and deep groundwater table including Indonesia. The reduction in soil shear strength resulting from elevated pore water pressure and reduced matrix suction can result in slope failure. The topic of rainfall-induced slope instability has been studied for example by Brand, 1984; Shaw-Shong, 2004; Rahardjo et al, 2005; Gofar and Lee (2008). Factors influencing the stability include the geometry of the slope, the soil characteristics, and the rainfall duration and intensity. The normal depth of the slip surface in rainfall induced slope failures is between one and three meters, and it is aligned in a direction that is parallel to the slope surface, thus analytical analysis is usually carried out for infinite slope stability analysis (Lee, et al., 2009). The integration of current computer programs enables the speedy execution of seepage and infiltration analysis in unsaturated soil, as well as the assessment of slope stability.

The primary causes of failures are primarily caused by complete or partial dissipation of matric suction within the unsaturated zone during the process of rainfall infiltration which yields a decrease in the soil's shear strength (Fredlund & Rahardjo, 1993; Fourie et al, 1999). Conventionally, the analysis of rainfall-induced slope instability is performed in conditions where the soil is intact. However, near-surface soil is subjected to various conditions which lead to heterogeneity for example, the presence of desiccated cracks in clay (Krisnanto et al., 2021). Besides, the residual soil formation process in tropical regions introduces minor hydraulic heterogeneities on the soil surface, which are significantly influenced by preexisting discontinuities such as the presence of relic and core-stone (Gerscovich et al 2006, Kassim et al, 2012). Moreover, the root of vegetation also introduces heterogeneity on the near-surface layer because roots uptake water from the soil, leading to variation in moisture around the root system with the distance between the trees and the soil (Ali et al, 2012). These three forms of heterogeneity had the potential to generate inconsistencies in the suction distributions, increase the rainfall infiltration into the slope, and subsequently decrease the suction. Figure 1 shows the appearance of the slope surface which indicates the presence of some heterogeneity on the near-surface soil layer.

Figure 1 Slope surface condition

However, considering the hydraulic heterogeneity of the near surface soil is a complicated task. Krisnanto & Rahardjo (2018) showed that the presence of crack at the surface should not considers only the soil matrix part of the crack soil, but also the crack network. The effects of relict discontinuities on the stability of residual soil slopes in tropical regions is difficult due to the unpredictable hydrological influences and the intrinsic heterogeneity of the indigenous soils (Au, 1998). Gofar & Kassim (2011) conducted laboratory test on the effect of relic on the permeability of soil and they found that the occurrence of relic and core-stones in Grade V material causes a variability of saturated mass permeability of the residual soil range over one order of magnitude. Ali et al (2012) concluded that trees contribute to slope stability both hydrologically as a result of increase in matric suction of the soil resulting in an increase in the shear strength and mechanically due to root reinforcement. Based on their research on the granitic residual soil in Bukit Timah, Singapore Agus et al (2005) concluded that the saturated coefficient of hydraulic conductivity in the residual soil mantle varies within two orders of magnitude. The impact of precipitation patterns on soils with varying permeability levels was investigated by Rahimi et al (2011) under conditions of delayed, regular, and advanced preceding rainfall patterns. The findings suggest that the soil with low permeability is comparatively more susceptible to instability than the soil with high permeability.

Based on the preceding discussion, considering the heterogeneity in the near-surface soil could lead to a more realistic evaluation of rainfall-induced instability. This paper presents the results of a study on the effect of heterogeneities of the near-surface soil on pore water pressure distribution and slope stability by varying the coefficient of permeability of the near-surface soil. In this study, the near-surface soil was modelled as a soil layer with higher permeability while other properties were kept similar. The slope was subjected to rainfall of high intensity short duration and low intensity and long duration with low to high infiltration rate, as well as combination of antecedent and major rainfall.

METHODOLOGY

Study Location and Geometry of the slope

The study focused on a sloping area in the city of Pagar Alam situated in the vicinity of Bukit Barisan, Sumatra. The topography is characterized by hills and mountains. The geomorphology of the is a rough undulating hill reaching a height of between 500 – 1800 m. The main constituent rock in this area consists of lava rock which is covered by pyroclastic on top. The soil is of the Latosol and Andosol types with undulating ground surface. Besides known for its beautiful landscape and extensive plantation as well as producer of vegetables and fruits, the city is also known for slope failure occurrences. Figure 1 shows the location of Pagar Alam city in South Sumatra Province. A slope in the South Sumatra National Road segment no 037 i.e. Simpang Air Dingin – Pagaralam was selected for this study. The coordinate of the location is 4° 4'23.67" South Latitude and 103°19'26.47" East Longitude.

