MEDIA KOMUNIKASI TEKNIK SIPIL
Jurnal Ilmu dan Terapan Bidang Teknik Sipil
Website : mkts.sipil.undip.ac.id
e-ISSN : 2549 - 6778
doi:10.14710/mkts.v30i2.62372

Identification of Rainfall Scenario Triggering Slope Failures in Pagar Alam and its Surrounding Area

*Nurly Gofar[1], Yudi Harianto[1], Anggi Purnama Sari Dewi[2]
[1] Prodi S2 Teknik Sipil, Program Pascasarjana, Universitas Bina Darma, Palembang
[2]Prodi Teknik Sipil, Fakultas Sains dan Teknologi, Universitas Bina Darma, Palembang
*)nurly_gofar@binadarma.ac.id

Received: 28 Februari 2024 Revised: 28 Februari 2025 Accepted: 11 Maret 2025

Abstract

Pagar Alam and its surrounding area are located in the Bukit Barisan Mountain Rang, thus, the topography is hilly and mountainous. National Road segments passing the area often experience slope failure, which causes distraction to the transportation of people and goods. Past observations showed that slope failures are related to frequent and prolonged rainfall. This paper presents the results of a numerical study on the mechanism of rainfall-induced slope failures in Pagar Alam. The study aimed to identify the critical rainfall scenario triggering slope failures. Data observation indicates that even though wet season started in October, most slope failures occurred between January and April. Thus, initial moisture is required to start the mechanism of failure. The transient pore-water pressure was assessed using SEEP/W while the slope stability was evaluated using Slope/W. The analysis showed that the critical rainfall scenario is a combination of antecedent and major rainfall. The duration of the antecedent rainfall is influenced by the slope angle.

Keywords: *Bukit Barisan, rainfall, porewater pressure, seepage, slope failures*

Abstrak

Kota Pagar Alam dan daerah sekitarnya terletak di Pegunungan Bukit Barisan, sehingga topografinya dicirikan oleh perbukitan dan pegunungan. Ruas Jalan Nasional yang melewati daerah tersebut sering mengalami kelongsoran lereng, yang menyebabkan gangguan pada transportasi orang dan barang. Pengamatan sebelumnya menunjukkan bahwa kelongsoran lereng terkait dengan curah hujan yang sering dan berkepanjangan. Makalah ini menyajikan hasil studi tentang mekanisme kelongsoran lereng yang disebabkan oleh curah hujan di Pagar Alam. Studi ini bertujuan untuk mengidentifikasi skenario curah hujan kritis yang memicu kelongsoran lereng. Pengamatan data menunjukkan bahwa sebagian besar kelongsoran lereng terjadi pada bulan Januari hingga April sementara musim hujan dimulai pada bulan Oktober. Dengan demikian, kelembaban awal diperlukan untuk memulai mekanisme kelongsoran. Tekanan air pori transien dan stabilitas lereng dinilai menggunakan program Seep/W dan Slope/W. Analisis numerik menunjukkan bahwa skenario curah hujan kritis adalah kombinasi dari curah hujan anteseden dan curah hujan mayor. Durasi curah hujan anteseden dipengaruhi oleh sudut lereng.

Kata kunci: *Bukit Barisan, curah hujan, tekanan air pori, rembesan, longsor*

Introduction

Pagar Alam is located near Bukit Barisan mountain range in Sumatra; therefore, hills and mountains characterize the topography. The city is known for its picturesque landscapes, cool climate, and natural beauty. It is the closest city to Gunung Dempo, the highest mountain in South Sumatra. Gunung Dempo, soaring high at 3.142 m, located at 04°02″ South Latitude and 103°008″ East Longitude, is a strato-type volcanic mountain. The main rock component is derived from lava, which is covered by pyroclastic (Erlangga et al., 2024). The soil in this area is of volcanic type with high fertility. Hence, Pagar Alam City Region is known as a producer of vegetables and fruits and one of the biggest Agribusiness Sub-terminals in South Sumatra Province (RPJMD Sumsel, 2019). Thus, road infrastructure is important to transport the produce from Pagar Alam to market.

Pagar Alam is recognized by its beautiful landscape and as a producer of vegetables and fruits. However, it is known for slope failure occurrences, which are often triggered by factors like heavy rainfall, geological conditions, deforestation, land-use changes, lack of drainage, poor construction practices, rainfall, and earthquakes. Slope failures include landslides, mudslides, and rockfalls, usually followed by flash floods, causing significant impacts on traffic disturbance along roads. The closing of the road after the slope failure needs to be handled as soon as possible to maintain the smooth flow of transportation and trade.

Previous studies suggested that rainfall is a significant contributing factor to failures slopes formed by residual soil with deep groundwater tables (Rahardjo et al., 2001). In this case, rainwater infiltrates into the unsaturated soil above the groundwater table resulting in the increase of pore water pressure. The reduction in soil shear strength resulting from the increase of pore-water pressure can result in slope failure (Gofar & Lee, 2008). Extensive research on unsaturated soil and rainfall-induced slope failures is carried out in Singapore. Rahardjo et al. (2001, 2020) concluded that the initial conditions (*antecedent rainfall*) are very decisive in the occurrence of landslides in locations where the slope-forming soil is clay. Rahardjo et al. (2001) stated that the delayed rainfall pattern is the worst rainfall pattern for soil conditions in Singapore. 5-day antecedent rainfall is needed to acquire the initial suction to trigger slope instability.

