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SLOPE STABILITY ASSESSMENT UNDER THE EFFECT OF ANTECEDENT RAINFALL-A CASE STUDY AT TELUK BAHANG PENANG

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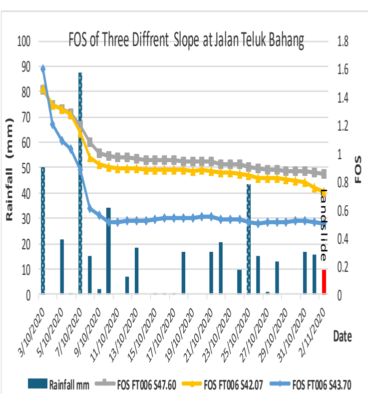
Graphical abstract



Abstract

Penang Island is one of the districts in Peninsular Malaysia that is highly subjected to frequent landslides. The selected study area is Jalan Teluk Bahang, located at Penang Island, Malaysia. This area has experienced a high frequency of shallow landslides in recent years. Jalan Teluk Bahang is a vital thoroughfare, connecting the city centre to Teluk Bahang. Understanding the annual rainfall pattern in Jalan Teluk Bahang area under different intensities and durations is crucial to establish a correlation between landslide events and rainfall infiltration. The study collected rainfall data for Jalan Teluk Bahang area from Department of Irrigation and Drainage Malaysia (JPS Malaysia). The slope was modelled for transient seepage and stability analysis based on geometrical information and soil parameters obtained from the subsurface investigation (SI) data. A transient numerical seepage analysis was conducted using SEEP/W software. The resulting pore-water pressure distributions were then utilised in SLOPE/W software for slope stability analysis. The analysis identified that, the prolonged low intensity of rainfall is a primary triggering factor for slope failure in the study area, with cumulative 30 days antecedent rainfall played a pivotal role. The integrated use of SEEP/W and SLOPE/W software facilitated a comprehensive understanding of the changing pore-water pressure conditions and the subsequent decrease in slope stability leading to landslides. This insight is supported by the gradual decrease in factor of safety (FOS) observed in the stability analysis leading up to landslide occurrences.

Keywords: Landslide, Penang Island, antecedent rainfall, slope stability, factor of safety

Abstrak

Pulau Pinang merupakan salah satu daerah di Semenanjung Malaysia yang sering mengalami kejadian tanah runtuh. Kawasan kajian yang dipilih ialah Jalan Teluk Bahang yang terletak di Pulau Pinang, Malaysia. Kawasan ini telah mengalami kekerapan tanah runtuh cetek yang tinggi sejak beberapa tahun kebelakangan ini. Jalan Teluk Bahang adalah jalan raya yang penting yang menghubungkan pusat bandar ke Teluk Bahang. Memahami corak hujan tahunan di kawasan Jalan Teluk Bahang di bawah intensiti dan tempoh yang berbeza adalah penting untuk mewujudkan korelasi antara kejadian tanah runtuh dan penyusupan hujan. Kajian ini mengumpul data hujan bagi kawasan Jalan Teluk Bahang daripada Jabatan Pengairan dan Saliran Malaysia (JPS Malaysia). Cerun telah dimodelkan untuk analisis resapan dan kestabilan berdasarkan maklumat geometri dan parameter tanah yang diperoleh daripada data penyiasatan tanah (SI). Analisis resapan berangka telah dijalankan menggunakan perisian SEEP/W. Pengagihan tekanan air liang yang terhasil kemudiannya digunakan dalam perisian SLOPE/W untuk analisis kestabilan cerun. Analisis mengenal pasti bahawa, intensiti hujan rendah yang berpanjangan merupakan faktor pencetus utama kegagalan cerun di kawasan kajian, dengan hujan kumulatif 30 hari anteseden memainkan peranan penting. Penggunaan bersepadu perisian SEEP/W dan SLOPE/W memudahkan pemahaman menyeluruh tentang perubahan keadaan tekanan air liang dan penurunan seterusnya dalam kestabilan cerun yang membawa kepada tanah runtuh. Pandangan ini disokong oleh penurunan beransur-ansur dalam faktor keselamatan (FOS) yang diperhatikan dalam analisis kestabilan yang membawa kepada kejadian tanah runtuh.

Kata kunci: Tanah runtuh, Pulau Pinang, hujan terdahulu, kestabilan cerun, faktor keselamatan

1.0 INTRODUCTION

Landslides have caused fatalities and economic damages in numerous countries globally, and the consequences continue to escalate. According to [1], more than 100 people lost their lives as a result of the approximately 28 landslide events that were documented in Malaysia between the years 1993 and 2011. In addition, several major landslide events have been reported in recent years in Malaysia such as Tanjong Bungah landslide on 21 October 2017 and landslide at Bukit Kukus Penang Island on 18 October 2018 that caused 14 and 12 casualties respectively [2]. [3] state that 31 were killed due to the Jalan Batang Kali-Jalan Genting Highlands landslide on 16 December 2022. Penang Island is one of the districts in Peninsular Malaysia that is highly subjected to frequent landslides. Landslides at Penang Island frequently occured in the mountainous terrain located at the centre of the island [4, 5]. Penang Island subjected to tropical climate where it receives high monthly rainfall all year around which become the main factor triggering the landslide at this area.

Rainfall-induced landslides refer to the event triggered by excessive rainfall that affects the slope's stability. [6] explained that the soil pore water pressure may increase due to the rainfall infiltration into the ground. This lead to the reduction of shear strength and effective stress of soil at the slope that triggered the failure. Theoretically, this phenomenon occurs when the rainfall duration and intensity surpass infiltration rate and storage capacity of soil. This state leads to the saturation of the soil, which in turn increases the pore water pressure. When the water pressure exceeds the critical threshold, the soil of the slope might lose its strength and become unstable, resulting in failure [7].