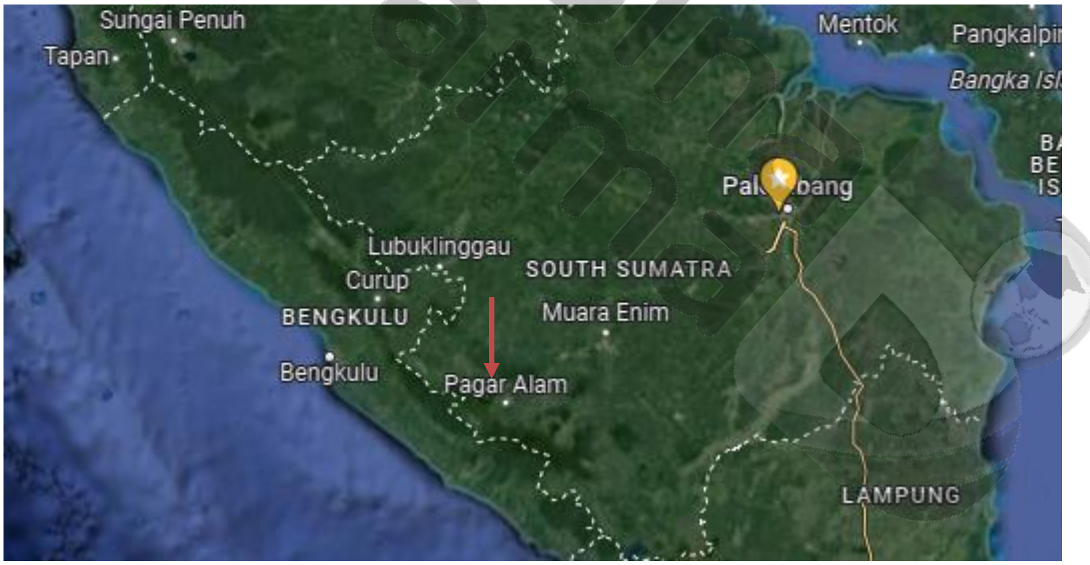


Figure 2 Study Location (Google Map)

Previously, research had been conducted on the effect of rainfall on the same slopes using PERISI program (Aisah & Gofar, 2022). Data was collected at six locations at an interval of 50 m along Jalan Lematang, Pagar Alam. The slopes along this range are inclined at an angle between 27^{o} dan 39^{o}. The height of the slope is between 10 and 30 m. The slope used for this analysis is inclined at 27^{o} and height of 10m (Figure 3). In this study, the near surface soil is modeled as a layer of 1 m with coefficient of saturated permeability one order of magnitude higher than the rest of the soil.

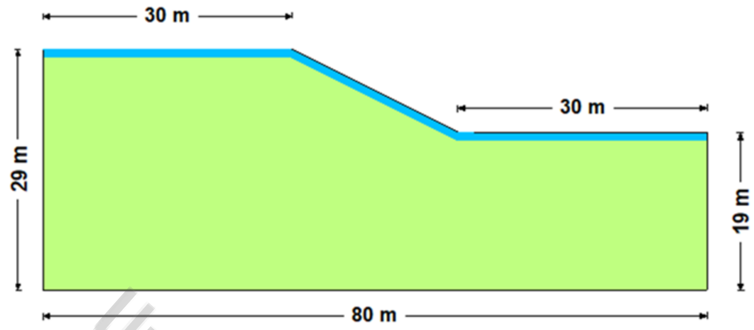


Figure 3 Geometry of the slope

Soil properties

Soil data collected by Aisah and Gofar (2022) was adopted in this analysis. They showed that the soil forming the slope is almost uniform i.e., clay with medium to high plasticity. The property of the soil selected for this study is summarized in Table 1. Undisturbed samples were retrieved from a depth of 2 m and were used for the determination of the saturated coefficient of permeability as well as the effective shear strength of the soil. The coefficient of saturated permeability of the soil is 4.5×10^{-6} m/s.

Table 1 Soil properties

Properties	**Unit**	**Soil 1**	**Soil 2 (near surface)**
Specific gravity (Gs)		2.62	2.62
Porosity (h)		0.62	0.62
Saturated coef of permeability	m/sec	4.5×10^{-6}	4.5×10^{-5}
Sieve Analysis			
Passing No 200 sieve	%	56.39	56.39
Clay	%	20%	20%
Atterberg Limits			
Liquid Limit	%	49.4	49.4
Plasticity Index	%	27.13	27.13
Soil Classification		CH	CH
Shear strength parameters			
Cohesion c’	kPa	5	5
Internal friction angle ϕ’	^{o}	21	21
Rate of increase in internal friction angle due to suction ϕ_b’	^{o}	14	14

Soil Water Characteristic Curve (SWCC) and permeability function are two primary soil properties used in the analysis of pore water pressure variation in soil. A straight forward estimation for plastic soil is proposed by Zapata (1999) and further developed by Perera et al., (2005). This method is based on the grain-size distribution and the plasticity index (*PI*) which are used to calculate parameters *a*, *m*, *n,* in the Fredlund and Xing (1994) fitting equation of SWCC (Equation 1).

$$\theta(\psi, a, n, m) = C(\psi) * \frac{\theta_s}{\left\{ln\left[e+\left(\frac{\psi}{a}\right)^n\right]\right\}^m} \tag{1}$$

whereas a, n , m are unknown fitting parameters, ψ is the matric suction (u_a-u_w), θs is the saturated water content, e is the natural number (≈2.72) and $C(\psi)$ is a correction factor defined as follow:

$$C(\psi) = \frac{ln\left(1+\frac{\psi}{\psi_r}\right)}{ln\left[1+\left(\frac{1'\ 000'\ 000}{\psi_r}\right)\right]} + 1 \tag{2}$$

The parameter ψ_r is a fitting parameter related to the residual suction. In this case ψ_r =500 should give a good prediction of SWCC. Zapata method predicts the shape of SWCC based on a weighed Plasticity index, wPI for non-plastic soils, whereby w and PI is the percentage of particle passing No 200 sieve expressed in decimal and the plasticity index expressed as percentage respectively. a, n, m are calculated using equations (3), (4) and (5).

$$a = 32.835\ \{\ln(wPI)\} + 32{,}438 \tag{3}$$

$$n = 1{,}421\ (wPI)^{-0.3185} \tag{4}$$

$$m = -0.2154\{\ln(wPI)\}+0.7145 \tag{5}$$

The SWCC used in this study presented in Figure 4.