Based on their research in Peninsular Malaysia, Gofar et al. (2015) concluded that the effect of rain on slope stability is determined by the type of soil forming the slope. Generally, coarse-grained soils are identified by high permeability and lack of ability to retain water. Thus, the negative pore water pressure in coarse-grained soils is low because the low suction does not cause changes in soil volume that affect the soil thrust. Under these circumstances, the influence of rainfall infiltration on the slope stability of coarse-grained soils may be insignificant. In contrast, fine-grained soils are characterized by low permeability and high ability to absorb water. Even though the rate is slow, the absorption force variation variation can be very significant due to the large difference in suction between dry and wet conditions. The presence of water in the soil increases the driving force and decreases the soil’s strength, therefore causing slope instability.

The most important properties of unsaturated soil are the soil-water characteristic curve (SWCC), permeability function, and rate of increase in shear strength of unsaturated soil due to suction. Laboratory tests required to obtain the SWCC are usually expensive and time-consuming; therefore, several mathematical descriptions were proposed for estimating the SWCC parameters based on particle size distribution and soil plasticity. For example, the estimation method by Fredlund et al. (2002) and Perera et al. (2005) fits the curve. The statistical method proposed by Childs & Collis-George, as presented in Satyanaga et al. (2017), was used to predict the permeability function based on the coefficient of saturated permeability and SWCC. The shear strength of unsaturated soil is usually higher than the strength of saturated soil, thus increase in strength due to suction can be estimated as ½ to 2/3 of effective shear strength parameters (Gofar and Rahardjo, 2017).

Another controlling facto in rainfall induced slope instability is the rainfall pattern. The rainfall pattern can be a combination of antecedent rainfall and major storms based on a statistical analysis of past rainfall. Research on the effect of rain patterns on slope stability has also been carried out by Rahimi et al. (2011) and Muntohar et al. (2013). They concluded that the delayed rainfall pattern is the worst condition that provides the lowest safety factor. The delayed pattern is a pattern where rain with low intensity precedes rain with higher intensity. However, as discussed by Gofar et al. (2015), the critical rainfall pattern is also affected by the type of soil.

Other contributing factors to rainfall-induced slope instability are slope geometry and surface condition, The effect of slope geometry was studied by Apriansyah & Gofar (2022) using SLOPE/W (Geoslope Intl., 2018b). They concluded that the slope height and inclination have the same effect on the stability of the slope. Gallage et al. (2021) used an instrumented slope model to study the influence of slope gradients on slope stability. such as slope geometry and soil type, could also determine the most critical rain pattern. The effect of surface condition was studied by Gofar et al. (2024). They concluded that the presence of non uniformity on slope surface speeds up water infiltration into soil and affect transient pore water pressure distribution. However, the effect on Factor of safety is inconclusive.

Numerical modeling has been used extensively to analyze slope stability and the effect of stabilization methods on slope stability (e.g. Wahab et al. 2023 and Kurnia et al. 2023). Numerical analysis of the slope model confirms that slope inclination influences the slope's vulnerability to rainfall infiltration. Furthermore, research by Sharipov et al. (2023) revealed that the influence of slope angle on the safety factor after rain is lower for higher slopes.

Not many research works on rainfall-induced slope failure were carried out in the Bukit Barisan area. Wilopo & Fathani (2021) studied the cause of the slide that occurred in Bukit Barisan (Beriti Hill). The field studies show that antecedent rain contributes more as a trigger for slope failure than earthquakes. The cumulative rain before the failure was 355.21 mm. Research by Darajaat et al. (2020) carried out on the Bukit Barisan route (Liwa – Kemuning) showed that rainfall effect on slope stability is more significant on slopes formed by soils with higher permeability, even though the soil types are the same.

Previous research conducted in Jalan Lematang Pagar Alam by Aisah & Gofar (2022) shows that using conventional analysis (simplified Bishop method), the slope is in critical condition with an average factor of safety of 1.2. However, assuming unsaturated conditions using the PERISI model (Gofar & Lee, 2011), the slopes are in a stable condition. However, prolonged rainfall significantly increased the pore-water pressure in slopes up to 5 m depth, reducing the soil's shear strength and decreasing the slope stability. The preceeding discussions reveal that the effect of rainfall on slope stability is controlled by the geometry of the slope itself, the nature of the soil, and the rainfall pattern.

This paper presents the results of a study on the mechanism of slope failures in Pagar Alam and its surrounding area. The study aimed to identify the critical rainfall scenario triggering slope failures, considering the various slope angles along Jalan Lematang in Pagar Alam. Three types of rainfall were used in the analysis, i.e. high-intensity short-duration rainfall and low-intensity long-duration rainfall, and the combination of the long-duration low-intensity and major rain with high intensity. Angles (27^o, 33^o, 39^o, 45^o, and 53^o) were chosen for seepage anlysis using SEEP/W and stability analysis using SLOPE/W software integrated in the Geostudio program (Geoslope International, 2018).

