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Numerical Modelling of Slope Stability and Transient Seepage Analysis: Jalan Puncak Borneo Road Case Study

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Abstract: A slope failure event in 2015 at KM 6+500 of Jalan Puncak Borneo in Padawan, Kuching was modelled using Seep/w and Slope/w software of commercial geotechnical programme GEOSTUDIO. The failure was occurred after a prolonged three days of heavy rain. The state road which connected the villagers from Puncak Borneo was cut off and caused traffic congestion. In this study, the slope stability was evaluated based on finite element and limit equilibrium method by considering the transient seepage analysis due to rainfall infiltration. The slope failure was modelled based on ground investigation report and published data to replicate the field condition. A hyetograph was plotted using daily rainfall data and cumulative rainfall depth was determined to obtain the total rainfall during the wet monsoon. As a result of numerical analyses, the factor of safety was observed to fluctuate with time of infiltration. Based on this case study, the factor of safety or FOS reduced with time and a perched water table also has been observed developed just below the pavement. However, the factor of safety calculated from Slope/w could not replicate the actual failure. Nevertheless, it can be observed that factor of safety had decreased with respect to infiltration in the analyses. The steady state condition provided FOS 1.38 and had reduced to 1.08 after 110 days of rainfall event. Thus, the analyses of this current study have illustrated that the transient analysis is essential to model the seepage behaviour and infiltration event that caused slope failure along Sarawak's roads.

Keywords: Numerical model, transient analysis, rainfall infiltration, factor of safety

1. Introduction

The slope failure regularly occurred during the raining monsoons in Malaysia which particularly appeared in residual soil slope. The hydrological factors, such as precipitation, infiltration, evaporation, and transpiration cycles, are greatly affect the stability of residual soil slopes [1]. Residual soil is the product of the decomposition of parent rock in-situ, and it is not transported over any significant distance. The properties of unsaturated soil are influenced by parent material and the degree of weathering [2]. The engineering behaviour of residual soils is different compared to other soil types due to the presence of negative pore water pressure. In dry seasons, unsaturated residual soils have great matric suction, but they can be lowered during the rainy seasons.

Most of the previous research work concluded that rainfall infiltration is the most significant triggering factor to unsaturated soil slope instability in either tropical or subtropical regions [3]- [13]. These research works were essentially considering how the distribution of suction and its redistribution affected slope stability. However, as stated by Wu et al. [14], it is a great challenge to accurately address the effect of rainfall to slope failure as the mechanisms of rainfall triggered slope failures are very complex due to several factors including erosion, soil softening, seepage, stress redistribution and other different failure modes. Lee et al. [15] studied slope in Hulu Kelang area also claimed that the

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main causes which have contributed to the slope failure were still debatable as the failures keep recurring during rainy season.

Based on the statistics, Sarawak experiences the most rainfall amongst the states in Malaysia and has had the most rainfall in between the month of December to April every year. The greatest rainfall amount that had been recorded is about 600 mm cumulative rainfall in the month of January and the least recorded is in the month of June, which is about 200 mm. From the online news article on March 6, 2020, a landslide was occurred at Jalan Ulu Spak, off Jalan Ulu Layar, where the landslides have cut off the road links in Betong as illustrated in Fig. 1(a) [16]. About 100 m long of the road was found sunk between Sri Aman and Kuching was reported at a section of the main road on 28th December 2011 and had caused major disruption to this main federal road [17] (Fig. 1(b)). These are examples of slope failure cases along Sarawak roads which had occurred after a continuous intense storm several days.

(a)

(b)

Fig. 1 - Example of slope failure reported along Sarawak roads in year (a) 2020 [16], and; (b) 2011 [17]

Therefore, in this paper, the research focuses to investigate the relation of Sarawak's rainfall pattern to the slope failure occurrences along the Sarawak roads. The slope stability analyses were performed using a commercial geotechnical engineering software namely GEOSTUDIO and transient analysis was considered to observe the changes of slope safety factor (FOS) with time. In addition, the matric suction profiles were also investigated to see the effect of infiltration on the variation. Past slope failure along Sarawak Road is considered for the case study. The study area is located within the municipality of Padawan, named as Jalan Puncak Borneo. The slope failure occurred on 19th January 2015. The collapse road caused an obstructed traffic and several villages such as Kampung Annah Rais, Kampung Simuti, Kampung Sadir and Kampung Semeru were affected too. Other than that, a few other roads along Jalan Puncak Borneo were also affected by the landslide [18].

2. Material and Methods

The methodologies of the research project included a desk study based on the remediation site investigation data, analysis of historical daily rainfall data, modelling the initial soil condition which includes selection of soil parameters and boundary conditions and lastly to perform transient analysis in the slope stability using seep/w software.

