Paper 5

The Effect of Transient State Rainfall on Stability of a Residual Soil Slope

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Abstract

Abstract. *Slope instability attributable to rainfall occurrence is a common geotechnical problem in tropical Asian countries especially Malaysia. Many slope stability studies have illustrated the effect of infiltration on slope stability through combined use of seepage and slope stability analyses that require the definition of various hydrological characteristics of the soil, in addition to climatic information. To further understand the effect of rainfall, numerical modelling is commonly used to study how infiltration into slope varies with respect to rainfall intensity, and how this infiltration affects the stability of the slope. This paper attempts to identify the effect of transient state rainfall on stability of a common residual soil slope during specific rainfall duration. A numerical modelling of the case study is presented to simulate the changes in pore-water pressure due to different rainfall patterns and these are used to calculate the factor of safety of the slope. The results demonstrate that the transient state rainfall does play an important role in slope stability.*

Key words: *Transient analysis, Residual slope, Seepage, Unsaturated soil, Slope stability*

1.0 Introduction

Slope failures can be attributed to a number of factors such as geological features, topography, vegetation covers, weathering, or combinations of these factors. In most of tropical countries such as Malaysia, disastrous slope failures occur mostly due to concentrated heavy rainfall in residual soil slopes. These slope failures can be dangerous, disruptive to the development of infrastructures and quite costly to repair. It widely known that rain induces a rise of the groundwater level and an increase in pore water pressure that results in slopes failure. In general, slope failures occur most frequently during wet periods when there is an increase in moisture content and a decrease in matric suction. The infiltration from rainfall events penetrates into the surface of the slope causing increases in pore-water pressure, particularly near the surface. The increase in moisture content will result in decrease in matric suction and increase in pore water pressure effectively decreases the shear strength of the soil, making it more susceptible to failure (Rahardjo et. al., 2000). Usually the stability of the slopes can be considered in safety condition when the factor of safety, FOS is greater than one but the slope failure can also occur especially during rainfall events. The appropriate technology for preventing the slope failure caused by rainfall can be developed with special consideration being given to the local climate and geology (Terado et. al. 1999). However, the technology can be developed only if the mechanism of rainfall-induced slope failures is properly understood. It is crucial for soil engineers to understand the mechanism of slope failure induced by rainfall, and to apply appropriate stability analysis technique for proper prediction of slope behavior.

The study is carried out to investigate the landslide occurrence at the proposed Project of Laboratory Buildings in Universiti Teknologi Malaysia, Skudai, Johor. The soil movement on the failed slope has caused substantial failure of sheet pile wall positioned at the toe of the slope in the middle of December 1999. The previous studies showed that the effects of loading from the newly filled water tank sited on top of the slope contributed to subsidence of the slope surface within the vicinity by creating tension cracks near its raft footing (Azman & Fauziah, 2003; Ling, 2003, Harahap, 2003). Although a few studies have been carried out on the site but those analyses were done without taking any considerations on the effect of seepage to the failed slope. In this study, the transient rainfall infiltration at the failed slope for two months period (from November to December 1999) was firstly simulated by using a finite element commercial software, SEEP/W Version 5.0 (GEO-SLOPE International Ltd.) for generating the pore water pressure distributions and seepage pattern in the slope. Subsequently, the slope stability analysis was carried out by using SLOPE/W Version 5.0 (GEO-SLOPE International Ltd.) on the seepage patterns generated from the earlier transient analysis.

The objectives of this study are

1. to investigate the changes of pore-water pressure and development of seepage pattern due to rainfall infiltration within the period from November to December 1999,
2. to determine the factors of safety of the slope based on the seepage patterns and pore-water pressure profile generated, and
3. to investigate the effects of antecedent rainfall on pore-water pressure distribution, seepage pattern, and slope stability.

2.0 Methodology

This study is carried out in three main stages, i.e.: (1) Data collection, (2) Seepage Analysis, and (3) Slope stability Analysis. The rainfall data for the analysis period was obtained Malaysian Meteorology Services (Ministry of Science, Technology and Innovation) particularly for Senai Station (Figure 1). The maximum rainfall intensity was 46mm/day recorded on 5th December 1999. Others related data such as the slope geometries and soil properties are acquired from previous reports (Kassim, 2002; Azman & Fauziah, 2003).

The transient seepage analysis was carried out by using a commercial finite element codes, SEEP/W Version 5.0. It can be used for analyzing groundwater seepage and excess pore-water pressure dissipation problems within porous materials such as soil and rock. Its formulation allows considering any analysis of saturated steady-state as well as the saturated-unsaturated time-dependent conditions. The saturated-unsaturated formulation makes it possible to analyze seepage as a function of time and to consider such processes as the infiltration of precipitation. In addition, the transient feature allows for analyzing transient conditions such as the migration of a wetting front and the dissipation of excess pore-water pressure.

Firstly, an initial condition was established prior to transient analysis. In order to establish the pre-storm initial condition, a steady state analysis was carried out by applying a low unit flux (1.2684×10^{-8} m/s) to the slope surface. The unit flux value was applied to generate steady state suction value of 20kPa near the slope surface as indicated at actual site. As many as 913 element meshes comprised of 997 nodes were designed to represent the 90 m deep and 500 m long slope profile. The bottom boundary condition was set to zero flux, while the left and right side boundaries were specified as constant total head boundaries and zero total flux boundaries for boundaries below and above groundwater table, respectively. Lastly, the slope surface is treated as a flux boundary condition with varying rainfall intensity.