A study by [8] critically reviewed the rainfall-induced landslide studies in the Indian Himalayan Region. The study found that the intensity of rainfall is a crucial factor affecting landslide incidents and had a higher frequency during heavy rainfall. In addition, the rainfall period may also influence the pore pressure volume that develops in the soil. Particularly, longer periods of rainfall may generate excessive pore water pressure that will increase the landslide susceptibility. Another study by [9] found that the antecedent rainfall may also play a major role in the occurrence of landslides. Antecedent rainfall is the accumulation of rainfall in a certain period, such as days or weeks before the landslide event. The previous rainfall event caused the saturation of soil in the slope. If the rainfall continuously occurs, it may cause an increase in pore pressure until it reaches the threshold limit that triggers the slope failure.

The current study utilised Geo-Studio software to assess the stability of the selected slope and determine the correlation of slope stability with antecedent rainfall. Geo-Studio is a software that integrates two-dimensional capabilities, incorporating stability analysis based on the Limit Equilibrium method (LEM) [10]. This commercial software is well accepted and used widely in many research studies to analyse slope stability [11-22]. The main advantage of utilising software that is primarily based on numerical methods is the flexibility of implementing various boundaries to effectively address complex engineering challenges [23].

The selected study area is Jalan Teluk Bahang, located on Penang Island, Malaysia. This area has been subjected to frequent shallow landslides in recent years due to the rapid development and intense human activities caused by the high demand for the urbanisation process [24]. Jalan Teluk Bahang is a vital thoroughfare, connecting the city centre to Teluk Bahang. It runs alongside a sloping area characterised by high elevation, heightening the potential of landslides. Furthermore, the study area has experienced frequent heavy rainfall, emerging as a prominent triggering factor for landslides.

The study area is influenced by a range of activities, making the analysis of landslide hazards in that area critical. Such analysis is pivotal as it has the potential to impact the safety of the surrounding infrastructure and society significantly. Therefore, this study will simulate geology and climatology factors that influence the slope failures on three case studies of slope failure in Jalan Teluk Bahang. The anticipated outcome of this research is to deepen the understanding of how antecedence rainfall affects slope stability of a single slope in Jalan Teluk Bahang.

Most studies emphasize on the correlation between intense rainfall events and slope failures. This research uniquely highlights the significance of cumulative, prolonged low-intensity rainfall as a primary trigger for landslides in the study area. This finding contributes to a more nuanced understanding of rainfall-induced slope instability. The combined use of SEEP/W and SLOPE/W software provides a comprehensive assessment of the interplay between rainfall infiltration, pore-water pressure build-up, and slope stability. This integrated approach offers a more accurate representation of the complex hydrological and geotechnical processes involved in landslide initiation.

The past in this research context involves the recognition of a problem and frequent landslides in Jalan Teluk Bahang, Penang Island. Previous studies likely explored the correlation between intense rainfall and landslides. However, a gap existed in understanding the impact of prolonged low-intensity rainfall on slope stability.

The current research focuses on filling this gap. It involves collecting rainfall data from JPS Malaysia, conducting subsurface investigations to gather soil parameters, utilizing SEEP/W and SLOPE/W software for seepage and stability analysis, identifying prolonged low-intensity rainfall as a primary trigger for landslides and establishing a correlation between cumulative rainfall and slope stability.

The future of this research involves implementing early warning systems based on rainfall thresholds, designing effective landslide prevention and mitigation measures for the Jalan Teluk Bahang area and expanding the research to other landslide-prone areas in Penang Island or Malaysia

2.0 METHODOLOGY

Selected Case Studies

Three slopes were selected as the case study: slope at road FT006 Section 42.07, FT006 Section 43.70, and FT006 Section 47.60. All these slopes were located at Jalan Teluk Bahang. This slope was selected due to the availability of the site investigation (SI) report and the Incident Proforma Landslide report obtained from JKR Malaysia. The report was the slope failure databank recorded by JKR Malaysia for every landslide that occurs under their jurisdiction. The details of slope failure criteria were recorded in that report, such as the coordinates of the slope failure location, type of landslide, date, slope geometry, and other slope features. The proforma report is essential as it describes the dimension of the slope failure. The length, width, and slope angle of the studied slope were taken from the Proforma report. Other than that, all the failures on the selected slope were reported on the same date, November 2, 2020.

Site Investigation

The SI work for three selected case studies was conducted by Pintas Utama Sdn Bhd, who was appointed by JKR, and the report was obtained from the JKR for use in this study. However, only a single borehole is drilled along every slope to ascertain the soil profile, collect undisturbed or disturbed soil samples for laboratory analysis, and determine the water table location. Due to the limitation of borehole number, the assumption needs to be made that the soil profile, soil parameter, and water table obtained from the borehole will represent the whole slope section for the case studies. Other than that, a limited number of tests are being conducted in the SI report. Several parameters that need to be used in Geo-Studio were absent, such as soil permeability and the frictional resistance angle due to the matric suction contribution, φb. The soil cohesion and internal friction angle were also limited to a certain soil depth. Therefore, the assumption was made for the absent parameter, and the parameter was obtained from the literature review and engineering judgment.

Rainfall Data

Understanding the annual rainfall pattern in Jalan Teluk Bahang area under different intensities and durations is crucial to establish a correlation between landslide events and rainfall infiltration. The study collected rainfall data for Jalan Teluk Bahang area from the Department of Irrigation and Drainage Malaysia (JPS Malaysia). Preferably, the rainfall data should be collected from the specific landslide location, but the rain gauge station is not available in the specific landslide location. Hence, the rainfall data from the closest rain gauge station, which is Tali Air Besar Sungai Pinang Station, was utilised. The specific rainfall data was considered adequate for interpreting the regional rainfall data at the landslide locations. The 3-month daily rainfall distributions prior to the incidents of the three selected case studies were analysed to assess the rainfall pattern that triggered the landslide. The rainfall data was utilised in the seep-w analysis to model transient seepage at the slope.

Slope Stability Analysis using Geo-Studio

The slope was modelled for transient seepage and stability analysis based on geometrical information and soil parameters obtained from the SI data. A transient numerical seepage analysis was conducted using SEEP/W software. The resulting pore-water pressure distributions were then utilised in SLOPE/W software for slope stability analysis. The analysis of slope's transient seepage is conducted using SEEP/W. The determination of initial conditions of pore-water pressure in the soil is based on the water table and the rainfall (unit flux) over time at the surface boundary of the model.