The permeability function calculated using Fredlund et al. (1994) fitting equation integrated in SEEP/W based on the coefficient of saturated permeability and SWCC is shown in Figure 5a for soil 1 and Figure 5b for soil 2 (near surface soil). Soil 2 has the same properties as Soil 1, only the coefficient of saturated permeability is increased by one order of magnitude to account for heterogeneity of the near surface soil.

The extended Mohr-Coulomb shear strength envelope for unsaturated soils require that three shear strength parameters be defined namely, c', ϕ' and ϕ^b. The c' and ϕ' parameters can be measured using standard laboratory equipment on saturated soil specimen. However, conventional triaxial and direct shear equipment require modifications prior to their use for testing unsaturated soils i.e., to measure the ϕ^b. In this study, the shear strength of the unsaturated soil was estimated based on direct shear test on undisturbed samples collected on the site from depth of 2 m. The direct shear test resulted in the effective cohesion (c') of 5 kPa, effective internal friction angle (ϕ') of 21^o and rate of increase in internal friction angle with suction or ϕ^b = 2/3 ϕ' = 14^o (Gofar & Rahardjo, 2017).

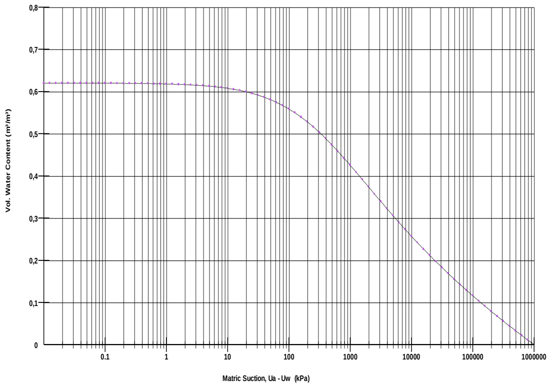


Figure 5 SWCC of soil forming the slope, estimated using Zapata (1999) equation

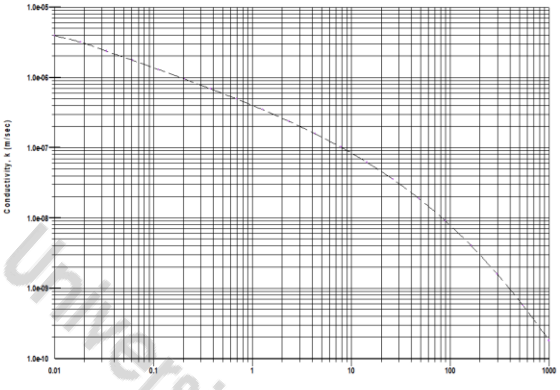


Figure 6 Permeability curve generated from SWCC and saturated coefficient of permeability using Fredlund and Xing equation

Rainfall Record

The rainfall data was collected from Pagar Alam PTPN VII Rainfall Station. Figure 6 presents the annual rainfall data from 1985 to 2021. The average annual rainfall recorded was 2767 mm with a standard deviation of 796 mm. The annual rainfall of more than 2000 mm is considered very high even in the tropical rainforest, thus rainfall induced slope failures and flash flood is normal occurrence in this area. The maximum daily rainfall is 219 mm/day occurred in 2001, and the maximum 5-day rainfall is 362 mm occurred also in 2001, while the maximum monthly rainfall is 861 mm in 2009.

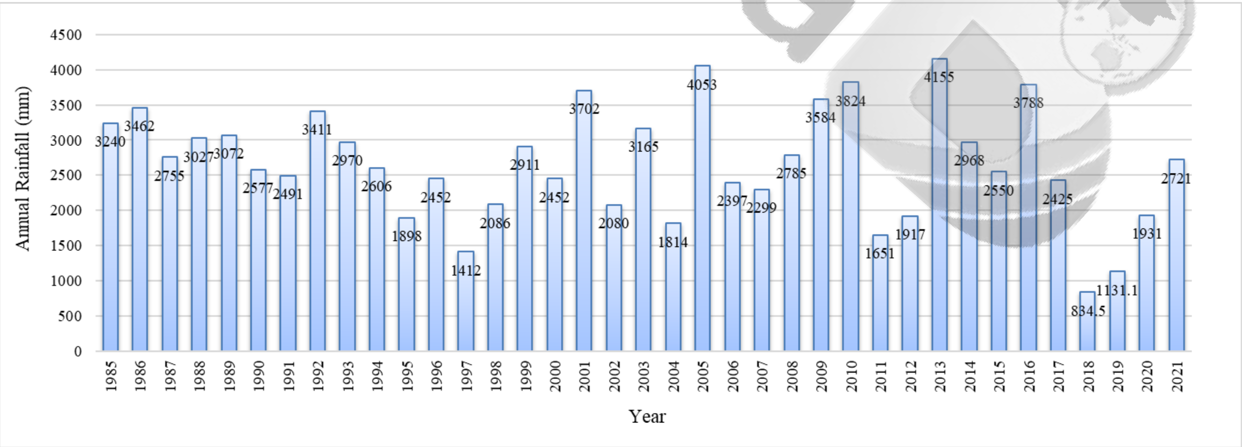
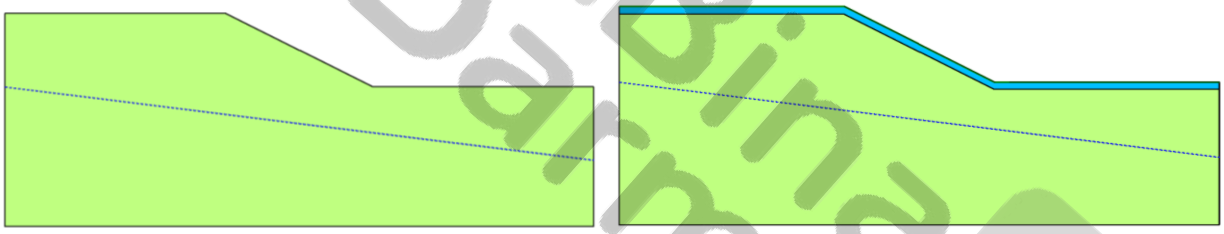