The transient seepage analysis was divided into two cases. For the first case, the seepage analysis was carried out for continuous rainfall within the entire period of analysis, i.e. 1st November to 31st December 1999 with daily time increment for 61 steps; while seepage analysis for antecedent rainfalls which were defined as Condition I, II, III and IV (Figure 1) was performed in second case.

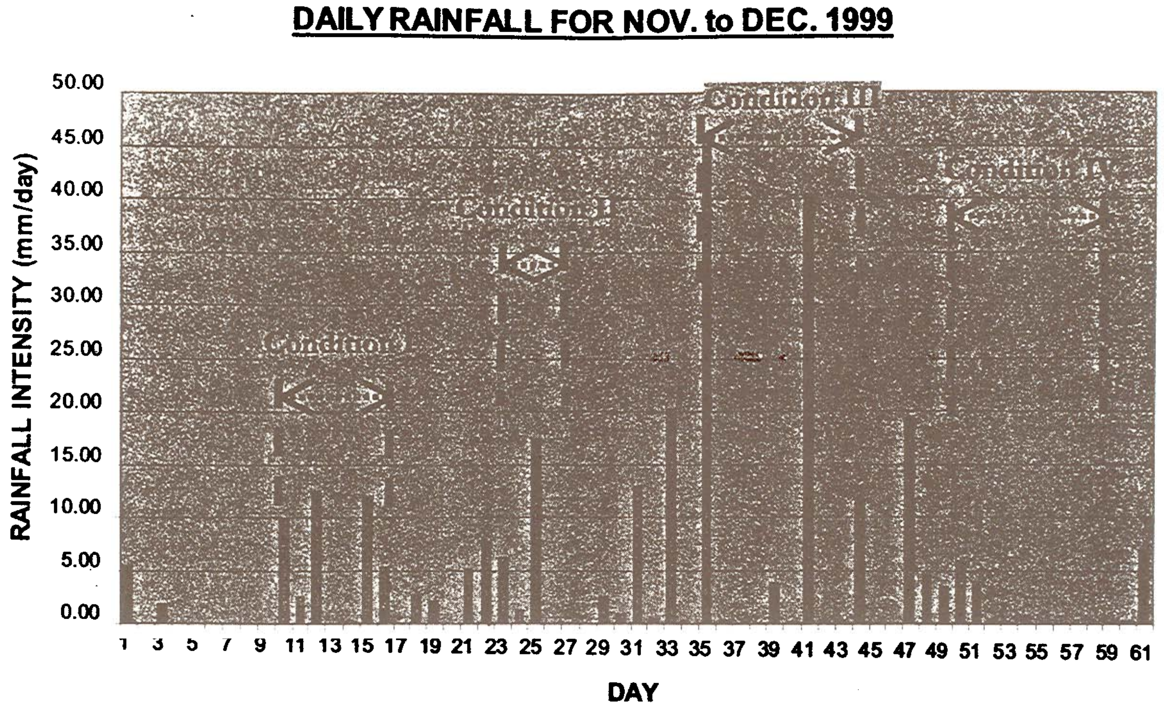


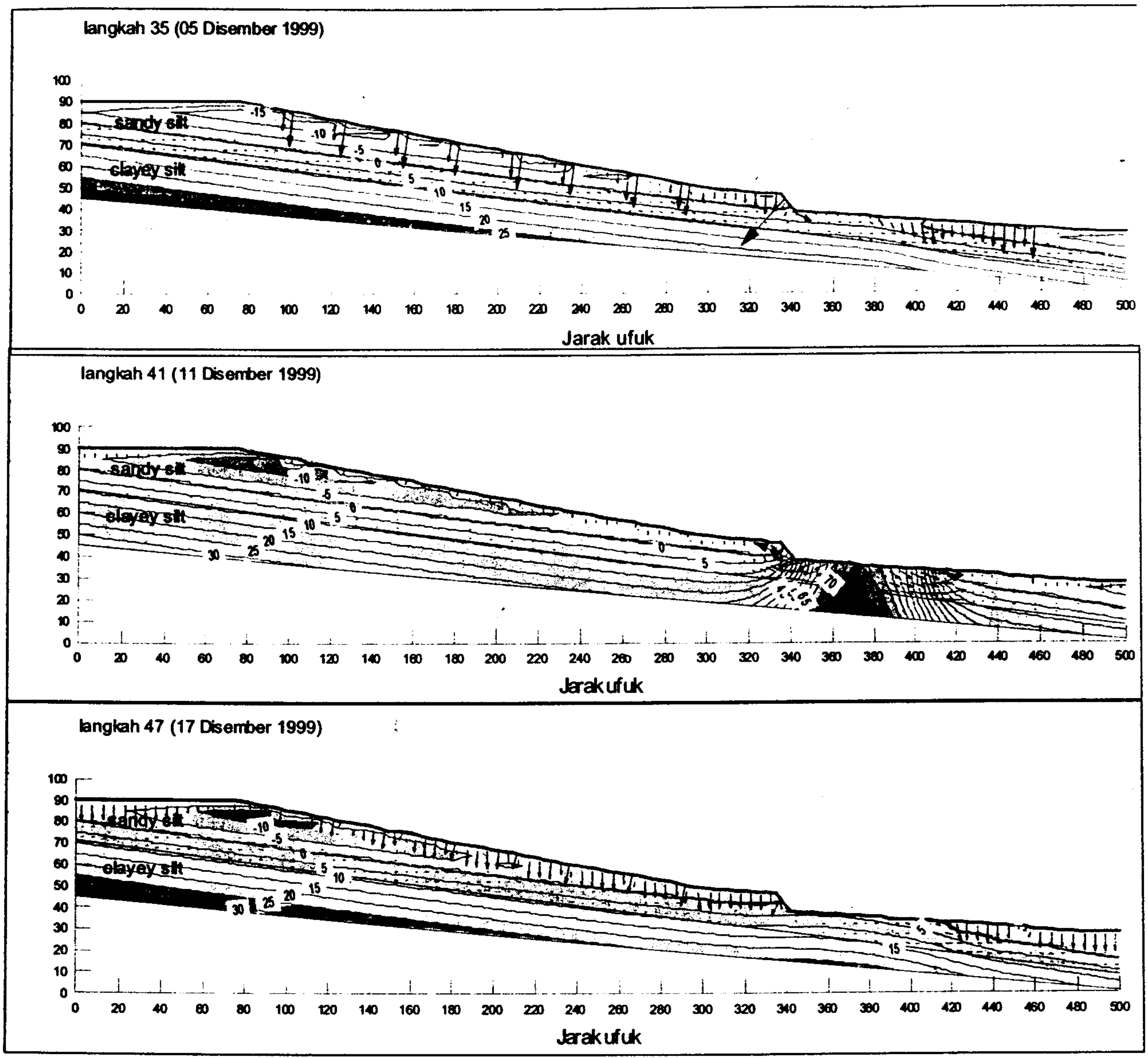
Figure 1: Rainfall intensity from November to December 1999 (Senai Station, Malaysian Meteorology Services)

In respect of slope stability analysis, the theory of limit equilibrium of forces and moments was used to compute the factor of safety against failure. A factor of safety (FOS) is defined as that factor by which the shear strength of the soil must be reduced in order to bring the mass of soil into a state of limiting equilibrium along a selected slip surface. The limit equilibrium formulation assumes that the soil behaves as a Mohr Coulomb material, and the FOS of the cohesive component of strength and the frictional component of strength are equal for all soil involved as well as for all slices.

3.0 Results And Analysis

For the first case in transient seepage analysis, three days with highest rainfall intensity were indicated, i.e. 5th December 1999, 11th December 1999, and 17th December 1999. The seepage pattern and pore-water pressure head profile, and the pore-water pressure head distribution at distance of 70m (crest), 200m (middle) and 375m (toe) for these three critical days are shown in Figure 2 and Figure 3 respectively. The correlation of rainfall intensity with the changes of pore-water pressure near the ground surface at crest, middle, and toe of the slope is shown in Figure 4.

Based on the pore water pressure profiles obtained, it showed that the pore-water pressure increased as rainfall infiltrated through soils and the infiltration rate depended on the rainfall intensity and frequency of the rainfall. The negative pore water pressure or matric suction changed to positive value at the soil layer near to the slope surface due to the rainfall infiltration. The rainfall infiltrated into the groundwater table in vertical direction. However, the infiltration could not penetrate into the second soil layer due to its permeability was very low as compared to the first soil layer, which resulted in accumulation of large pore water In addition, the results of total head distribution diagram showed that the total head at the toe of the slope is lower than the crest of the slope. It can be concluded that the seepage direction is flowing downwards due to the differences in pressure head gradient.


langkah 35 (05 Disember 1999)

langkah 41 (11 Disember 1999)

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Figure 2: Seepage patterns and pore-water pressure head profile on 5th, 11th and 17th December 1999