The analyses are performed according to the steps given below:

(1) The geometry of the slope was determined and drawn using SEEP/W.
(2) Each soil layer in SEEP/W and SLOPE/W was assigned a set of material properties, and boundary conditions were determined for both models.
(3) The limiting suction at the initial water table is assumed to be 70 kPa as that value is considered an acceptable pore-water pressure value obtained in tropical residual soils, as suggested by Lee *et al*. (2014).
(4) The hydraulic conductivity function for each soil layer was determined for a transient seepage study using SEEP/W.
(5) The simulation was conducted for 30 days before the landslides happened at all the chosen case studies on March 11, 2020.
(6) The transient seepage analysis results, which show the changing pore-water pressure conditions in the soil slope over time, were then utilised in SLOPE/W to determine the pore-water pressure in the slope and assess its factor of safety (FOS) at a specific time.
(7) For the stability analysis using SLOPE/W, it is necessary to provide the shear strength parameters (c, φ, and φb) and the unit weight for each layer. It was assumed that the frictional resistance angle resulting from the influence of matric suction, denoted as φb', is equivalent to two-thirds of φ'.
(8) The General Limit Equilibrium (GLE) was conducted using the SLOPE/W software to determine slope stability (FOS). The analysis relied on the interslice shear forces in the GLE formulation, which were calculated using an equation provided by Morgenstern & Price (1965). Figure 1 illustrates the steps mentioned above.

3.0 RESULTS AND DISCUSSION

Soil Properties

The proposed parameters used for the current study derived from the field and laboratory testing in the SI report and also from engineering judgement. It should be emphasized that the borehole was restricted to a single unit for the SI in each case study. Therefore, engineering judgment is primarily employed in certain conditions to determine certain values because there were limited laboratory tests or samples taken from the site. Table 1 summarised the soil parameters for the four different slopes in Jalan Teluk Bahang used in the slope stability analysis in this study.

Table 1 Soil properties data of three different slope in Jalan Teluk Bahang

Soil Layer	Soil Type	Effective Cohesion C' (kPa)	Effective Friction angle Ø' (°)	Soil unit weight ɣ' (kPa)	Saturated Permea-bility (m/s)
		FOS FT006 S42.07			
1	Medium Silty Sand	1	35	21.1797	1E-06
2	Medium Dense Sandy Silt	7	34	18.6684	1E-08
3	Medium Silty Sand	1	35	21.1797	1E-06
4	Dense Gravel	0	40	22	1E-02
5	Dense Silty Sand	1	35	21.8959	1E-06
		FOS FT006 S43.70			
1	Loose Gravelly Sand	0	30	19.5742	1E-04
2	Loose Sandy Gravel	0.5	32	19.7377	1E-02
3	Loose Gravely Silt	0	32	19.6101	1E-06
4	Medium Dense Gravelly Sand	0	35	19.2962	1E-04
5	Dense Sandy Gravel	0.5	40	19.904 4	1E-02
6	Dense Gravelly Sand	0	38	19.9829	1E-04
7	Dense Silty Sand	1	39	19.8750	1E-06
8	Dense Sandy Gravel	0.5	40	20.0712	1E-02
		FOS FT006 S47.60			
1	Medium Stiff Silty Sand	1	34	19.3060	1E-01
2	Medium Stiff Sandy Gravel	0.5	36	20.1006	1E-02
3	Stiff Silty Sand	1	34	19.3355	1E-06