Figure 6 Annual rainfall in Pagar Alam

Based on this data, two rainfall scenarios were designed. The first scenario was the high intensity short duration rainfall of 220mm/day lasted for 10 hours. The second scenario was 861 mm of rain for 30 days resulting in a low intensity long duration rainfall of 1.17mm/ hour for 30 days. The third scenario is the combination of antecedent rainfall and major rainfall which was selected based on the results of scenario 2.

The analysis was carried out for 27^{o} slope angle in two conditions i.e., homogeneous soil and two layers of soil as shown in Figure 7a and 7b. The second condition considers the homogeneity in the near surface soil. The near surface soil (soil 2) is 1 m thick with the same soil properties as Soil 1 but higher coefficient of permeability. The saturated permeability was set as one order of magnitude higher that the rest of the soil.

Both conditions were analyzed for three cases by varying rainfall scenarios as shown in Table 2. The initial suction was set based on the position of the groundwater table. In the first case, rainfall with an intensity of 22mm/hr (6.1×10^{-6} m/sec) applied for 10 hours was used for the seepage analysis, while slope stability analysis was carried out at the interval of 1 hour from the start of rainfall application up to 1 day (24 hours). The second analysis is by applying rainfall of 1.17 mm/hr (3.24×10^{-7} m/sec) for 30 days, while slope stability analysis was carried out at the interval of 1 day from the start of rainfall application up to 1 month (30 days). The third analysis was aimed at evaluating the effect of antecedent rainfall. In this case, initial suction is created by applying rainfall of 1.17 mm/hr (3.24×10^{-7} m/sec) for seven days before applying heavy rainfall with intensity of 22mm/hr (6.1×10^{-6} m/sec) for 10 hr. The duration of low intensity rainfall was estimated based on the analysis in Scenario 2 and criteria for slope stability given in SNI 8460-2017 i.e., Factor of Safety ≥ 1.5.



(a) Homogeneous soil

(2) Layered soil considering heterogeneity

Figure 7 Soil condition used in the analysis

Table 2 Matrix of Analysis

			Rainfall scenario	
Case	**Slope angle**	**Soil**	**Antecedent rainfall**	**Major Rainfall**
1	27°	1 layer	No	22mm/hr applied for 10 hr
			1.17 mm/hr for 30 days	No
			1.17 mm/hr	22mm/hr applied for 10 hr
2	27°	2 layers Layer 1 with $k_{sat} = 4.5 \times 10^{-5}$ m/s	No	22mm/hr applied for 10 hr
			1.17 mm/hr for 30 days	No
			1.17 mm/hr	22mm/hr applied for 10 hr
3	27°	2 layers Layer 1 with $k_{sat} = 4.5 \times 10^{-4}$ m/s	No	22mm/hr applied for 10 hr
			1.17 mm/hr for 30 days	No
			1.17 mm/hr	22mm/hr applied for 10 hr

Numerical Modeling

Numerical modeling was carried out to investigate the factor of safety of the selected slope in Pagar Alam. The finite element analysis was conducted for transient seepage analysis using SEEP/W, followed by slope stability analysis using SLOPE/W at some designated times (Geoslope International, 2018). The present analytical approach conducts an assessment of the effect of heterogeneity in the near-surface soil by adopting a soil layer with higher permeability. Figure 8 shows the simplified model of the slope inclined at an angle of 27° and height of 10 m. Left and right boundary conditions were placed at three times the height of the slope. A hydrostatic initial condition was set based on the position of groundwater table as shown in the figure. The left and right edges above the water table were specified as no flow boundaries (Q=0), while the edges below the water table were assigned as head boundaries with pressure head equal to the vertical distance from the water table. These boundary conditions were necessary for enabling lateral flow to take place within the saturated zone. The bottom boundary located at 19 m from the ground surface at the toe and was assumed as an impermeable layer (no flow).