Methodology

The study uses a numerical analysis of a slope representing typical geometry and the characteristics of soil in Pagar Alam. Data was collected at six points at an interval of 50 m along Jalan Lematang (coordinate: 4°4'23" S and 103°19'26" E). This slope is part of the road segment no 15-037 i.e., Simpang Air Dingin – Pagaralam. Figure 1 shows the slope at the location.

The geometry of the slope, measured using a global positioning system (GPS), shows that the slope angle varies between 21° and 60° while the slope's height is between 10 and 30 m. The slope angle on the overall slope is obtained by drawing a line from the lower limit (toe) of the lowest level to the upper limit (crest) of the highest level. By visual identification, the soil forming the slope can be classified as clay.

Figure 1. The slope at Jalan Lematang, Pagar Alam

Disturbed and Undisturbed soil samples were retrieved from the study location and brought to the laboratory to determine index properties, grain size distribution, Atterberg limits, the coefficient of saturated permeability, and the shear strength parameters. In this study, a direct shear test was carried out to obtain the shear strength parameters of the soil, All laboratory tests were performed following relevant ASTM Standards.

The SWCC describes the correlation between the water content and the suction of unsaturated soil Satyanaga et al. (2017). In this study, Zapata method, as presented in Perera et al. (2005), was adopted to determine the SWCC based on the percent particles passing No. 200 sieve and the plasticity index of the soil. The statistical method proposed by Childs & Collis-George, as presented in Satyanaga et al. (2017), was used to predict the permeability function based on the coefficient of saturated permeability and SWCC. Similarly, empirical methods could be used to estimate the shear strength parameter of the unsaturated soil. while the unsaturated shear strength properties were estimated as $\phi^b = 2/3\ \phi'$ (Gofar & Rahardjo, 2017).

Rainfall data was collected from PTPN VII Rainfall Station in Pagar Alam from 1985 to 2020. The distance between the rain station and the research location is 18 km or less than the maximum distance between the rainfall recording station and the review site, which is 20 km (Gofar & Lee, 2008). From this rainfall data, an intensity duration frequency (IDF) curve was constructed using the Gumbel method and was used in seepage and slope stability analysis.

Upon determination of the soil characteristics, the effect of rainfall on slope stability can be evaluated using numerical analyses via computer programs. The seepage analysis was performed using SEEP/W and stability analysis was assessed using SLOPE/W integrated in GEOSTUDIO (Geoslope Intl. 2018 a and b). The analysis was carried out for three cases. In the first case, the slope is subjected to high-intensity rainfall. The initial suction was set based on the groundwater table position. The second analysis was aimed at evaluating the effect of antecedent rainfall. In this case, low-intensity rainfall was applied for a long time to create initial moisture. The third analysis was aimed at investigating the actual scenario for slope instability by identifying the results of analysis on scenario 2 in terms of the duration of antecedent rainfall causing the slope to reach critical condition before applying the major rainfall.

Numerical Modelling

Slope geometry and boundary conditions

The slope geometry adopted in this study is 10 m high with inclination angles of 27°, 33°, 39°, 45°, and 53°. Figure 2 shows the geometry of the 27° slope with relevant boundary conditions for seepage analysis using SEEP/W and slope stability analysis using SLOPE/W.

The groundwater table is specified at 4 m below the base of the slope. The left, right, and bottom boundary conditions are set at 3 times the slope's height. The initial suction was determined based on the position of the groundwater table. Rain is applied on the slope as a flux boundary. The mesh used for seepage analysis for a slope angle of 27° is shown in Figure 3. The transient pore water pressure along the depth of the slope is analyzed on cross-section A-A.

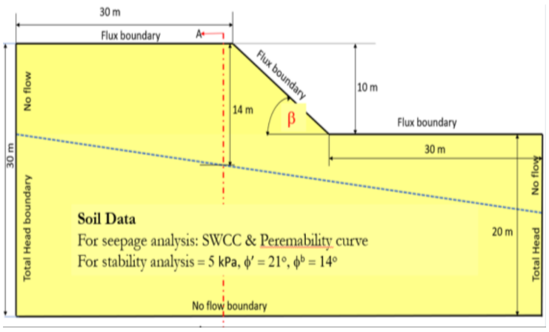

Figure 2. Geometry and boundary conditions of the 27° slope

Soil properties

The soil's properties are summarized in Table 1, while the grain size distribution is presented in Figure 4. Results of laboratory tests show that the soil obtained in this location is classified as high-plasticity clay (CH). From Table 1, the soil contains more than 56.39% fines, 26.39% silt, and 20% clay. The liquid limit was 49.40%, while the plasticity index of the soil was 27.13%. The coefficient of saturated permeability of the soil is 4.5×10^{-6} m/s.