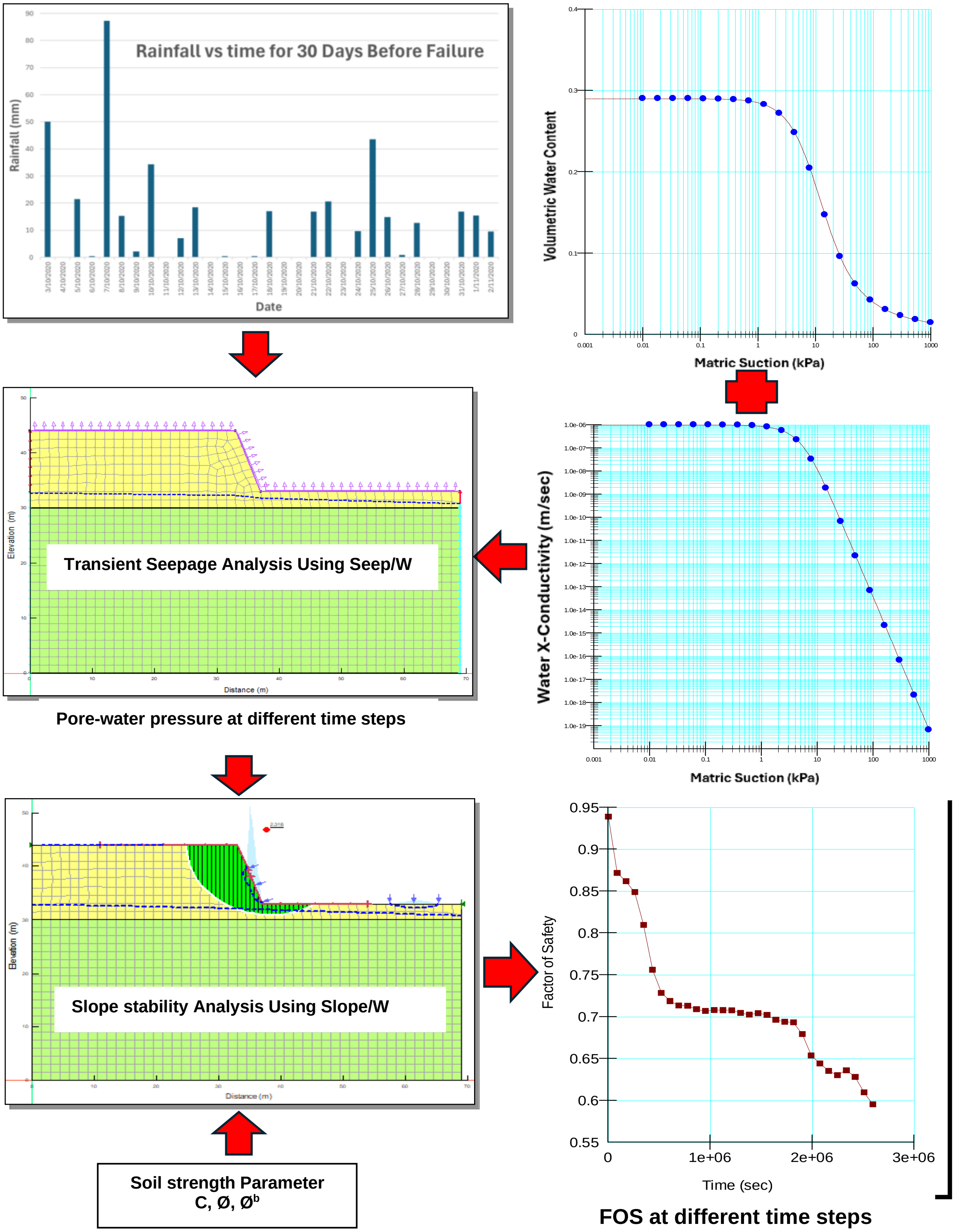


Figure 1 An illustration demonstrating the integrated analysis of SEEP/W and SLOPE/W

There were several parameters required that were not tested and reported in the SI. Therefore, it was taken from other sources, such as Saturated Permeability from [25]. The frictional resistance angle due to the matric suction contribution ($\varnothing^b$) was estimated to be 2/3 of the effective friction angle $\varnothing'$, as suggested by [26]. The groundwater level was observed during SI work. However, it was limited to 1 location which is at the toe of the slope. Therefore, the groundwater level was assumed to be the same as reported in SI, and the pressure head for the slope's right and left boundaries was considered identical. The initial condition of a limiting suction of 70 kPa was selected because it represents a realistic pore-water pressure value observed in tropical residual soils, as determined from field experience [26].

Rainfall Profile

All three selected case studies in Jalan Teluk Bahang reportedly occurred on November 2, 2020. Figure 2 illustrates the daily rainfall pattern for three months preceding the events of the three chosen landslide case studies in Jalan Teluk Bahang. The analysis of rainfall patterns before the landslide events of road FT006 Section 42.07, FT006 Section 43.70 and FT006 Section 47.60 reveals that none of these failures occurred during periods of highest daily rainfall. That pattern of rainfall indicates that the high daily rainfall is not the primary factor contributing to slope instability. In other words, the cumulative antecedent rainfall plays a pivotal role in developing the landslide mechanism. [26] elucidate this mechanism by stating that a prolonged and low-intensity rainfall event may cause a comparatively greater amount of infiltration, increasing the landslide susceptibility. In addition, a study by [26] revealed that landslides can be triggered by short-intense rainfall and prolonged antecedent rainfall.

The cumulative antecedent rainfall pattern was analysed to find out the most suitable pattern to represent the antecedent rainfall that caused slope failure in those three case studies. When incorporating antecedent rainfall into landslide prediction models, the fundamental concern is establishing the period during which cumulative rainfall must be accounted for. According to [26] various durations of antecedent rainfall were used to assess slope stability globally and resulted in different conclusions. However, they highlight that the antecedent rainfall duration should be determined based on the condition of local rainfall.

The analysis was conducted for 3,5,7,14, and 30 days of cumulative antecedent rainfall before the failure, and the result is shown in Figure 3(a-e). The evaporation rate was assumed at the rate of 5mm/day as suggested by [27] and described on the MET Malaysia website [28]. The result shows that 30-day cumulative antecedent rainfall was the most realistic and practical for predicting the three case studies of landslides at Jalan Teluk Bahang. The critical duration is established as the time period during which the maximum amount of rainfall on the day when a landslide takes place. The notion that the heaviest rainfall should be indicative of a landslide occurrence was the basis for the formulation of this conception.