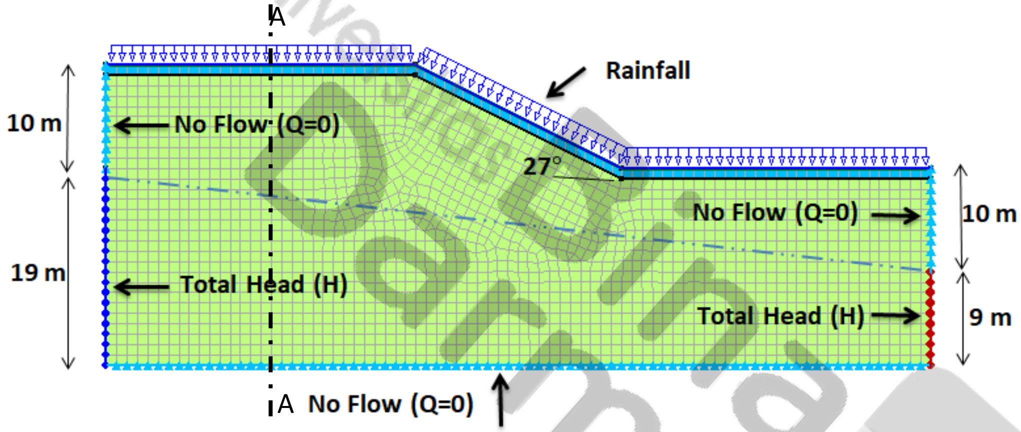


Figure 8 Slope model and boundary conditions for seepage analysis

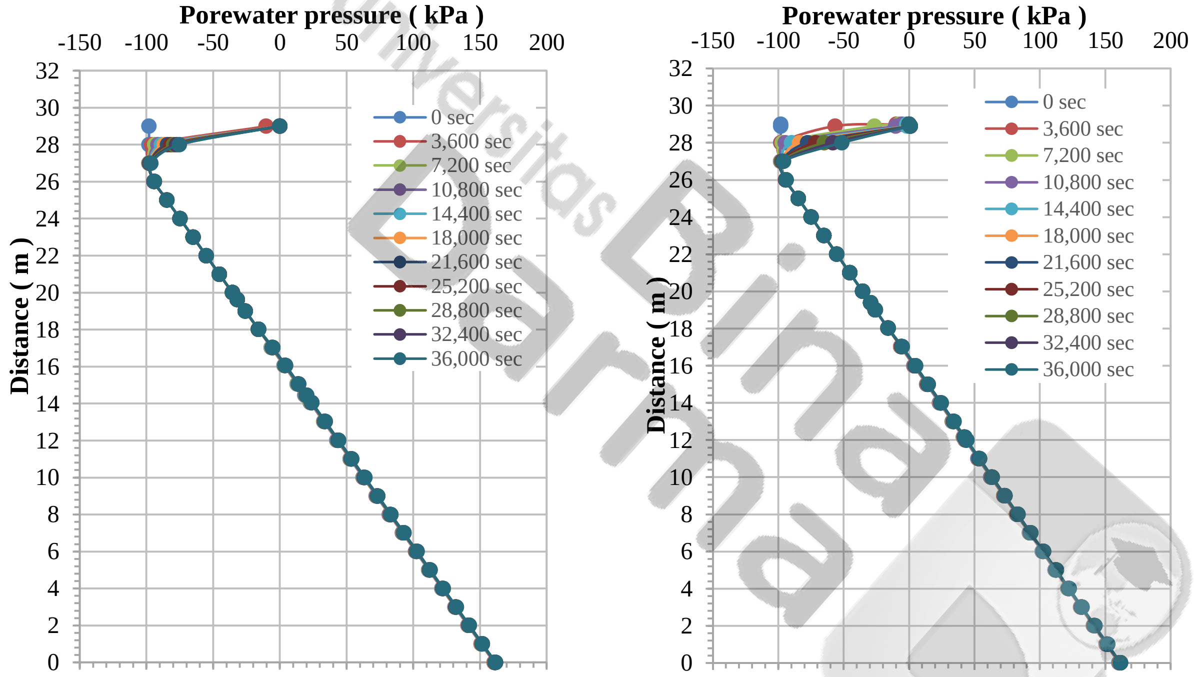
RESULTS AND DISCUSSION

Pore-water Pressure Distribution and Redistribution during and after Rainfall

The pore water pressure distribution is presented as a function of depth for cross-section A-A (Figure 8). Before rainfall (t = 0) the distribution of pore-water pressure is hydrostatic i.e., zero at the groundwater level. For this cross-section, the elevation of the groundwater level is 16m from the datum. Before rainfall, the suction at the surface is 100 kPa.

The pore water pressure distribution during major rainfall application in Scenario 1 is shown in Figure 9. It can be seen from Figure 9a that for Case 1, rainfall of 22 mm/hour for 10 hours only wets the soil surface until it is saturated at 10 hours but water does not infiltrate into the soil. Thus for scenario 1, rainfall did not cause slope failure as the initial suction is very high. The presence of a near-surface layer with higher permeability (Case 2) caused the water to infiltrate into soil 2 and was retained in this layer (Figure 9b).