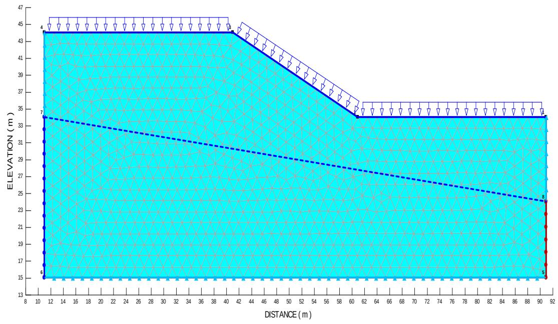

Figure 3. Finite element mesh for seepage analysis for the 27° slope

Table 1. Soil properties

Properties	**Unit**	
Specific gravity (G_s)		2,62
Porosity (n)		0.62
Saturated coefficient of permeability	m/sec	$4,5 \times 10^{-6}$
Sieve Analysis		
Passing No 200 sieve	%	56,39
Clay	%	20%
Atterberg Limits		
Liquid Limit	%	49,4
Plasticity Index	%	27.13
Soil Classification		CH
Shear strength parameters		
Cohesion c'	kPa	5
Internal friction angle f'	o	21
Rate of increase in shear strength due to suction f_b'	o	14

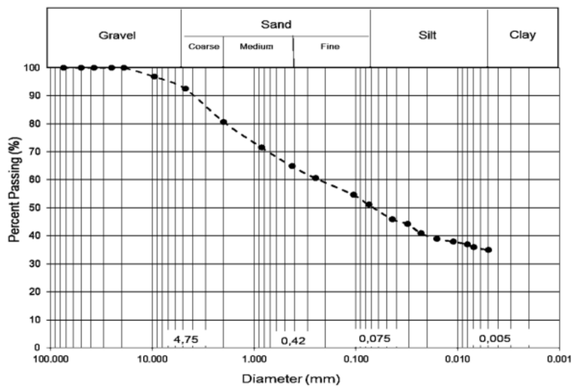

Figure 4. Grain size distribution of the soil

The SWCC of the soil was estimated using Zapata equation as shown in in Figure 5. The permeability function was calculated using the Fredlund and Xing fitting equation integrated in SEEP/W as shown in Figure 6. The shear strength was estimated based on a direct shear test on undisturbed samples collected on the site from a 2 m depth. As shown in Table 1, the direct shear test resulted in the effective cohesion (*c'*) of 5 kPa and effective internal friction angle (ϕ') of 21°. The rate of increase in internal friction angle with suction or ϕ_b is estimated as (2/3 ϕ') = 14°.

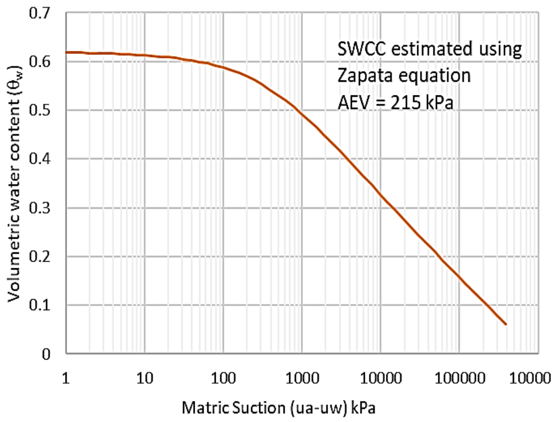

Figure 5. SWCC of soil, estimated using Zapata equation

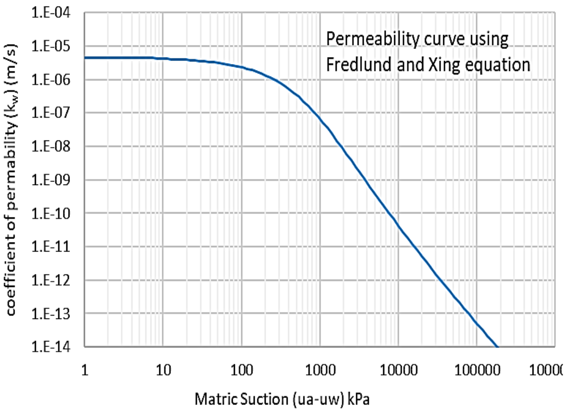

Figure 6. Permeability curve generated from SWCC and saturated coefficient of permeability using Fredlund and Xing equation

Intensity-duration frequency (IDF) curve

The 10-year return period Intensity Duration Frequency (IDF) function was constructed using the Gumbel method based on 1985 – 2020 data from the Rainfall station in Pagar Alam. The curve is shown in Figure 7. It can be seen from the figure that as compared to other locations such as the Malaysian Peninsular (Gofar & Lee, 2008), the rainfall in this area is quite high even for the return period of 10 years. The analysis was carried out for three cases by varying rainfall scenarios, as shown in Table 2. The first scenario represents heavy rainfall. A rainfall with an intensity of 22 mm/hr (6.1×10^{-6} m/sec) was applied for 10 hr. was used for the seepage analysis. In this case, slope stability analysis was carried out at the interval of 1 hr since the start of rainfall application up to 1 day (24 hours).

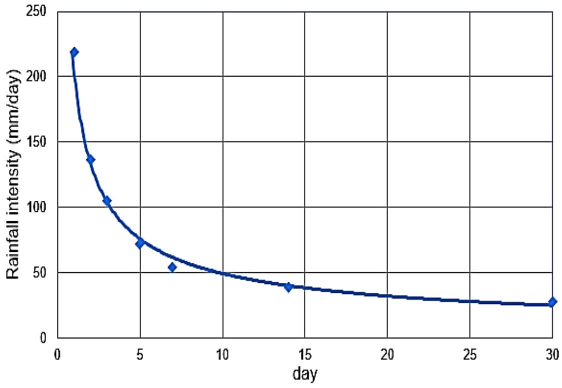

Figure 7. The 10-year Return Period IDF curve for seepage analysis

The second scenario represents a light rain. A rainfall of 1.17 mm/hr (3.24×10^{-7} m/sec) was applied for 30 days. 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 scenario was aimed at evaluating the effect of antecedent rainfall. Initial suction is created by applying rainfall of 1.17 mm/hr (3.24×10^{-7} m/sec) for a certain time before applying heavy rainfall with an intensity of 22 mm/hr (6.1×10^{-6} m/sec) until failure. The duration of low-intensity rainfall was estimated based on the results of scenario 2. The criteria for slope stability given in SNI 8460-2017 (Badan Standarisasi Nasional, 2017), i.e., a Factor of Safety greater than 1.5.