2.1 Locality and Soil Formation

The area of study is Jalan Puncak Borneo located at N 1º 23’ 57.8076”, E 110º 19’ 24.9276” in Kuching, Sarawak. The soil at the study area belongs to the Pedawan Formation, which is believed to have an age from Upper Jurassic to Upper Cretaceous. It consists of a thick sequence of moderate to steeply dipping marine shale, mudstone, and sandstone, with beds of conglomerate, limestone, and radiolarite [4]. For this study, the Kuching Zone is the focus because the incident at Jalan Puncak Borneo is situated within this zone. From the geological map in Fig. 2, the soil at the incident has been from the Pedawan Formation, indicated as the green-coloured region. The Pedawan formation is comprised of predominantly moderate to steep dipping marine shale, mudstone, and sandstone, with traces of conglomerate, limestone and radiolarite. The formation is at least 15,000 feet and covers 168 square miles of the Penrissen area. It is believed to be of Upper Jurassic to Upper Cretaceous age.

2.2 Geometry and Soil Profile

The soil profile of the numerical slope model was determined from the soil borelog and key in parameters were decided based on the soil properties data and field testing. The site investigation (SI) report of Proposed Rectification Works at KM 6+500 Jalan Puncak Borneo, Kuching Division, Sarawak was used in this study. As illustrated in Fig. 2, the ground investigation was consisted of four boreholes (BH) in which Standard Penetration Test, SPT was performed to acquire number of blows representing N-values for SPT. In addition, four Mackintosh probe test and hand auger sampling were performed near to the BH3 and BH4 to confirm the ground profile. The soil profiling and its geometry were estimated from the soil borelog of four boreholes and the layering was developed with respect to ground reduced level (RL) or point of reference during boring.

Fig. 3 displays the finalized geometry of numerical slope model of this study. Borehole 1 displays very soft to soft clayey SILT soil from the ground level up to 4.50 m depth and followed by 3 m stiff clayey SILT. The very stiff reddish-brown clayey SILT of 3m thickness was located in between of 1.5 m hard reddish clayey/sandy SILT layer on top and 6m at bottom layer. The boring was terminated at 21.04 m at hard dark grey silty CLAY layer. Borehole 2 shows that the hard material was reached at the depth of 6.75 m which the boring had encountered highly weathered, fractured SANDSTONE. The soil above SANDSTONE is consisted of a 3.75 m clayey silt and 3.0 m of gravel. Borehole 3 illustrates a very soft reddish-brown clayey SILT up to 6.0 m, followed by a thin loose silty SAND, hard clayey SILT and the boring had been terminated at 12.0 m at the very dense GRAVEL. The last borehole i.e Borehole 4 displays soft clayey SILT up to 6 m followed by firm clayey SILT, hard grey SILT, and very dense GRAVEL at 3m, 1.5 m and 1.55 m depth, respectively.