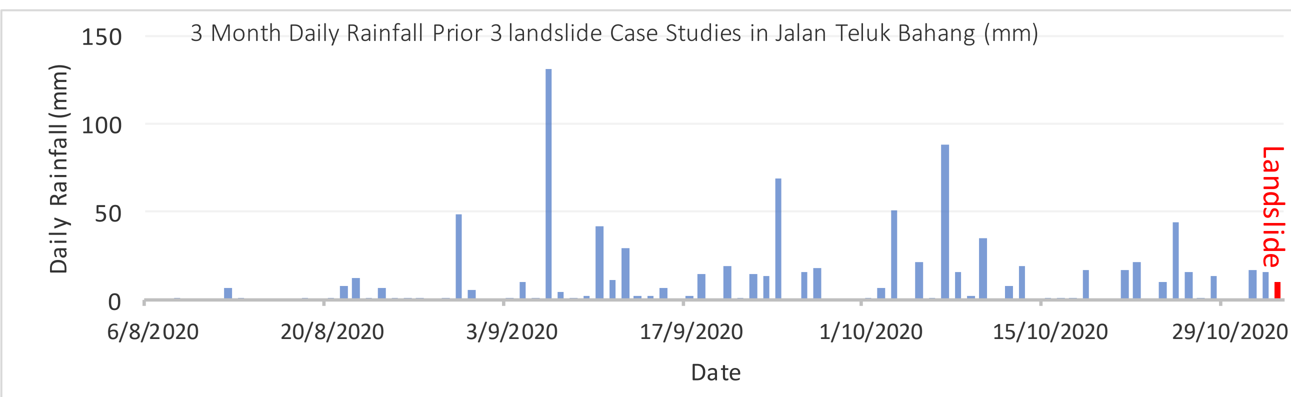


Figure 2 3-month daily rainfall from Tali Air Besar Sungai Pinang Station

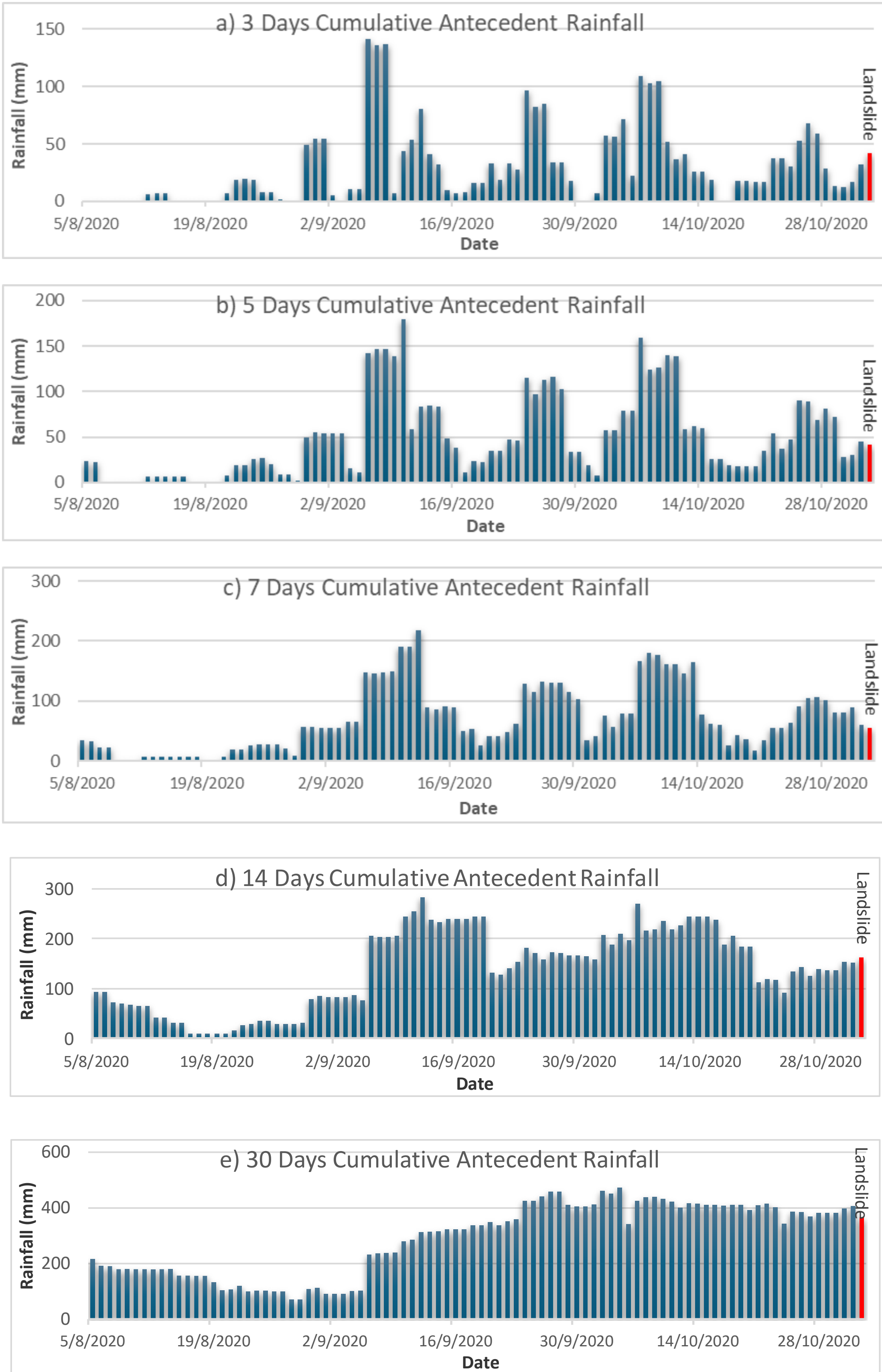


Figure 3 (a-e) Critical duration cumulative rainfalls at 3,5,7,14 and 30 days for four selected case study at Jalan Teluk Bahang (Landslide Occurance at 2.11.2020)

Slope Stability Analysis

The slope geometry of the three case studies was almost similar, as there was a cut slope beside the major road in Teluk Bahang. The dimensions of slope FT006 Section 42.07 and FT006 Section 47.60 were identical: the slope length was 12m, base length was 4 m, slope height was 11m, and slope angle was 70°. Slope FT006 Section 43.70 slightly differed as the slope length was 13m, base length was 4 m, slope height was 12m, and the slope angle was 71.56°. The LEM was conducted by utilising SLOPE/W software to estimate the stability of the selected case studies.

Theoretically, the slope was classified as stable if the FOS calculated using LEM was ≥ 1. According to [29], the suggested minimum global FOS for the treated cut slope should be 1.5 to minimise user risk. The initial stability of all selected slopes shows a similar pattern where the Global FOS was more than 1.0, as shown in Figure 4(a-c). The initial global slope stability of slope FT006 Section 42.07, FT006 Section 43.7, and FT006 Section47.60 were 1.464, 1.596 and 1.449, respectively.

The transient analysis was conducted based on the 30-day rainfall record before it was utilised in SLOPE/W to determine the FOS of every slope. The slope stability analysis of the all-selected case study shows a similar pattern where the negative pore-water pressure or suction decreases from day one (3 October 2020) until the day of failure occurs (2 November 2020), as shown in Figure 5(a-c). Figure 5 shows the matric suction that is observed along the slope surface. The reduction of the suction is due to the effect of antecedent rainfall until the day of the slope failure occurrence. Therefore, the FOS of all the slopes in the case studies was found to be decreased from October 3 2020, until the occurrence of the failure on November 2 2020, as shown in Figure 6. The result indicates that the FOS was at the lowest value at the failure date for all the slopes in the case study. Figure 7 shows the slope stability during the days of landslide occurrence.

The pictures of actual landslide of the case studies are shown in Figure 8 which extracted from SI report. The mode of failure of real condition (Figure 8) is consistent with the software simulation (Figure 7) indicating shallow mode of failure. The factor of safey is lesser than unity indicating the slope has failed.