Table 2. Matrix of analysis

Scenario	Slope angle (°)	Antecedent rainfall	Major rainfall
1	27 33	no	22mm/hr applied for 10 hr
2	39 45	1.17 mm/hr for 30 days	no
3	53	1.17 mm/hr for ?? days*)	22mm/hr applied for 10 hr

Notes *) The number of days was determined from the results of scenario 2 (different for each slope angle)

Results and Discussion

The pore water pressure distribution along the cross-section A-A is shown in Figure 2. In this paper, the pore water pressure distributions are illustrated for the 27° slope only. However, the results for all slope angles are presented for all slope angles.

Rainfall Scenario 1

Figure 8 shows the pore-water pressure distribution for slope angle 27° subjected to rainfall in Scenario-1. Figure 8 shows that the heavy rain of 22 mm/hour only wets the soil surface until it is saturated at 10 hours, but water does not infiltrate into the soil, so it does not affect soil strength. Analysis performed for other slope angles shows a lower initial factor of safety due to geometry. However, the effect of rainfall on the stability is minimal for all slope angles.

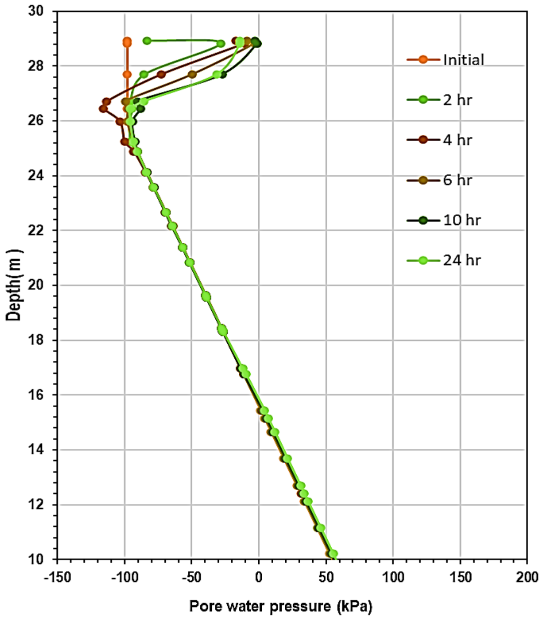

Figure 8. Pore water pressure distribution due to heavy rainfall in Scenario 1 for slope angle 27°.

Figure 9 shows the effect of heavy rainfall on slopes for various slope angles. Observation of Figure 9 indicates that no failure was observed even for a slope angle of 53°. The effect of rainfall is slightly greater for a greater slope angle.

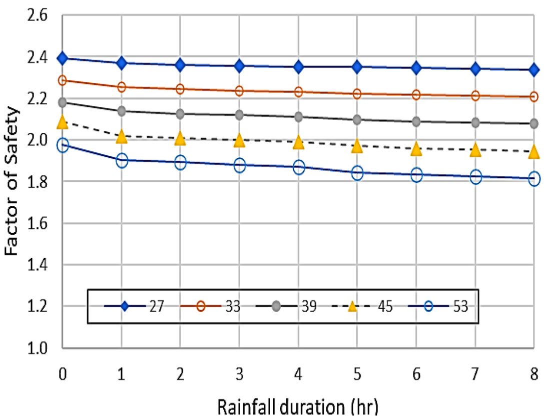

Figure 9. Variation of factor of safety with rainfall duration (Scenario 1)

Rainfall Scenario 2

Figure 10 shows the porewater pressure distribution for slope angle 27° subjected to rainfall in Scenario-2. Figure 10 indicates that the long-duration light rain wets the surface and infiltrates into the soil, decreasing the soil resistance and thus affecting the slope stability. The effect decreases as the duration of rainfall increases. The change in the slope stability with rainfall duration (days) for different slope angles is presented in Figure 11.

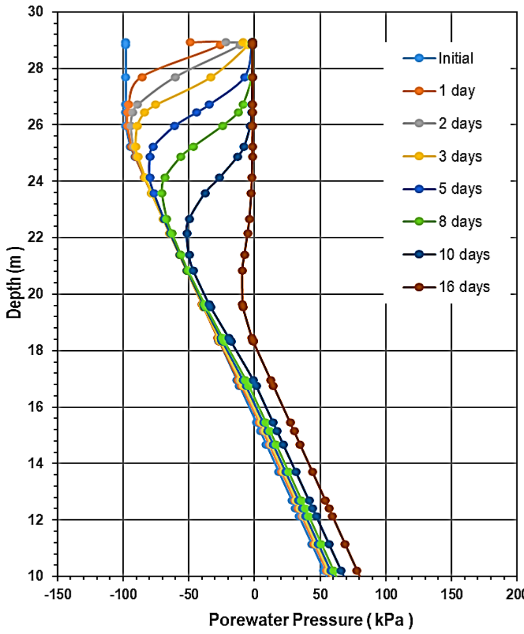

Figure 10. Pore water pressure distribution due to light rain in Scenario 2 for slope angle 27°.