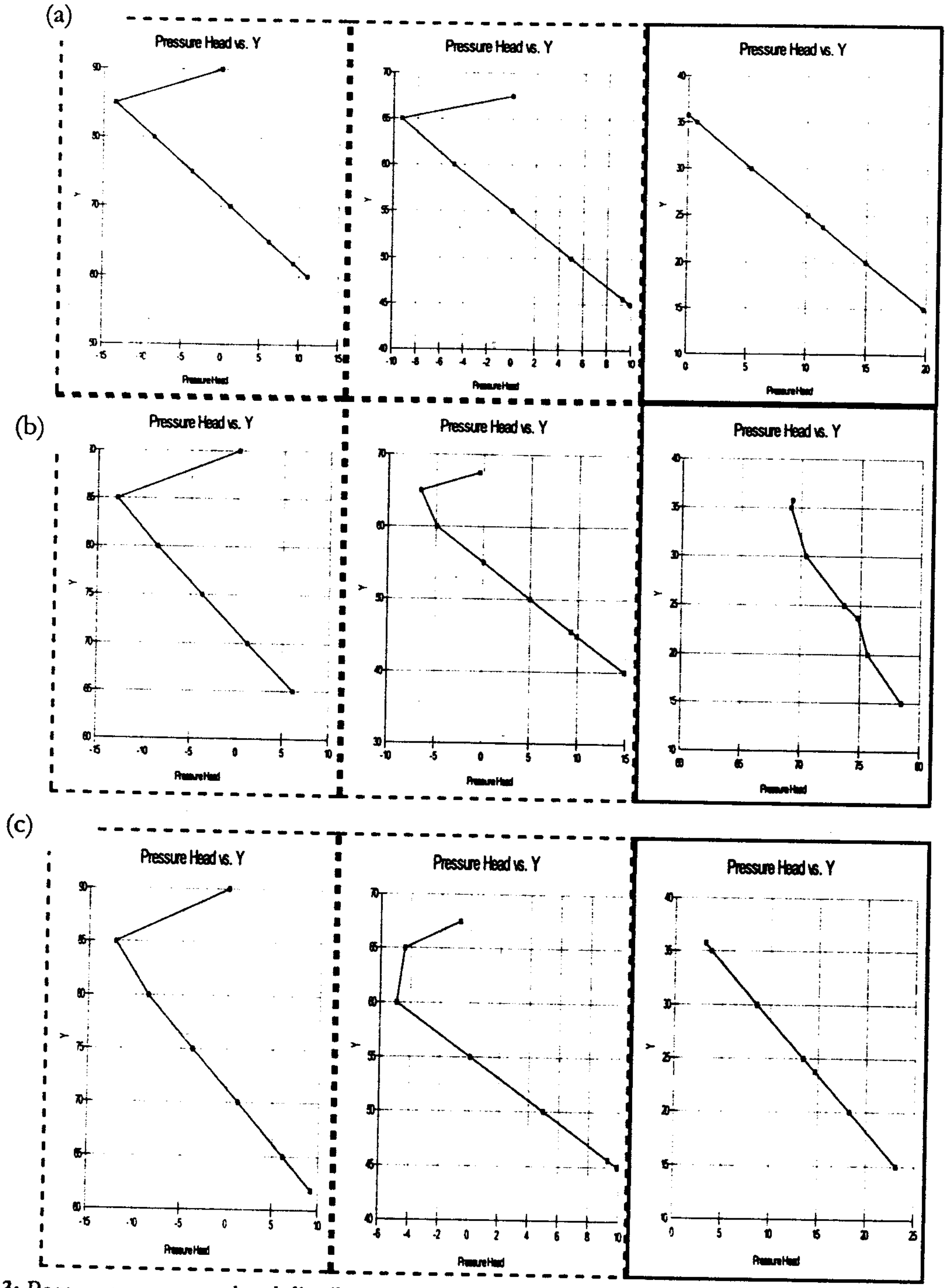


Figure 3: Pore-water pressure head distribution at distance of 70m, 200m and 375m for (a) 5th December 1999, (b) 11th December 1999 and (c) 17th December 1999