A study by [23] utilised SIGMA/W and SEEP/W to assess the influence of antecedence rainfall on pore water pressure and slope stability in Haflong Hill, North East India. They found that the pore water pressure gradually increased with the prolonged rainfall event. Conversely, the matric suction and FOS gradually decreased as a result of the pore-water increment. They highlight that the pore water pressure is crucial in maintaining soil strength and preventing slope failure. The prolonged antecedence rainfall will change the pore-water pressure continuously, and the soil mass will lose its strength, which will cause the failure surface to develop at a point in time. The finding of this study was significant to the current study as both show a similar trend of the effect of antecedence rainfall toward the matric suction and slope stability.

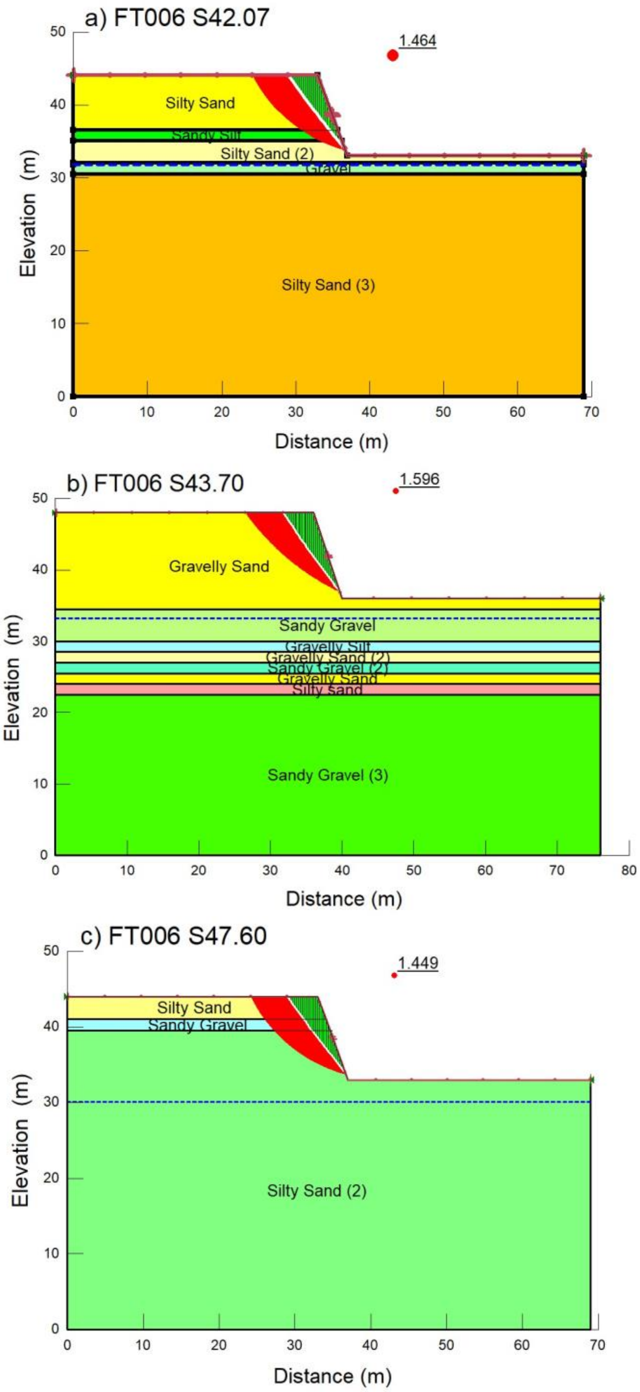
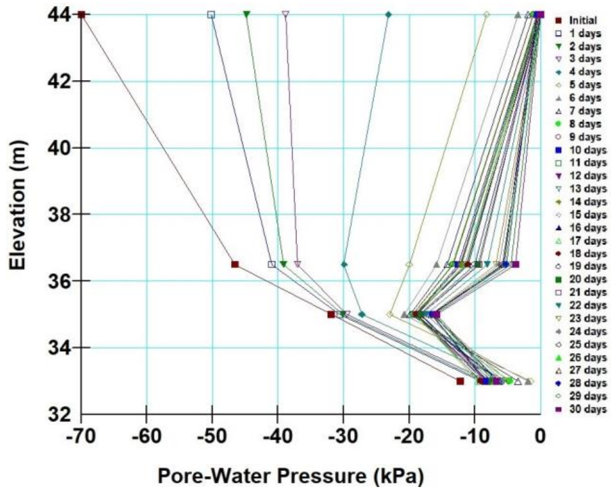
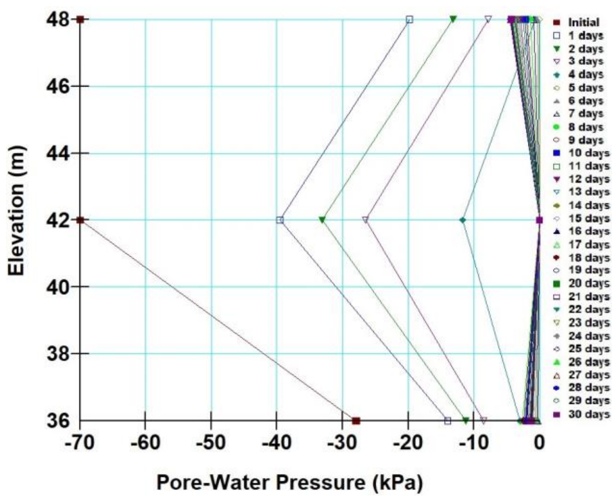


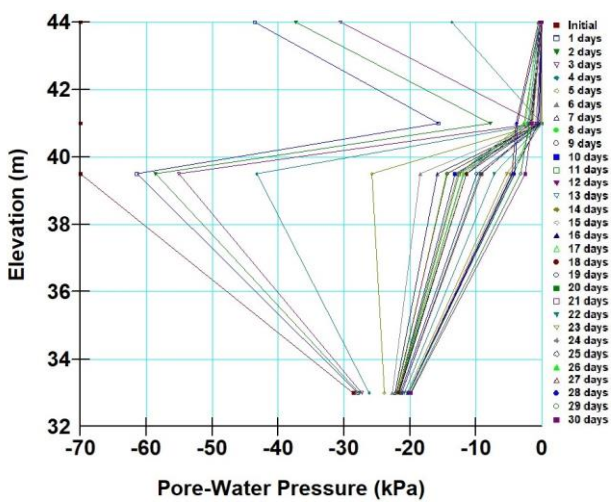
Figure 4(a-c) Initial Global FOS of the three different slope for case studies



a) Porewater pressure during a period of 30 days prior to the landslide FT006 S42.07



b) Porewater pressure during a period of 30 days prior to the landslide FT006 S43.70



c) Porewater pressure during a period of 30 days prior to the landslide FT006 S47.60