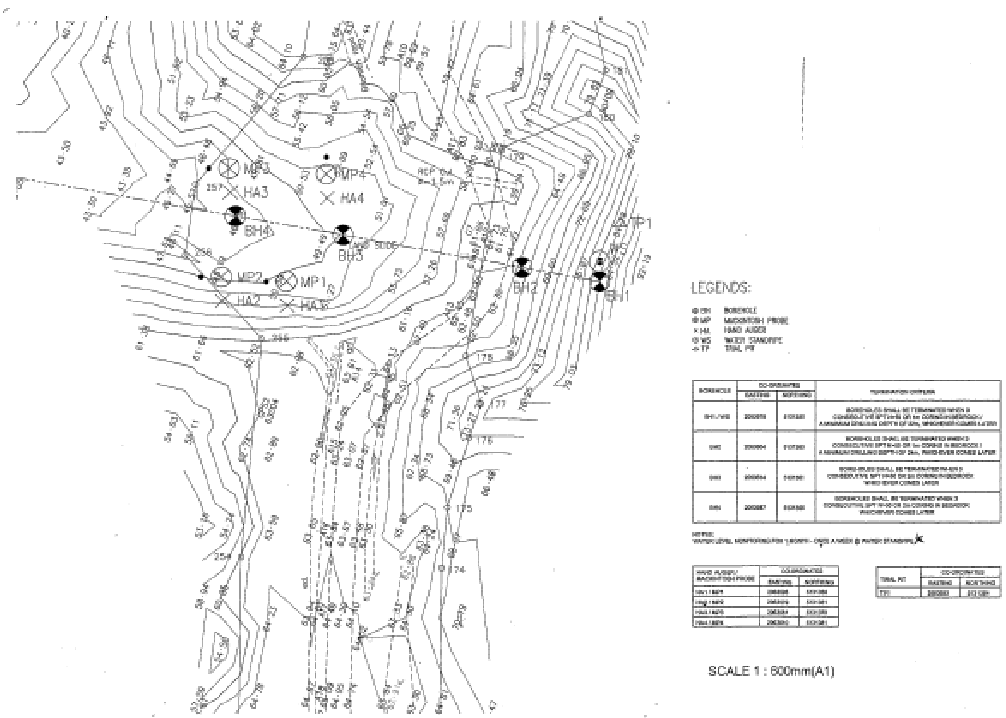


Fig. 2 - Plan profile of boreholes location

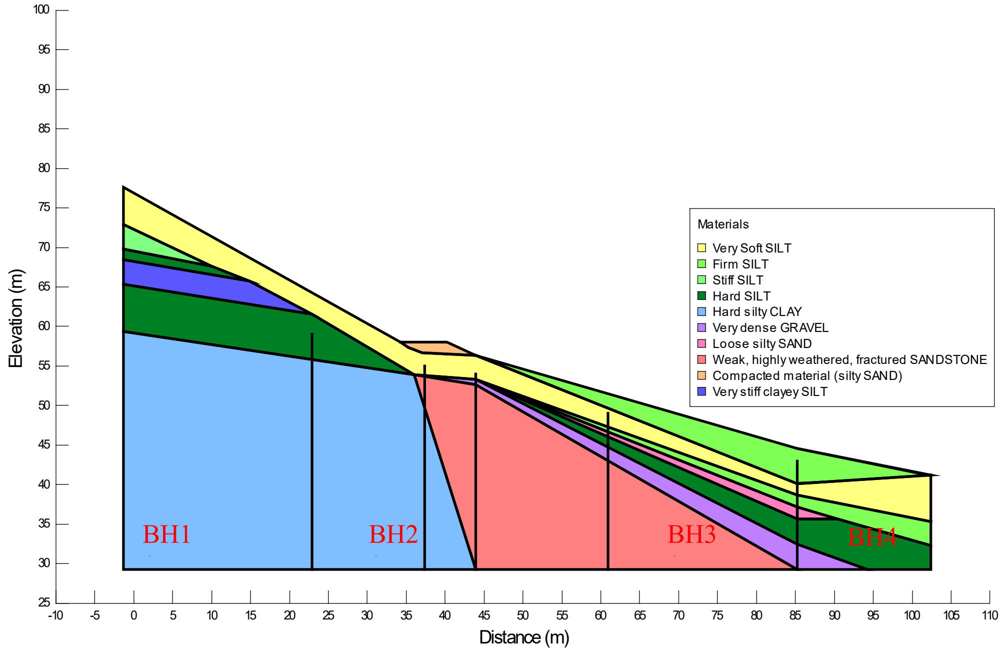
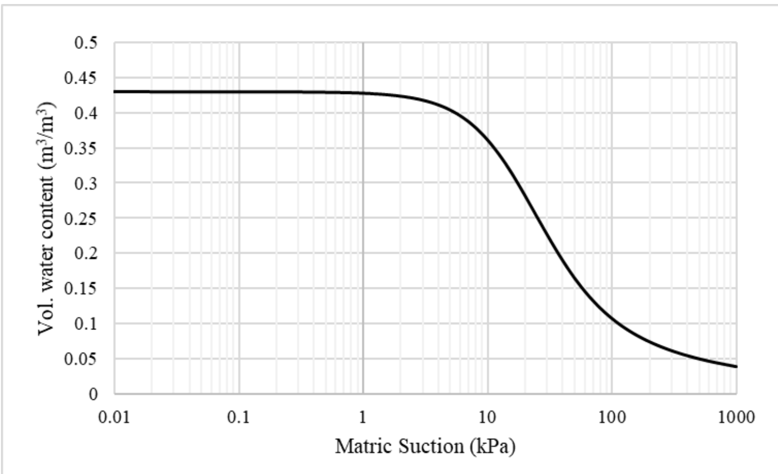