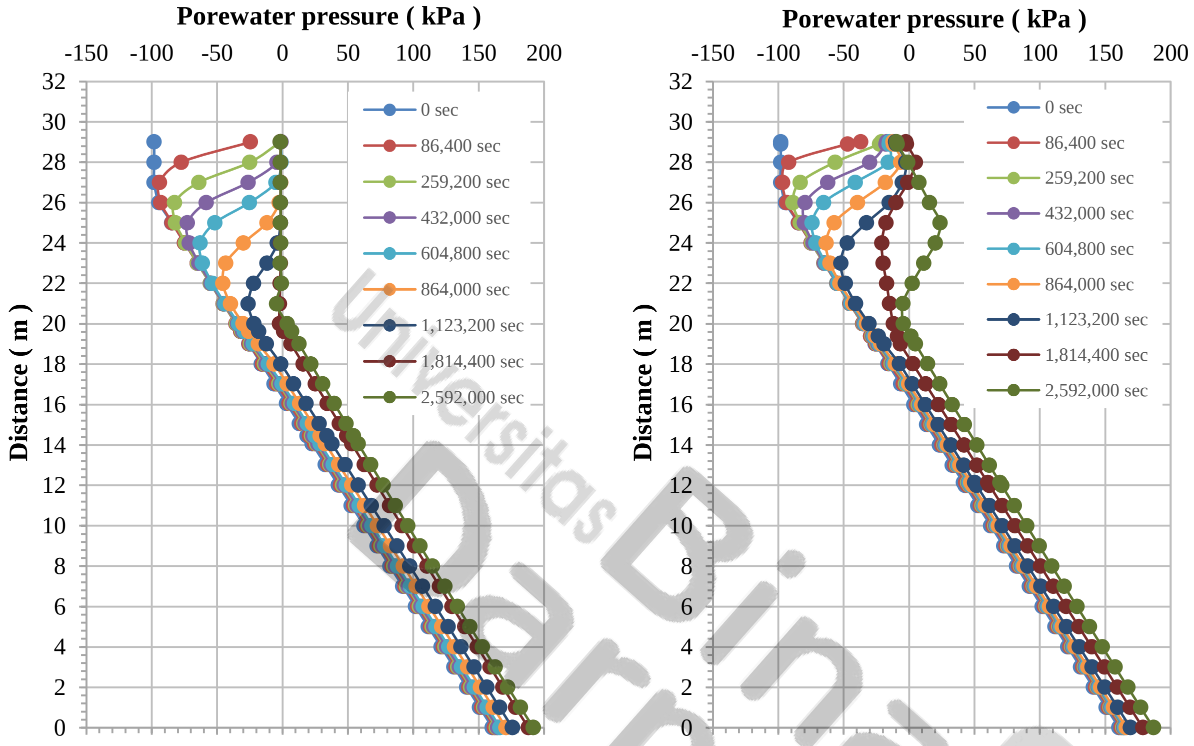
The pore water pressure distribution during the application of low-intensity long-duration rainfall in Scenario 2 is presented in Figure 10. Figure 10a shows that in Case 1, rainfall of 1.17 mm/hr for 30 days changed the pore water pressure distribution from days 1, 3, 5, 7, 10, 14, and 30. The rainfall wets the soil surface until it is saturated in 1 day, then water begins to infiltrate into the soil after 5 days of rain and continues to cause soil saturation until it reaches the groundwater table on the 10th day of rain. The groundwater table has raised to elevation 20 m at the end of rainfall (day 30). The presence of near surface layer with higher permeability (Case 2) speeds up the rainwater infiltration into the soil that the water reached groundwater level on day 6. Then the ground water table increases and saturates the soil near the surface (Figure 10b).



(a) Case 1 – 1 layer

(b) Case 2 – 2 layer

Figure 9 Pore water pressure distribution due to rain application in Scenario 1



(a) Case 1 – 1 layer (b) Case 2 – 2 layer

Figure 10 Pore water pressure distribution due to rain application in Scenario 2

Variations in factor of Safety in slope

The change in the factor of safety for rainfall scenario 1 is shown in Figure 11. It can be seen from the figure that the Factor of safety (FOS) decreases with the application of rainfall from 2.388 to 2.333. The FOS continued to decrease even after the rainfall stopped. Thus the rain with high intensity and short duration does not cause slope failure in this area where the soil forming the slope is CH. The presence of heterogeneity in the near-surface soil by increasing the saturated permeability by one order of magnitude, increases the factor of safety. The FOS decreased from 2.408 to 2.344 during the 10-hour rainfall. However, when the saturated permeability was increased by two orders of magnitude the factor of safety decreased significantly from 2.408 to 2.239. The most significant reduction of FOS was from 9 to 10 hours because at this point infiltration has reached the groundwater table.

The change in the factor of safety for rainfall scenario 2 is shown in Figure 12. It can be seen from the figure that the Factor of safety (FOS) decreases with the application of rainfall from 2.388 to 1.261 due to the low-intensity long-duration rainfall. The FOS continued to decrease even after the rainfall stopped. If the heterogenenity in the near-surface soil is modelled by the coefficient of saturated permeability one order of magnitude higher, the factor of safety decreased from 2.408 to 1.402, which is slightly higher than the factor of safety for one layer. Further increase in the coefficient of saturated permeability caused a further increasin FOS. . Thus rain with low-intensity and long-duration can cause slope failure in this area where the soil forming the slope is CH.