Figure 5(a-c) Transient pore-water pressure distributions

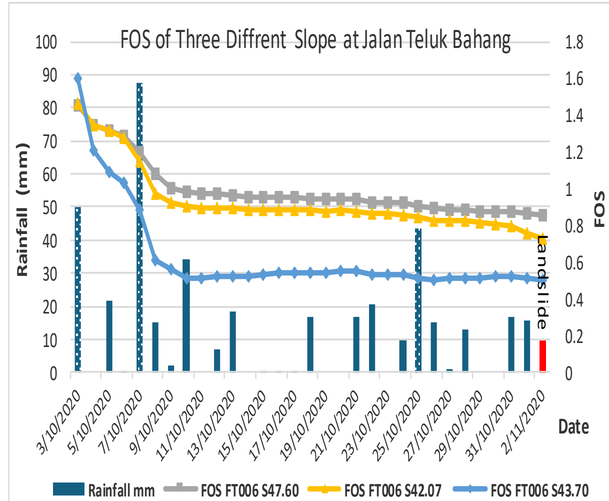
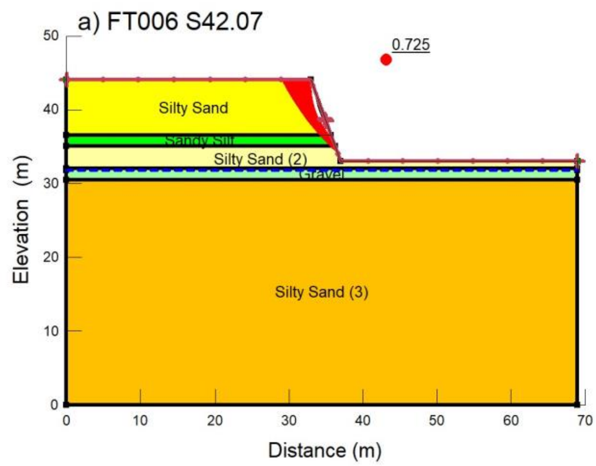
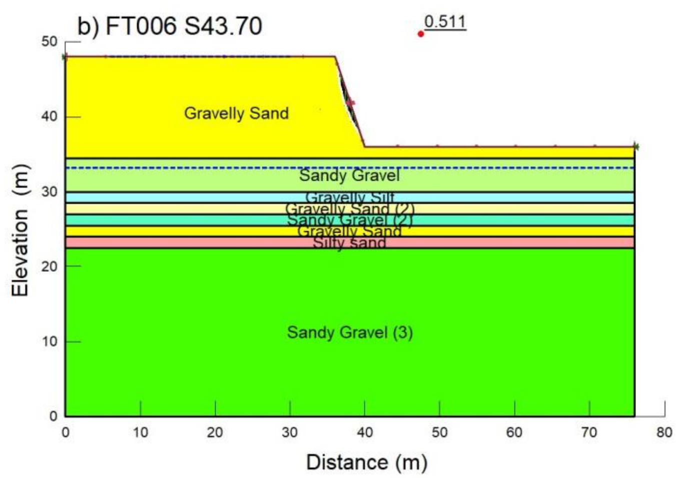


Figure 6 Changes of global FOS of the slope during a period of 30 days prior to the landslide event





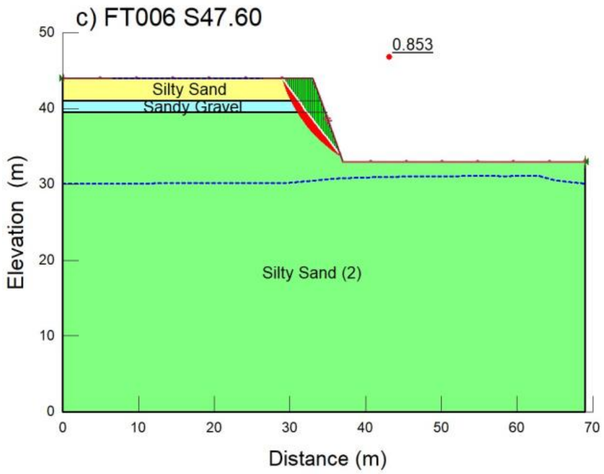
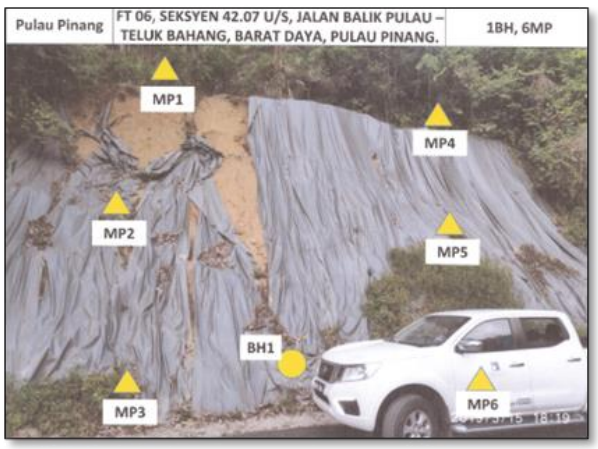
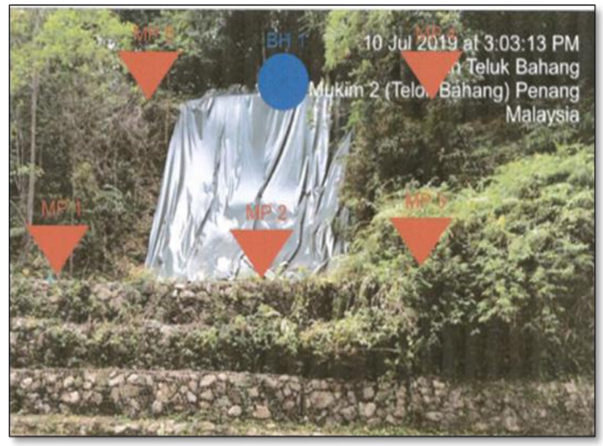