Fig. 3 - Geometry and soil profile

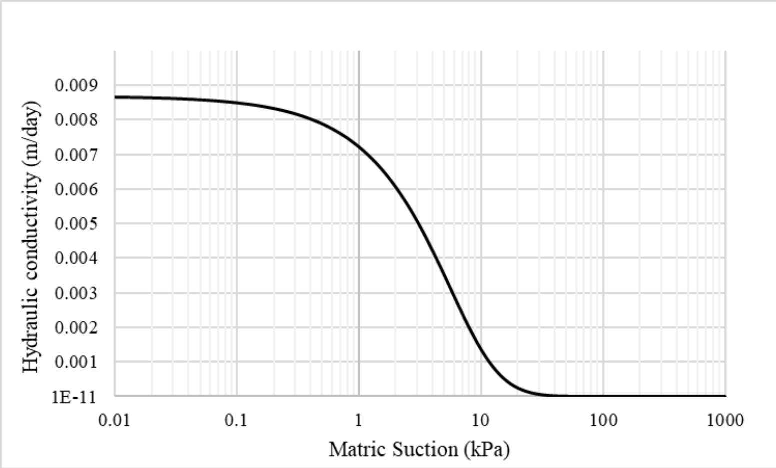
2.3 Initial Condition

Fig. 4 shows the example of soil water characteristic curve (SWCC) and hydraulic conductivity function for SILT. Very soft to soft SILT was found up to 6 m in average, which then followed by the firm to very stiff SILT from the elevation of 6 m to 12 m depth. Towards deeper the soil borelog had illustrated a mixed of hard SILT with CLAY and highly weathered SANDSTONE. The values of saturated water content and its residual water content were estimated based on the published empirical data and both plotting's were generated based on the sampling function in SEEP/w software. Since the values were estimated from the typical values of SILT which had made available in the software, a validation model to the soil parameters also had been performed, but not been presented in this paper. The validation model also was purposely to create correct boundary condition to the analyses.

Table 1 shows parameter selection used in SEEP/w software and SLOPE/w software. The saturated permeability of different type of soils were estimated from the published literature [19]. The initial condition of the numerical slope model was designed in SEEP/w software in which the initial matric suction was established based on the ground water level position. The position of ground water level was acquired from the borelog records for each borehole. Therefore, this initial condition was established in a steady state seepage by assigning the hydraulic boundary conditions based on Head (H) or the elevation of water level in meter. As illustrated in Fig. 5, the ground water level was established and therefore, pore pressure distribution is generated by which above water level is negative pore pressure or defined as matric suction. The matric suction of SILT was estimated at its residual water content. The residual water content is represented as the highest matric suction that can be developed at its driest condition. The matric suction that could develop for SILT is ranging from 50 to 120 kPa as modeled.



(a)



(b)

Fig. 4 - (a) SWCC of SILT, and; (b) hydraulic conductivity function

Table 1 - Soil parameters used in SEEP/w and SLOPE/w

Soil Layer	**K_{sat} (m/s)**	**Saturated Water Content, θ_{sat}**	**Residual Water Content, θ_{res}**	**γ (kN/m^3)**	**SPT N (average)**	***c'* (kPa)**	***φ'* (°)**
Very soft to Soft Silt	1×10^{-6}			16	3	0	19
Firm Silt	1×10^{-7}			17	7	0	28.5
Stiff Silt	1×10^{-8}	0.43		18	11	0	31
Very stiff clayey SILT	1×10^{-9}		As0.043	18.5	20	0	33.5
Hard Silt	1×10^{-9}			19	> 50	250 – 300*	0
Hard silty CLAY	1×10^{-9}			19.5	> 50	250 – 300*	0
Loose silty Sand	1×10^{-5}	0.36	0.036	16	6	0	28.8**
Very dense Gravel	1×10^{-5}	0.3	0.03	21	> 50	0	38**
Weakly high weathered fractures SANDSTONE	1×10^{-5}	0.3	0.03	24	**Generalized Hoek-Brown criteria** Uniaxial compressive strength, sigma c = 20000 kPa Intact rock parameter, mi = 19 Geological strength index, GSI = 35 Disturbance factor, D (0 to 1) = 1		

Note: *[2] ; **[3]

As stated in Table 1, the SLOPE/w uses unit weight and the value of soil shear strength parameters, which are the cohesion and phi value to define the material and the analyses are using the limit equilibrium method to obtain the safety factor. The analyses of this study however, incorporate the transient analysis which can be performed by using SEEP/w to create the initial condition and investigate the pore pressure changes during rainfall infiltration. Therefore, the SILT material is modeled in effective stress condition with pore pressure changes measurement. Thus, the shear strength of the soil would be dependent on the frictional soil angle as stated in Table 1.

2.4 Rainfall Patterns

The historical rainfall data was collected from the Padawan rain-gauge station which is the nearest rainfall station to the study area. The hyetograph is plotted using the historical daily rainfall data against time as illustrated in Fig. 6. The cumulative amount of rainfall for Northeast monsoon was also plotted in the same graph. Antecedent rainfall is defined as days which consecutive rainfall with or without rainfall, before the landslide occurred [20]. According to Tay & Selaman [20], antecedent rainfall for 11 days were adopted to observe the significant of antecedent rainfall to landslides occurrence along Sarawak road and therefore a threshold value was determined from the rainfall pattern analysis. In this study however, the infiltration was modelled continuously for four months (i.e October 2014 to January 2015) to observe the effect of precipitation to the ground water level and pore pressure distribution.