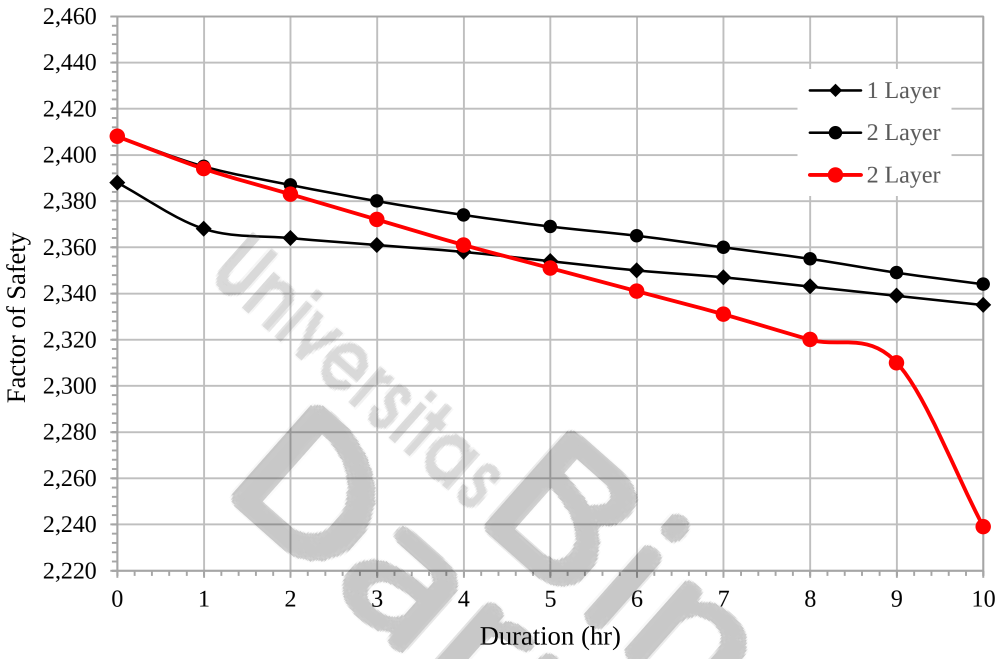


Figure 11: Change in safety factors of slope subjected to high-intensity short-duration rainfall

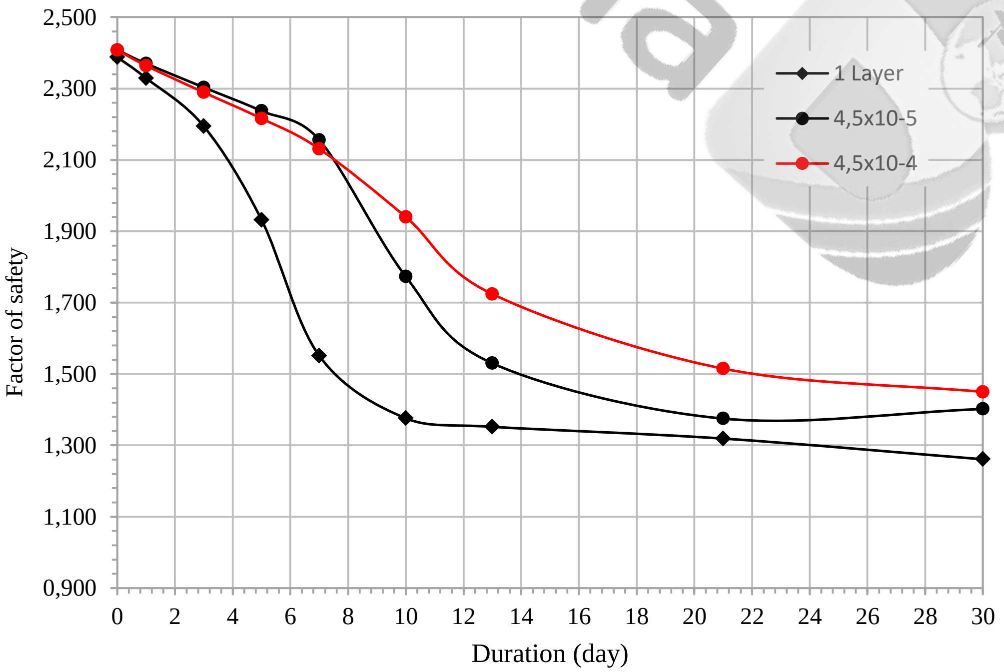


Figure 12: Change in safety factors of slope subjected to low-intensity long-duration rainfall

If according to SNI 8460-2017 we assume that the slope failed at FOS about 1.5, then the major rainfall cannot lead to slope failure. The lowest FOS (1.239) was obtained for Case 3 where the near-surface soil was modeled as a 1-m thick layer with a coefficient of saturated permeability two orders of magnitude higher than the original soil. However, the long-duration rainfall creates enough moisture to initiate a reduction in the shear strength of the soil and lead to slope failure. From Figure 12, we can see that for 1 – layer soil the FOS = 1.5 was reached after about 7 days of rainfall. The higher coefficient of saturated permeability in the near-surface layer by one order of magnitude increased the duration needed to reach FOS = 1.5 in 13 days while increasing the coefficient of saturated permeability by 2 orders of magnitude increased the FOS, thus FOS = 1.5 was reached only after 22 days of rainfall.

Figure 13 shows the effect of the combination of antecedent rainfall for 7 days and major rainfall for 10 hours on a slope modelled as 1 1 soil layer (rainfall scenario 3 on Case 1). The factor of safety decrease from 2.408 to 1.551 due to antecedent rainfall, than decreased further to 1.122 due to 10 hours of heavy rainfall. At this point the slope is considered fail.