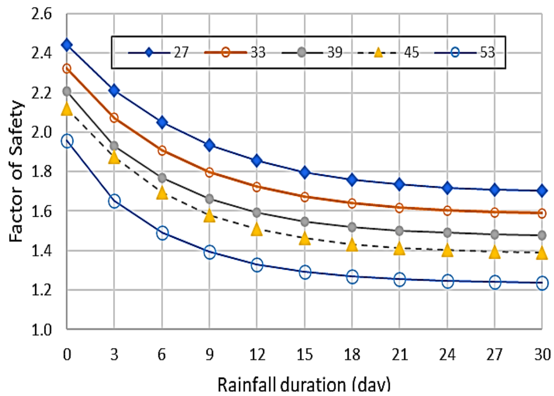

Figure 11. Variation of factor of safety with rainfall duration (Scenario 2)

Observation of Figure 8 and Figure 10 indicates that low-intensity rainfall has a bigger influence on slope stability because all rainwater infiltrates into the soil (rainfall intensity less than the coefficient of permeability of soil), thus decreasing the soil resistance and affecting the slope stability. The effect decreases as the duration of rainfall increases.

From scenarios 1 and 2, it was found that the slope failure at Pagar Alam is unlikely to occur due to heavy rainfall without the initial moisture that lowers the suction at the surface. Thus, scenario 3 was considered with the application of 1.17 mm/hr, followed by 22 mm/hr for 10 hours. The low-intensity rainfall application was needed to create the initial suction to model the actual initial moisture on the ground surface. The duration of the light rain is estimated based on the plot of the factor of safety against rainfall duration obtained in scenario 2. The criteria of slope stability according to SNI 8460-2017 (i.e., FS ≥ 1.5) was used.

Rainfall Scenario 3

Analysis using rainfall scenario 3 was performed for slope angles 27° and 39°. Pore-water pressure distribution along the cross-section A-A due to the application of rainfall in Scenario 3 for a slope angle of 27° is shown in Figure 12.

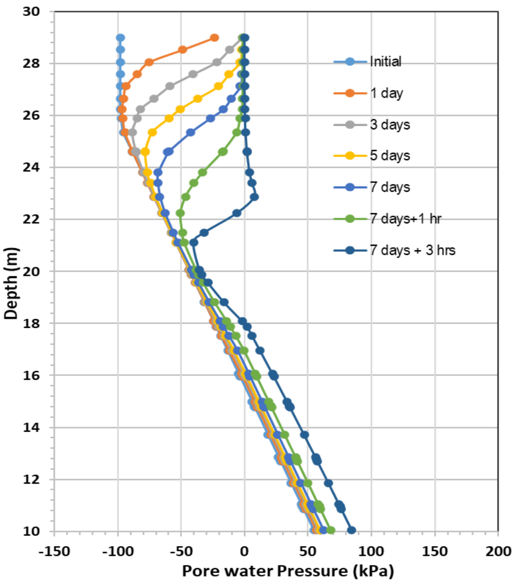

Figure 12. Pore water pressure distribution due to rain application in Scenario 3 for slope angle 27°.

From Figure 12, the 1.17 mm/hr rainwater infiltrates into the ground, causing the groundwater level to rise slightly on day 7. Consequently, the factor of safety dropped from 2.400 to 1.551 after seven days of low-intensity rainfall. The following heavy rainfall caused puddles on the ground surface but quickly seeped back, and the safety factor dropped to 1.192 after 10 hours of heavy rain. In this case, slope failure is considered to have occurred.

Figure 13 presents the change in the slope stability due to the application of rainfall in Scenario 3 for slope angles 27° and 39°. For the slope angle of 39°, the 1.17 mm/hr rainwater seeps into the soil, causing a decrease in the safety factor from 2.181 to 1.429 on day 5. The subsequent heavy rainfall caused the reduction of the safety factor to 1.009 in 9 hours.

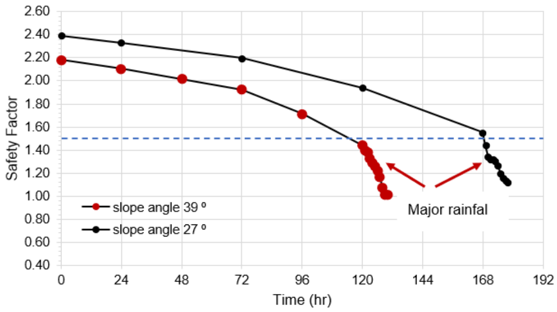

Figure 13. Change in factor of safety due to rain application in Scenario 3 for 27° and 39° slopes

Field observation

Most slope failures in Pagar Alam occur in the early morning after a heavy rainfall that lasts for the night. For example, a slope failure at Desa Terkul on 5th January 2020 occurred at 04:00 AM after heavy rainfall for about 10 hours, causing the closing of the main road between Lahat and Pagar Alam for 9 hours and one fatality. Data shows that the rainfall on the day of rainfall was 18 mm, while the cumulative 5-day rainfall before slope failure was 136 mm, and the cumulative 30-day rainfall was 331 mm. Therefore, the local community and government have identified rainfall as the main cause of slope failure in those locations.