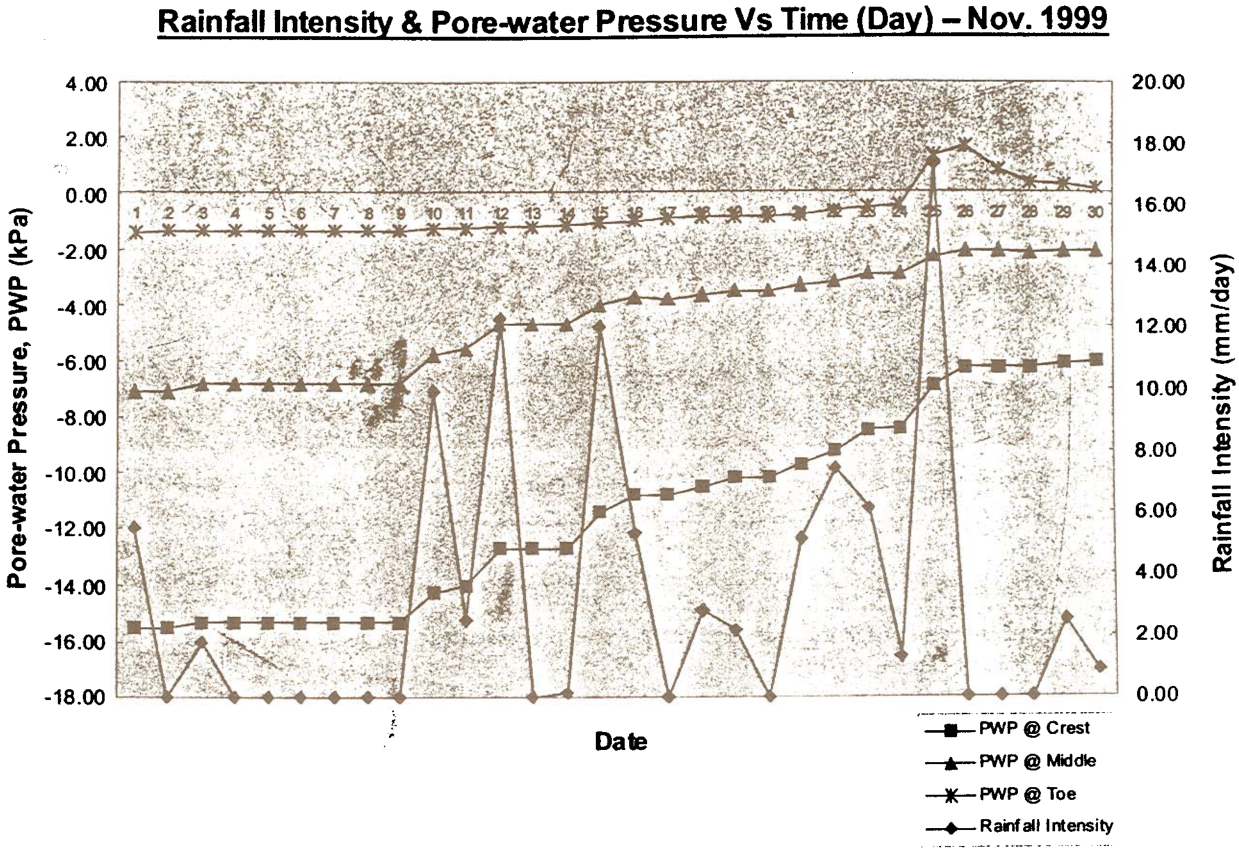
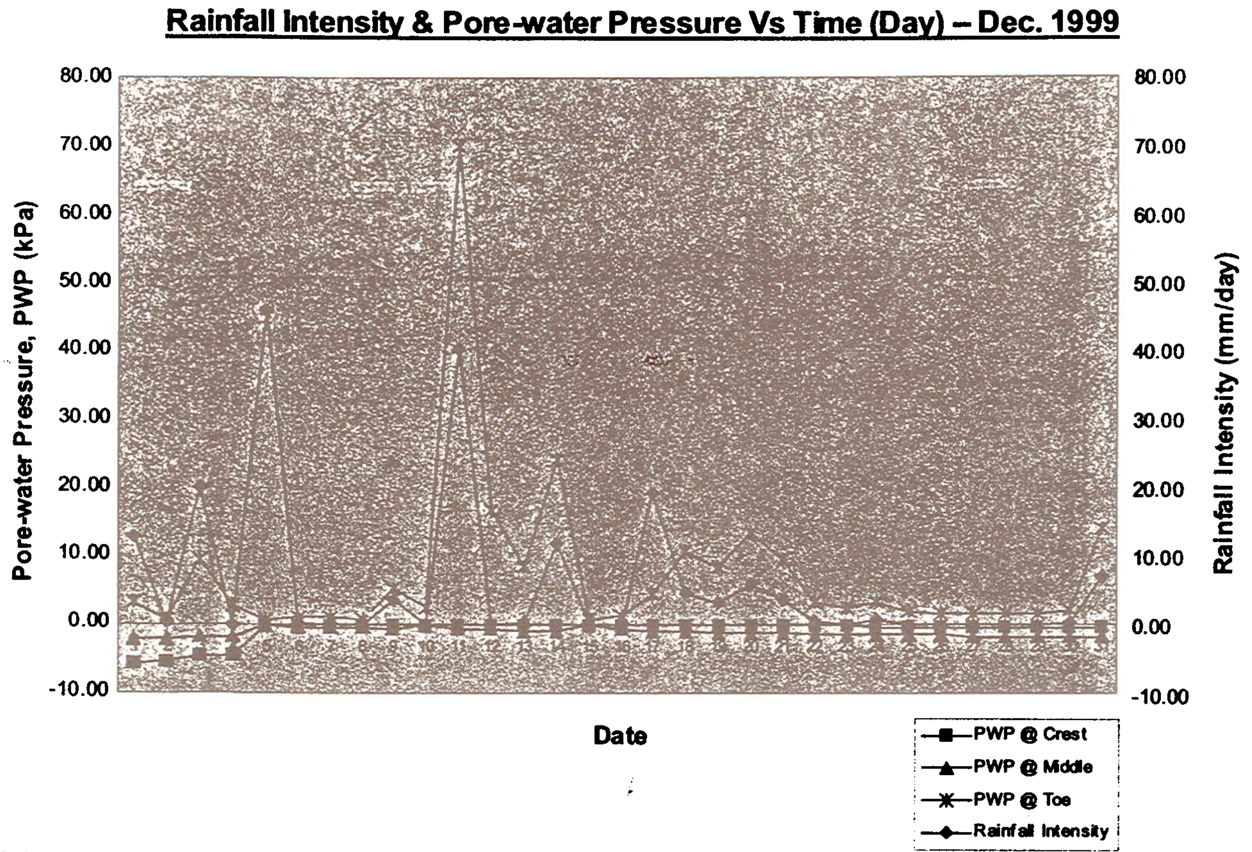
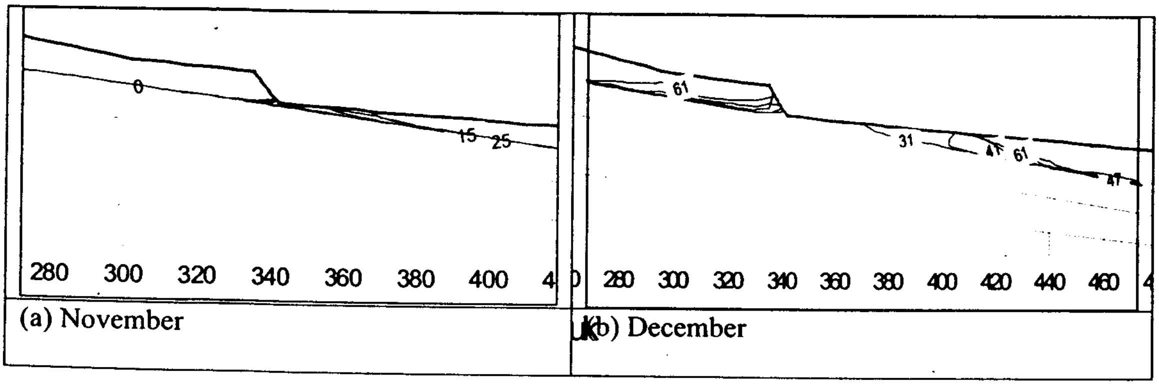