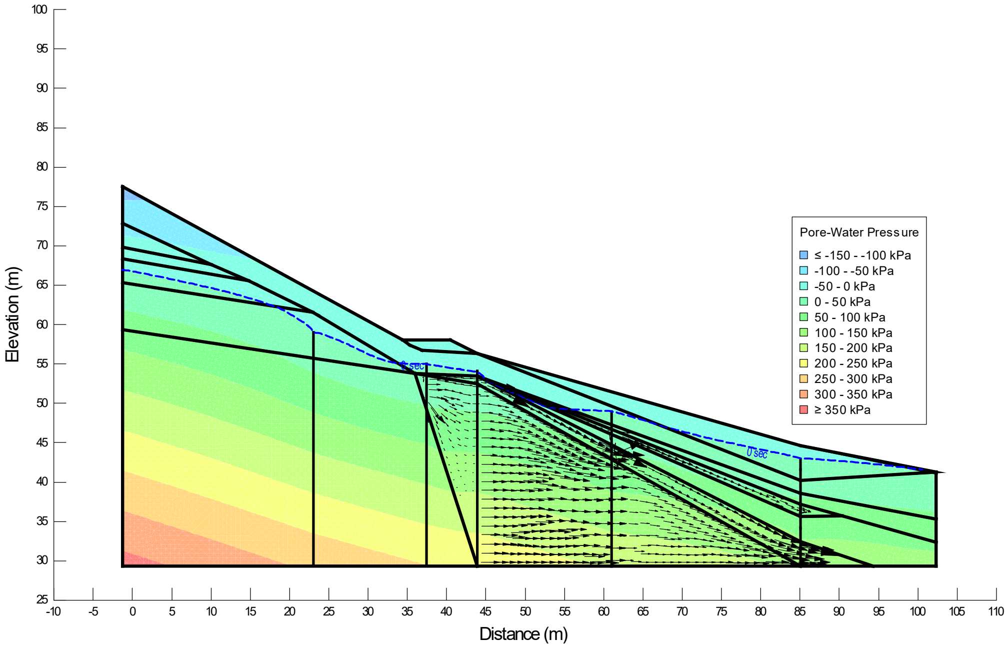


Fig. 5 - Initial condition (steady state)