The regional disaster management agency (BPBD) Pagar Alam recorded 113 slope failure occurrences in the last 10 years (2013 – 2022). There is no trend regarding the time of failure. However, most slope failures occurred in January to April (60%) (Figure 14), while the rainy season starts in October. Figure 15 shows the average monthly rainfall intensity, while Figure 16 shows the number of days with rainfall. Based on data collected at the rainfall station in Pagar Alam from 1985 to 2020, the average annual rainfall in Pagar Alam is 2528 mm, while the maximum monthly rainfall in January is 317 mm.

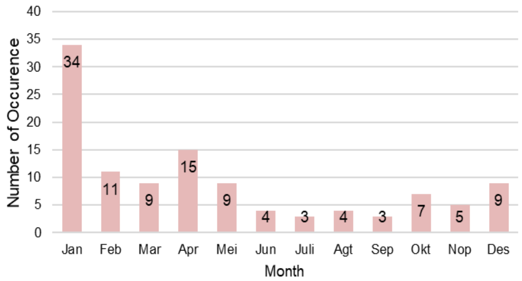

Figure 14. Number of slope failures in Pagar Alam according to month

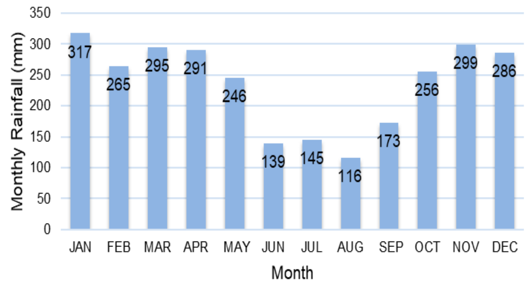

Figure 15. Monthly rainfall in Pagar Alam (intensity)

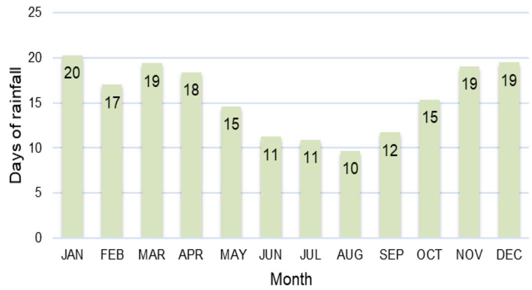

Figure 16. Monthly rainfall in Pagar Alam (number of days)

Discussion

The results of the numerical study on three rainfall scenarios suggested that Scenario 3 is the most critical for the slope in Pagar Alam. This agrees with the previous study that for slopes formed by CH soil, the most critical condition is a delayed pattern, i.e., light rainfall followed by heavy rainfall. This finding is also supported by the fact that most slope failures occurred in January to April, while the rainy season started in October. Thus, initial moisture was required to trigger the mechanism of slope failure.

The numerical study also indicates that the duration of antecedent rainfall to create initial moisture varies with the slope angle. The steeper the slope, the shorter the duration. The total amount of rainfall causing slope failure also depends on the slope angle. The steeper the slope, the less amount of rainfall is required to cause slope failure.

The amount of rainfall causing the failure in the 27^o and 39^o slopes was 416.55 mm and 338.40 mm, respectively. This is similar to the study by Darajat et al. (2020) in Beriti Hill Bukit Barisan, which stated that the cumulative amount of rainfall causing failure in the site was 335.21 mm.

This result is also in accordance with the data obtained from the slope failure at Desa Terkul, whereby the combination of cumulative 30 days of rainfall before the slope failure and the major storm was 331 mm.

Conclusions

The study is conducted for a slope along Jalan Lematang, Pagar Alam, with coordinates 4'23.67"S -103°19'26.47"E. The slope being analysed has an inclination angle of 27^o, 33^o, 39^o, 45^o, and 53^o and a height of 10 m. The groundwater table is deep enough so that the slopes are in an unsaturated condition. Slope-forming soils can be classified as high-plasticity clay (CH). The following conclusions could be derived from this study:

Antecedent rainfall plays an important role in the initiation of slope failure in Pagar Alam area. This is consistent with the fact that most slope failures occurred in January to April, while the wet season started in October. The result of the analysis is in accordance with previous studies that for clayey soil, the critical condition for rainfall-induced instability is the low-intensity long duration rainfall.

The most critical condition of slope stability in Pagar Alam is the combination of antecedent and major rainfall. The duration of antecedent rainfall is influenced by the slope angle. The steeper the slope, the shorter the duration required to start the mechanism of slope failure. The cumulative amount of rainfall required to cause slope failure for the 39° slope angles is 338.40 mm. This is in agreement with the results of the previous study by Darajat et al. (2020) and the data obtained from the slope failure at Desa Terkul. Both slopes are located in Bukit Barisan.

This study did not consider the presence of cracks on the slope surface because, as shown in Figures 15 and 16, Pagar Alam experiences rainfall all year, even in the dry season from May to September, and a wet season from October to April. Thus, cracks may not be developed on the soil surface. The results of this study can contribute to local governments in planning slope failure mitigation and management.