Figure 4: Relationship between rainfall intensity and pore-water pressure near the ground surface at crest, middle, and toe of the slope for (a) November



Relationship between rainfall intensity and pore-water pressure near the ground surface at crest, middle, and toe of the slope for (b) December 1999

In respect to the groundwater table, the changes of groundwater table responses to the rainfall infiltration are shown in Figure 5. It was observed that groundwater table increased dramatically at the toe of the slope after rainfall events. However, the groundwater table at the crest of slope was considerably constant throughout the analysis. This was due to the gradient of water table was quite steep along the slope. These conditions may be caused by a water regime that developed along the more impermeable layer (e.g. second layer) flowed in downwards direction.



(a) November

(b) December

Figure 5: Changes of ground water table in (a) November and (b) December 1999

In the second case, four conditions of rainfall were singled out from the continuous rainfall data in order to study the effect of antecedent rainfalls on the pore-water pressure distribution, hence on slope stability, i.e.:

1. Condition I: no rainfall at the beginning and following with low rainfall intensity.
2. Condition II: constant low rainfall intensity.
3. Condition III: heavy rainfall at the 3rd and 9th steps within 10 steps (days).
4. Condition IV: medium rainfall intensity in the beginning and followed by no rainfall in the end.

The seepage pattern and the pore-water pressure head distribution for these four conditions are illustrated in Figure 6, 7, 8 and 9 respectively. The result showed that Condition III has the most significant changes in pore water pressure. In this condition, there are two heavy rainfall events, in which the second rainfall event resulted in huge impact on the development of pore-water pressure, especially at the toe of slope. The pore water pressure increased greatly to 55kPa and a quick condition might be developed at the toe of the slope.

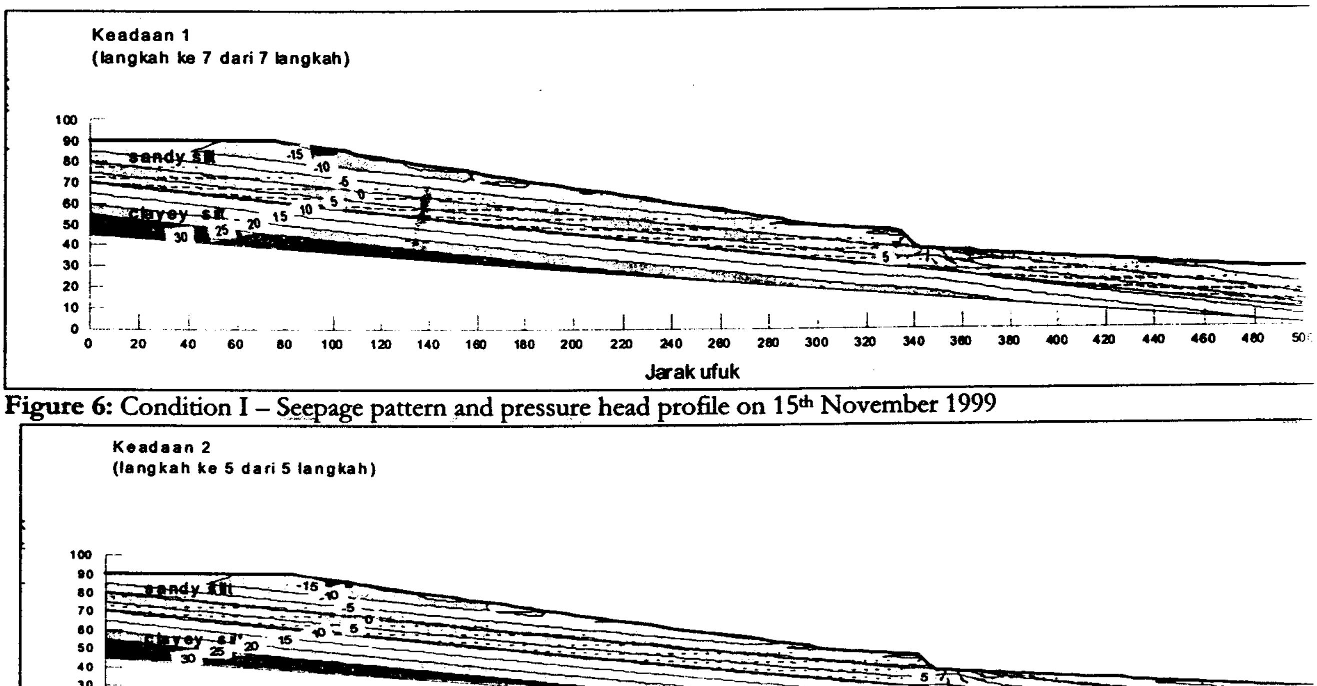


Figure 6: Condition I – Seepage pattern and pressure head profile on 15th November 1999