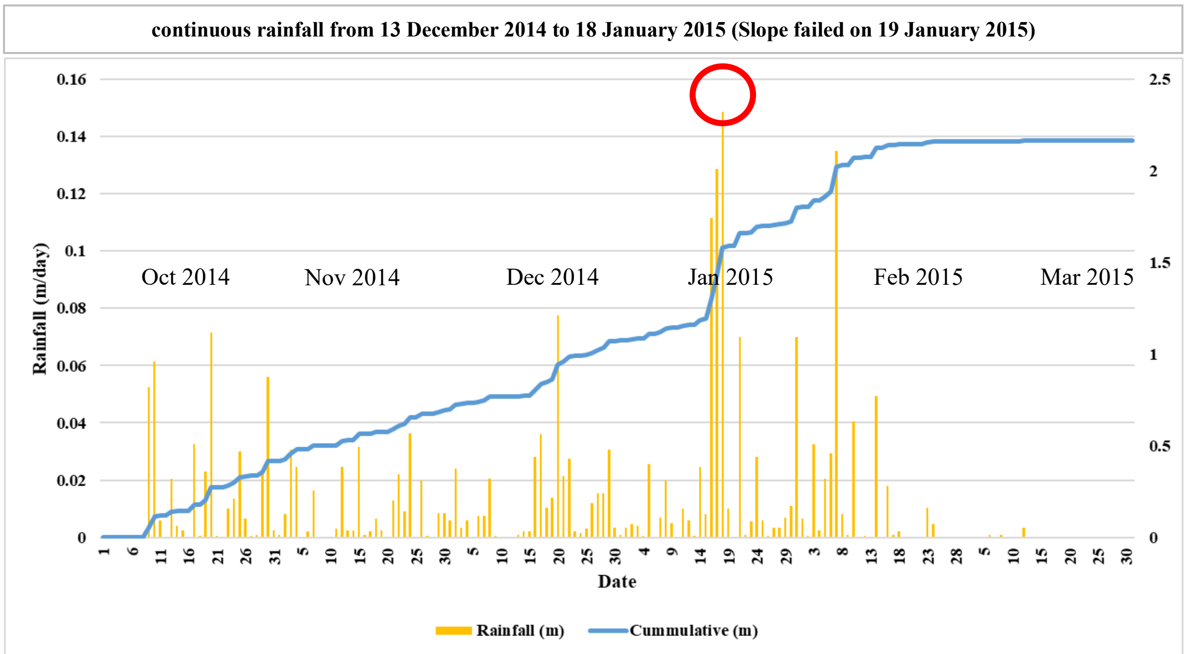


Fig. 6 - Rainfall hyetograph from October 2014 to March 2015

2.5 Numerical Simulation

This study investigated numerically the slope failure due to rainfall infiltration by using past failure as case study. The SEEP/w and SLOPE/w software in GEOSTUDIO 2012 package were used to perform the seepage analysis due to infiltration and slope stability analysis, respectively. SEEP/w is a finite element software that has been well-known able to model saturated and unsaturated flow which would be advantageous to model transient seepage behaviour in soil. The SLOPE/w uses limit equilibrium method to analyses stability of slope which able to incorporate various dependent and independent variables includes soil properties, loading methods and pore water pressure conditions which imported from SEEEP/w file. Thus, in this study, the initial condition was firstly constructed in SEEP/w model using a steady state groundwater level as displayed in borelog records. Then, the SEEP/w was to simulate the transient seepage under the influence of antecedent rainfalls. The changes of ground water level and matric suction profiles were also examined to investigate the relationship of pore water pressure development with respect to time of infiltration in saturated and unsaturated soils. The boundary conditions for initial condition in SEEP/w were generated with reference to elevation of ground water level or Head in meter. While the rainfall infiltration was modelled using water flux or intensity in m/days. The flux equals to zero was assigned along the bottom of slope to simulate a no flow zone. Table 1 also shows the soil parameters for SLOPE/w. The soil parameters were estimated from empirical equation associated to SPT N-value as recorded in borelog data for cohesive soil [21]. The estimation of cohesion value is for SPT N value range from 2 – 30.

$$c = -2.2049 + 6.484N \tag{1}$$

The friction angle values were acquired from Karol [22] by referring to the SPT N value from the borehole records. As for the Generalized Hoek Brown criteria, the selection of parameters for the weakly high weathered fractures SANDSTONE was based on the Rock Quality Designation (RQD) and Total Recovery Ratio (TCR) values [23]. Since the values of soil parameters were mostly estimated based on the SPT-N value from the soil borelog, this analysis can be used as a preliminary data to illustrate the importance of transient analysis in a slope stability analysis.

3. Result and Discussion

The results of this study cover the analysis of pore pressure distribution, the ground water level changes under the influence of Northeast monsoon in 2014 and the effect of infiltration to the stability of slope along the Sarawak roads. From Fig. 6, we can observe that almost every day was raining event, and this continuous rainfall pattern indicates the accumulation of soil moisture in soil mass and had progressively caused instability which finally leads to landslides as cited in Tay & Selaman. [20]

3.1 Pore-Water Pressure Profile

Fig. 7 illustrates the pore water pressure distribution against time from October 2014 till the day of landslide occurrence. The location of pore pressure profile was located as illustrated in the figure. The initial water table was located about 3 to 4 m below the road embankment and the accumulation of rainfall consecutively within the monsoon had generated perched water table beneath the embankment. The top layer of the soil stratigraphy was found to be very soft to firm SILT and the saturated permeability, k_{sat} is within 1×10^{-6} to 1×10^{-7} m/s. The average rainfall intensity from month October 2014 to January 2015 until the day of landslide is 1.5×10^{-6}m/s. The matric suction would be diminished when the steady-state rainfall flux had approximately reached the saturated permeability near the ground surface. Besides, the two main factors that predominantly governed the matric suction distribution (steady-state condition) are the ratio of rainfall infiltration rate to saturated permeability (i.e., q/ksat) and the air-entry value [24]. Since the ratio of q/ksat is larger than 1 [12], the depth of wetting front is governed by the saturated permeability of the soil as shown in Eq. (2).

$$L_f = \frac{k_{sat} \times t}{\theta_{sat} - \theta} \tag{2}$$

Fig. 7 shows a gradual reduction of matric suction against time of infiltration because pore spaces are continuously filled as well as the saturated permeability of the top layer was higher in magnitude. Fig. 8 illustrates the example of pore pressure distribution at random locations for three different parts of slope: crest, middle and toe. The wetting front advancement was found to be approximately 2 m below the ground surface. The water table is located around 3 ~ 4 m, and the wetting front can reach up to 2 m below the ground surface. This occurrence could cause high moisture content at the upper layer of slope and could create perched water table at this location. Since the permeability of the upper soil layer is within the range of its saturated permeability, the excess pore pressure would take a delay to diminish due to low porosity at this layer. When the soil density increases as the moisture content, the phenomenon had increased the normal stress subsequently magnified the driving shear stress which caused the landslides.