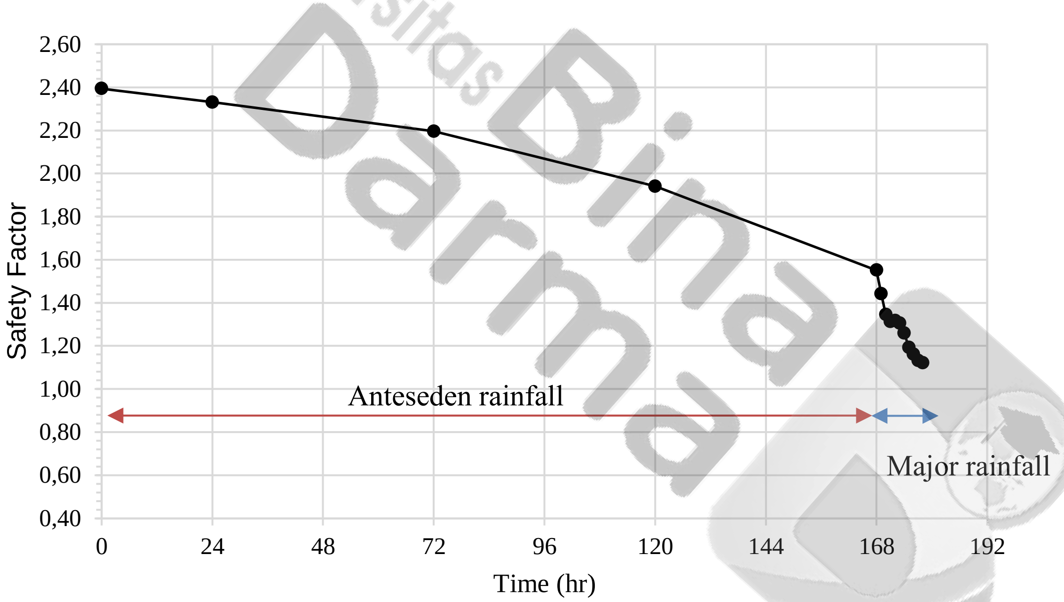


Figure 12: Change in safety factors for Case 1 slope subjected to rainfall scenario 3

Conclusions

This paper focuses on investigating the effect of near-surface soil heterogeneity on the transient pore water pressure induced by rainfall infiltration. The heterogeneity is assumed to have an effect on the permeability of the near-surface soil, thus; a higher permeability coefficient was used for the analysis. Numerical analyses of soil slopes were performed under different rainfall scenarios i.e., high-intensity short-duration, low-intensity, long-duration, and a combination of antecedent and major rainfall. SEEP/W program was used to evaluate the transient pore-water pressure distribution in the soil during and after the rainfall scenarios. Furthermore, the slope stability analysis was carried out at any time by the limit equilibrium method to evaluate the change in the factor of safety of the slope during and after rainfall. Based on the results obtained from the finite element analysis of transient water flow and slope stability, the following conclusions were drawn.:

1. Heavy rain that lasts for 10 hours does not cause landslides because the soil is still dry. The rainfall only wets the surface of the soil without seeping in. The lowest factor of safety (2.239) was obtained when the near-surface layer was modeled as a material with a coefficient of saturated permeability 4.5 x 10^{-4} (two orders of magnitude higher than the original soil)
2. Prolonged events with less intense rainfall critically reduce the stability of the slope. The factor of safety decreased from 2.408 to less than 1.5 for all cases. This reduction in the factor of safety is due to the increase in pore water pressure and reduction in matric suction which contributes toward the reduction in soil strength. The lowest factor of safety (1.261) was obtained for the case of 1 layer.
3. Non-uniformity of the surface soil (cracks, relics, plant roots) has an effect on changes in the pore water pressure in the soil due to seepage. Modeling of heterogeneities of near-surface soil by assuming a soil layer with higher permeability can effectively predict the pore water pressure distribution in soil. However, the effect on the safety factor is not conclusive especially when a higher coefficient of saturated permeability was used.
4. For the type of soil on Jalan Lematang Pagar Alam, namely CH (clay with high plasticity) the rain pattern with antecedents provides critical conditions because the antecedent rain causes the soil to become moist and the water absorption capacity becomes smaller, thus high intensity rain can cause landslides.

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Program Studi : MAGISTER TEKNIK SIPIL
Fakultas : TEKNIK
No. WA : 0821-8608-7914
Nama Pembimbing : PROF. IR. NURLY GOFAR., MSCE., PH.D.
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Menyatakan memang benar belum mendapatkan *Letter of Acceptance* (LoA) dan masih tahap *submit*/menunggu proses *review* dari pihak penerbit jurnal. Mengingat pendaftaran wisuda sedang berlangsung, untuk itu saya mohon dapat diizinkan mendaftar wisuda walaupun belum mendapatkan LoA, dengan konsekuensi tidak mendapatkan Transkrip Akademik saya. Saya secara sadar tidak akan menuntut Transkrip Akademik saya sebelum saya mendapatkan LoA dan mengumpulkan ke Pusat Pelayanan Mahasiswa (PPM).

Demikian surat pernyataan ini saya buat dengan sebenarnya untuk dipergunakan sebagaimana mestinya. Terima kasih.

Mengetahui,
Ketua Program Studi

Dr. Ir. Firdaus, ST, M.T, IPM

Palembang, 22 September 2023

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