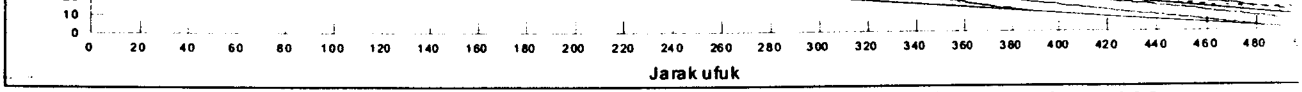


Figure 7: Condition II – Seepage pattern and pressure head profile on 25th November 1999

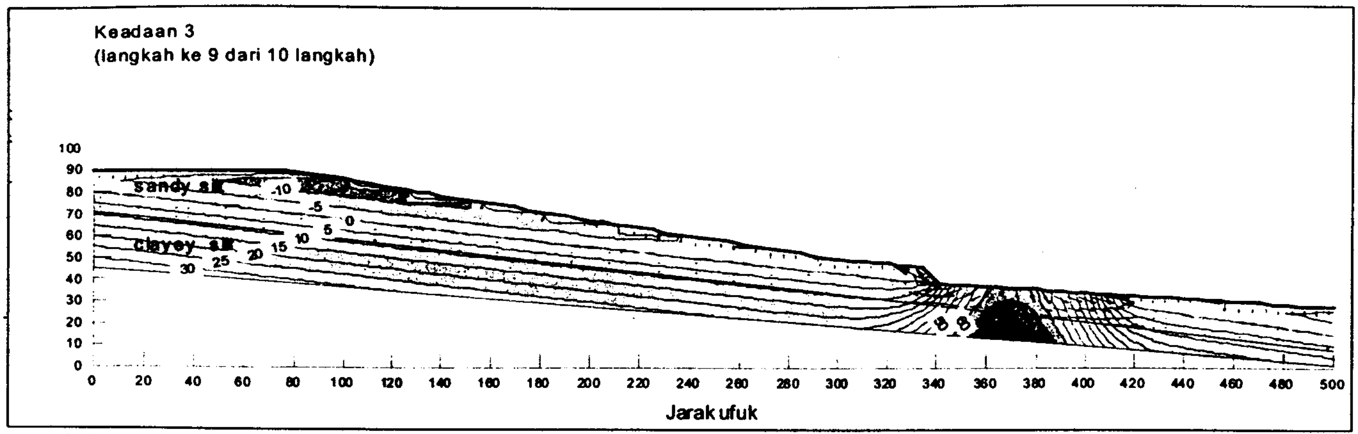


Figure 8: Condition III – Seepage pattern and pressure head profile on 11th December1999

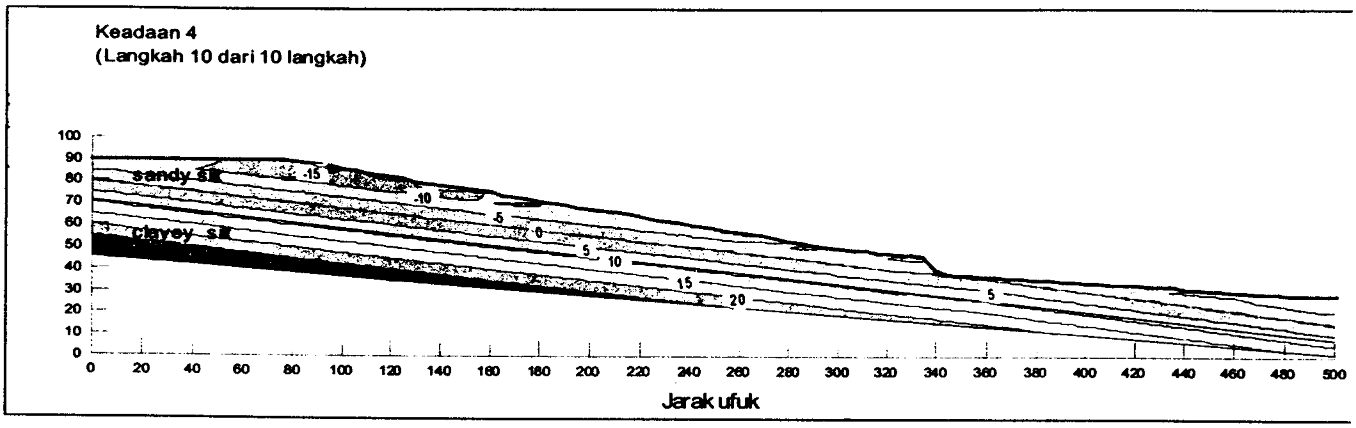


Figure 9: Condition IV – Seepage pattern and pressure head profile on 26th December1999

Based on the seepage patterns and pore-water pressure profiles obtained from the transient seepage analysis, the slope stability analysis was performed by using SLOPE/W. Figure 10 shows the correlation between factor of safety (FOS) and rainfall intensity for the entire analysis period. The result showed that the factor of safety of the slope did not change significantly from step 1 to step 40 (FOS between 1.2 and 1.4). The slight changes in FOS were mainly due to the slight changes in pore water pressure distribution initiated by rainfall infiltration.