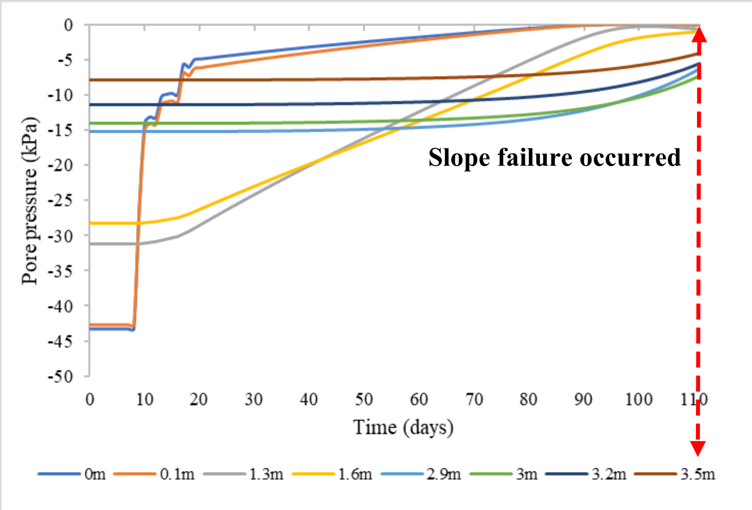
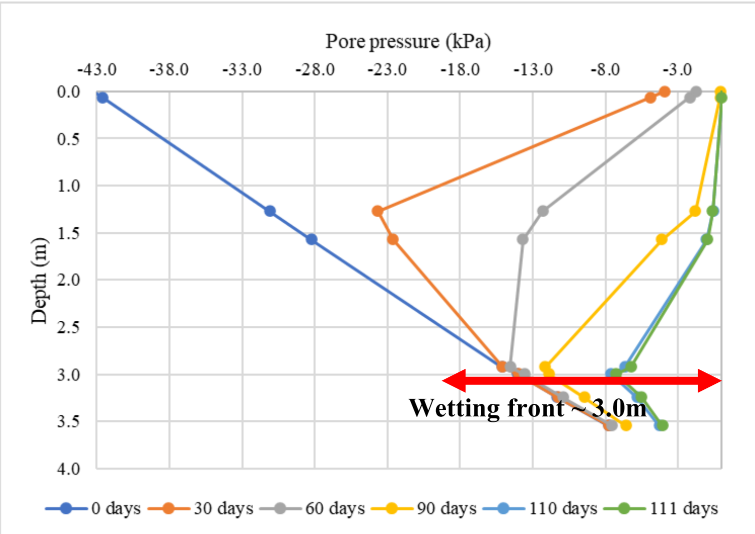
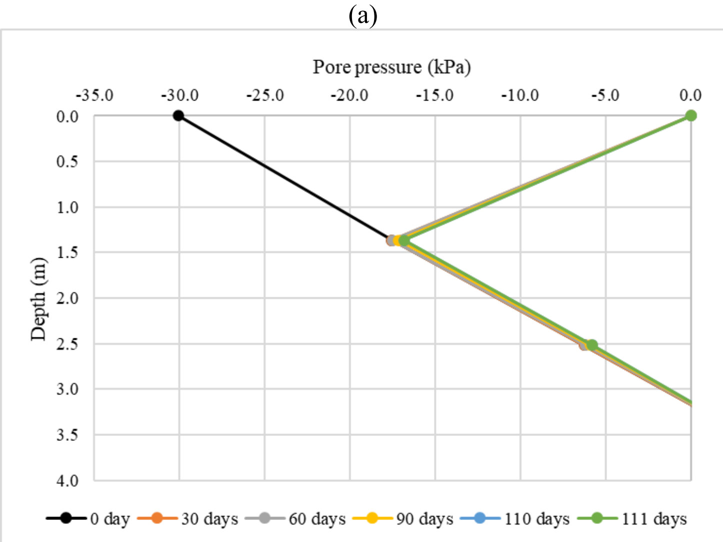


Fig. 7 - The pore water pressure distribution against time at random location (i.e crest)