Figure 7 Global FOS value at the day of slope failure occurrence



a)Landslide FT006 S42.70

b)Landslide FT006 S43.70



c)Landslide FT006 S47.60

Figure 8(a-c) Slope failure at the actual condition

Many other studies, such as [30-37] found similar trends where the antecedence rainfall plays a major role in triggering slope failure in the different study area. [32] investigated the effect of antecedent rainfall on the stability of unsaturated weathered granite slopes in Inje, Korea. They concluded that higher initial matric suction (less antecedent rainfall) delays slope failure, and slopes with higher saturated permeability are more susceptible to rainfall-induced landslides. Furthermore, [36] discovered that the impact of antecedent rainfall on slope stability becomes more significant as the soil's saturated permeability coefficient reduces.

It can be seen from Figure 6, that the FOS was steadily reduced without any drastic drop until the slope failed. This trend was significant with the rainfall data, as shown in Figure 2, where the low intensity of rainfall (<30mm/day) was recorded a few days before the occurrence of those landslides. Nevertheless, only one intense rainfall event (>80 mm/day) occurred on October 7, and also medium rainfall events (30>mm/day<80) occurred on October 3 and 25, 2020. The gradual decrease in FOS was attributed to the prolonged antecedent rainfall events and the subsequent redistribution of the infiltrating rainwater.

It is possible that the extended rains that occurred before the landslide were the primary factor that caused it to occur. The findings of this simulation indicated that the occurrence of a landslide may not always be contingent upon the occurrence of a significant major rainfall event. Conversely, the landslide may have been primarily triggered by prolonged antecedence rainfall. A study by [38] at Hulu Kelang also found that prolonged and continuous low-intensity rainfall occurred before the landslide in that area. They highlighted that cumulative attendance rainfall plays a significant role in triggering the landslide in Hulu Kelang.

[26] also found a similar trend in their study in Hulu Kelang Area where the prolonged 30-day

antecedent rainfall was the main triggering factor of landslides in Hulu Kelang. The studies by [26] were conducted with variations of rainfall and landslide events to determine the threshold value of the Hulu Kelang Area. The studies conclude that both short-intense rainfall and prolonged antecedence rainfall may also trigger the landslide. Compare this to the current case study, whereby the landslide occurred under only one rainfall event. Hence, it is not feasible to ascertain the specific local threshold in Teluk Bahang in the current study due to the necessity of observing numerous landslides triggered by varying rainfall events to establish the range of minimum and maximum rainfall that can trigger the landslide.

Antecedent rainfall signifies the total amount of rainfall accumulated in a specific region during a period leading up to a particular event, such as a storm or landslide. This variable holds great significance in hydrology and environmental studies, particularly in evaluating flood risks, soil saturation levels, and slope stability. The assessment of landslides triggered by rainfall frequently takes into account antecedent rainfall, wherein saturated soils resulting from prior rainfall events can cause a decrease in soil strength and increase pore-water pressure. Consequently, slopes become more susceptible to failure when subjected to prolonged rainfall. This conception is essential, especially in regions subjected to intense and frequent rainfall, where the soil usually does not have a chance to completely dry. Penang Island is recognised as an area with hilly terrain that experiences a tropical climate with frequent intense rainfall, especially during the monsoon event. Therefore, the consideration of antecedent rainfall in the analysis of slope stability in Penang Island was a crucial factor to be considered.

The soil's permeability is crucial in enabling the infiltration of rainwater. The slope wetting front depth of the rainfall depended on soil permeability and rainfall intensity. A reasonable explanation for this phenomenon is that the moderate permeability of the soils may limit the infiltration of intense rains, as suggested by [26]. The main factor in determining soil unsaturated shear strength is the matric suction, also known as the soil's negative pore water pressure ($U_a - U_w$) [39]. The rainfall infiltration phase involves a continuing decrease in matric suction, resulting in a subsequent decrease in shear strength. The decrease in shear strength results in a reduction in the FOS of the slope until the slope fails, hence triggering a landslide. Therefore, the correlation between rainfall infiltration and slope stability is a significant factor in the analysis. Prolonged and low-intensity rainfall may increase rainfall infiltration and thus increase the slope failure susceptibility.

4.0 CONCLUSION

In conclusion, this study reveals the critical influence of antecedent rainfall on slope stability in Jalan Teluk Bahang area of Penang Island, Malaysia. The analysis identified prolonged low-intensity rainfall as a primary trigger for slope failure in the study area, with cumulative 30 days of antecedent rainfall playing a pivotal role. The integrated use of SEEP/W and SLOPE/W software facilitated a comprehensive understanding of the changing pore-water pressure conditions and the subsequent decrease in slope stability leading to landslides. This insight is supported by the gradual decrease in FOS observed in the stability analysis leading up to landslide occurrences. The study highlights the importance of considering cumulative antecedent rainfall in slope stability assessments, especially in regions prone to frequent rainfall and hilly terrain like Penang Island. However, the study faced limitations due to uncertainties in soil parameters and the absence of comprehensive pore-water pressure data. These findings shed light on the need for a deeper understanding of rainfall-induced landslides in similar tropical, hilly terrains and emphasize the significance of considering antecedent rainfall in slope stability analysis. The research offers valuable insights to guide future investigations and measures aimed at mitigating the impact of rainfall-induced landslides at Penang Island and similar regions. Further study is required to determine the specific local threshold for landslide in Teluk Bahang, which requires numerous analyses of landslides triggered by varying rainfall events to establish the range of minimum and maximum rainfall that can trigger the landslide.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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