Acknowledgement

The authors acknowledge Bina Darma University for the licensed software used in this study. The author also appreciates the assistance from BPJNSS and BPBD Pagar Alam City in procuring the data needed for this research.

References

Aisah, E., & Gofar, N. (2022). Studi Pengaruh Curah Hujan Terhadap Stabilitas Lereng

Menggunakan Program PERISI. *Jurnal Rekayasa Sipil*, 18(2), 133-147.

Apriansyah, A. & Gofar, N. (2022) Pengaruh Geometri terhadap Kestabilan Lereng. *Dinamika Teknik Sipil*. 15(2): 85-90

Badan Standarisasi Nasional (2017) *SNI 8460 Pedoman Perancangan Geoteknik.* Jakarta

Darajat, MR., Iqbal, P., Zakaria, Z., & Muslim, D. (2020) Pengaruh Intensitas dan Durasi Hujan terhadap Kestabilan Lereng Tanah Residual Vulkanik di Jalur Liwa-Kemuning, Lampung Barat. *Pajajaran Geosicence Journal*. 4(2) 181 – 190.

Erlangga, S., Bulkin, F. & Gofar, N. (2024) Mapping of Risk Levels and Types of Slope Failure in South Sumatra. *Rekayasa Sipil*. 18(1):66-71

Fredlund, M.D., Wilson, G.W., and Fredlund, D.D. (2002). Use of the grain-size distribution for estimation of the soil-water characteristic curve. *Canadian Geotechnical Journal* 39(5):1103-1117

Gallage, C., Tharindu, A., and Uchimura, T. (2021) Instrumented model slopes to investigate the effects of slope inclination on rainfall-induced landslides. *Soils and Foundations* 61:160–174

Geo-Slope International Ltd. (2018a). *SEEP/W Seepage Modelling*. Calgary, Canada

Geo-Slope International Ltd. (2018b) *SLOPE/W for Slope Stability Analysis*. Calgary, Canada

Gofar, N. Pangestika, E.N, Harianto, Y., Gumay, H., Satyanaga, A. (2024) Effect of Near-Surface Heterogeneities on the Pore-water Pressure Distribution and Slope Stability. SINERGI 8(2):27-336.

Gofar, N., & Rahardjo, H. (2017) Saturated and Unsaturated Stability Analysis of Slope Subjected to Rainfall Infiltration. *MATEC Web of Conferences* 101, 05004

Gofar N. Lee M.L., & Rahardjo, H. (2015). Field Monitoring of Suction Distribution in Coarse-Grained and Fine-Grained Residual Soil. *in Unsaturated Soil Mechanics, From Theory to Practice – Proceedings of the 6th AP-UNSAT2015* :679-683.

Gofar, N. & Lee M.L. (2008). Extreme Rainfall Characteristics for Surface Slope Stability in the Malaysian Peninsular. *GEORISK: Assessment & Management Risk for Engineering Systems & Geohazards*. 2 (2) 65-78.

Kurnia, P., Hamdhan, I.N., Tohari, A. (2023). Pemodelan Numerikal Kestabilan Lereng Galian Abutment Jembatan pada Ruas Jalan Tol Bogor – Ciawi – Sukabumi. *Media Komunikasi Teknik Sipil*. 29(2): 183-194.

Muntohar, A.S. Ikhsan, J. Liao, H.J. (2013) Influence of Rainfall Patterns on the Instability of Slopes. *Civil Engineering Dimension.* 15(2):120–128

Perera, Y. Y., Zapata, C. E., Houston, W. N., & Houston, S. L. (2005). Prediction of the Soil-Water Characteristic Curve Based on Grain-Size-Distribution and Index Properties. *Paper presented at the Geo-Frontiers Congress*.

Rahardjo, H., Li, X. W., Toll, D. G., and Leong, E. C. (2001). The effect of antecedent rainfall on slope stability. *Journal of Geotechnical and Geological Engineering.* 19:371-399.

Rahardjo, H., Nistor, MM., Gofar, N., Satyanaga, A., Qin, X. & Yee. SIC. (2020). Spatial distribution, variation and trend of five-day antecedent rainfall in Singapore, *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*. 14(3): 177 - 191.

Rahimi, A., Rahardjo, H., and Leong, E. C. (2011). Effect of Antecedent Rainfall Patterns on Rainfall Induced Slope Failure. *Journal of Geotechnical and Geoenvironmental Engineering*. 137(5):483-491.

Rencana Pembangunan Jangka Menengah Daerah (RPJMD) Provinsi Sumatera Selatan tahun 2019-2023. Palembang

Satyanaga, A., Zhai, Q., & Rahardjo, H. (2017). Estimation of Unimodal Water Characteristic Curve for Gap-graded Soil. *Soils and Foundations*, 57(5):789-801.

Wahab, D.A., Tohari, A., Hamdhan, I.N. (2023). Pemodelan Numerikal Kestabilan Lereng Batulempung (Studi Kasus Ruas Jalan Sumedang-Cirebon Km 68+750). *Media Komunikasi Teknik Sipil*. 29(2):173-182

Wilopo, W., & Fathani, T.F. (2021). The Mechanism of Landslide-Induced Debris Flow in Geothermal Area, Bukit Barisan Mountains of Sumatra, Indonesia, *Journal of Applied Engineering Science*, 19(3):688-697.