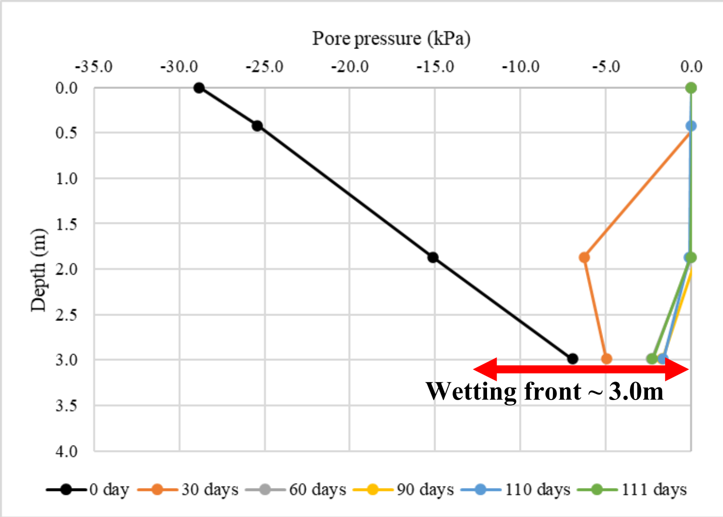
Fig. 8 shows the pore pressure profile at the crest, middle and toe respectively, of slope model (i.e for the first layer only; very soft silt).



(a)



(b)



(c)

Fig. 8 - Pore pressure distribution in very soft SILT (a) crest; (b) middle, and; (c) toe

From the figure, the wetting front had advancing up to 3.0m below surface level. After 110 days, the negative pore pressure gradually decreased towards zero matric suction when the rainfall was prolonged with the average 1-day rainfall intensity from the Intensity-Duration Frequency curve. The wetting front has already extended to the almost total depth of the first layer of slope model (i.e very soft to soft data). The matric suction at the middle (below embankment) was constant and did not affect much because the rainwater had taken a longer time to penetrate the embankment, by assuming a good construction practice to build the embankment.

3.2 Factor of Safety

Fig. 9 illustrates the factor of safety (FOS) against time. The FOS decreases with the daily rainfall within the wet season. As displayed in Fig. 7, the matric suction decreases as the rainfall proceeds. Therefore, the FOS of the slope model reduces once the matric suction decreases. In this modelling however, substantial changes were observed at the top layer of slope which can be seen that the slope failure plane also had developed within 3 m to 4 m from the ground level.

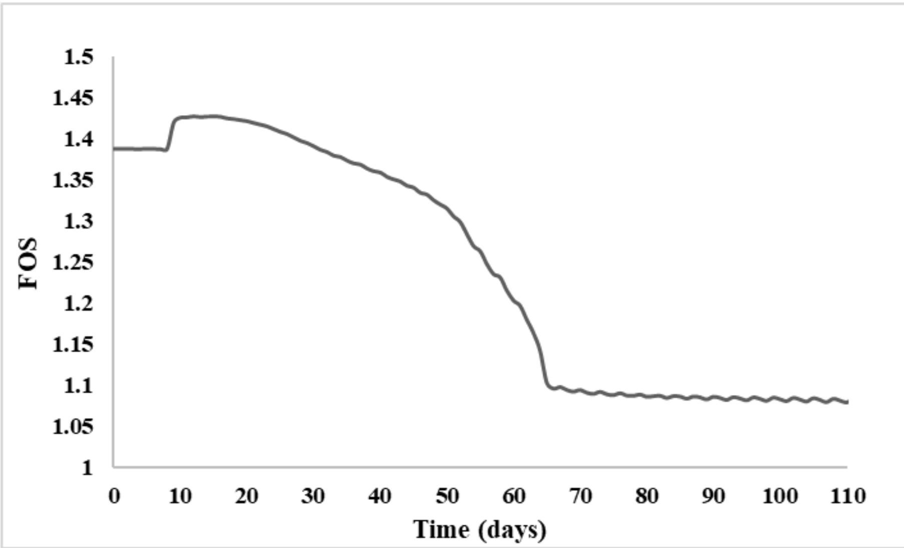


Fig. 9 - FOS versus time

4. Conclusion

In this study, a slope failure of Sarawak roads i.e Jalan Puncak Borneo, Padawan that happened on January 19th, 2015, was chosen as a case study to investigate the slope stability subjected to Sarawak rainfall pattern. A hyetograph of four months during the wet season in Sarawak region which normally occurred from October to February has been analysed to acquire the daily rainfall intensity function against time. From the hyetograph plotted, the Padawan area had experienced its highest rainfall in January 2015 with a total of 148.5 mm rainfall depth and the slope failure had occurred the next day. At the beginning of the monsoon season, the factor of safety of the slope was observed at 1.38. The factor of safety of the slope decreased with time and had reached 1.08 by the end of the monsoon period. The factor of safety, however, could not replicate the actual condition because most of key parameters were established based on empirical predictions and previous published data. The continuous rainfall event during the wet season or Northeast monsoon increased the moisture content of the soil mass and had consequently caused an increase of soil weight which reduces the stability of the slope. At the same time, the unsaturated strength that contributed by the matric suction of the soil mass also had diminished with time and substantially reduced the strength of the soil mass.

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