It was found that most of the critical slip surface computed from SLOPE/W passed through soil Layer 2 with the average depth of 50m. However, exception was observed for step 41 where the critical slip surface only passed through soil Layer 1 at the toe of slope. The FOS dropped dramatically on step 41 (FOS = 0.279) indicated that the slope has failed. The seepage pattern and the pore-water pressure profile for step 41 revealed the worst condition recorded for the entire analysis period. Thus, it can be concluded that the slope failure was initiated by the failure at the toe of slope due to high pore-water pressure accumulated at that particular area. The slope stability analysis for step 42 to step 61 were ignored since the slope has failed and the results was unrepresentative.

Figures 11 to 14 show the effect of antecedent rainfall on slope stability. Similar to changes in pore-water pressure distribution, the FOS of the slope for Condition I, II and IV were only slightly affected the by the rainfall. However, the FOS dropped significantly in Condition III, which was found to have close relation with the changes in the pore-water pressure distribution as explained previously in above paragraph. The critical slip surfaces with the minimum FOS computed for the four conditions are shown in Figure 15.

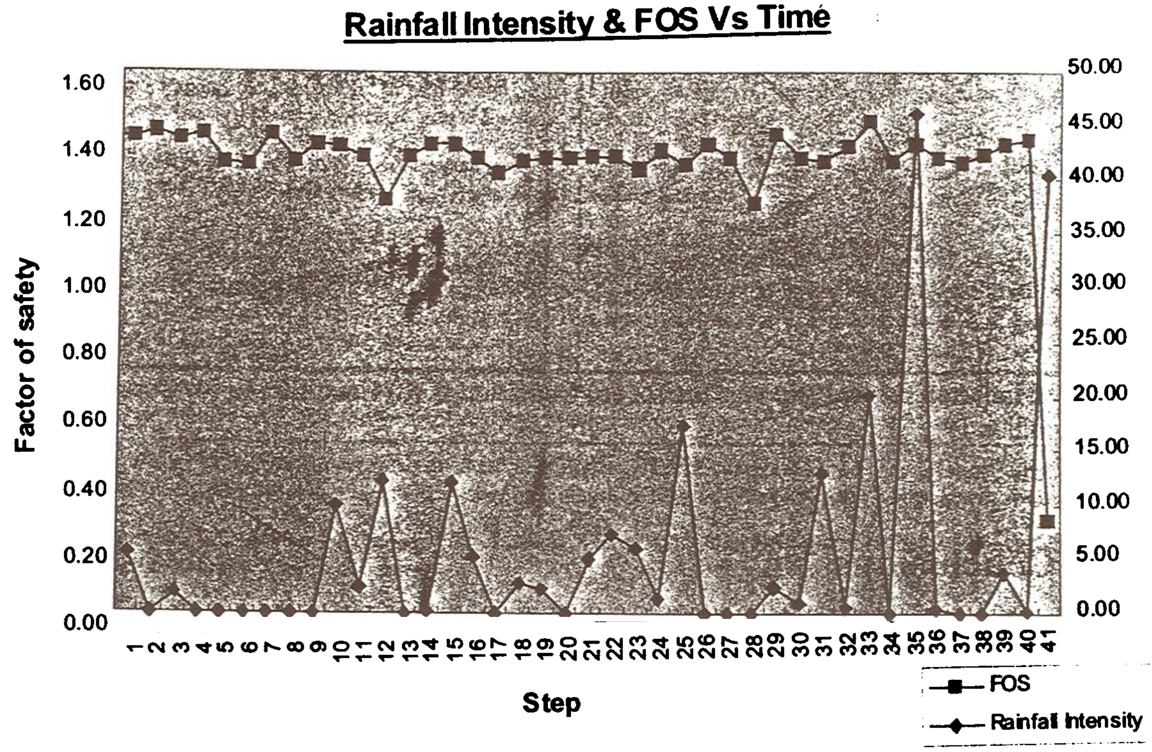
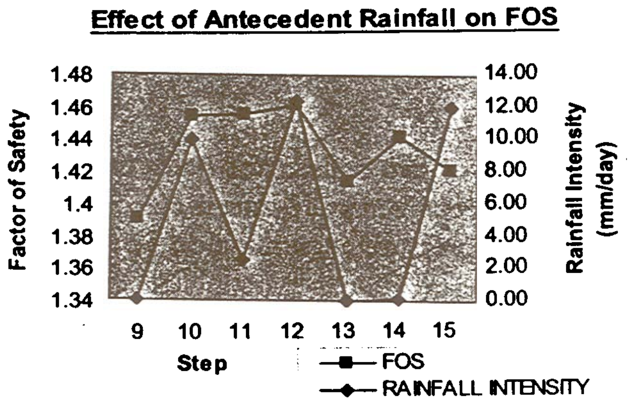


Figure 10: Relationship between factor of safety and rainfall intensity



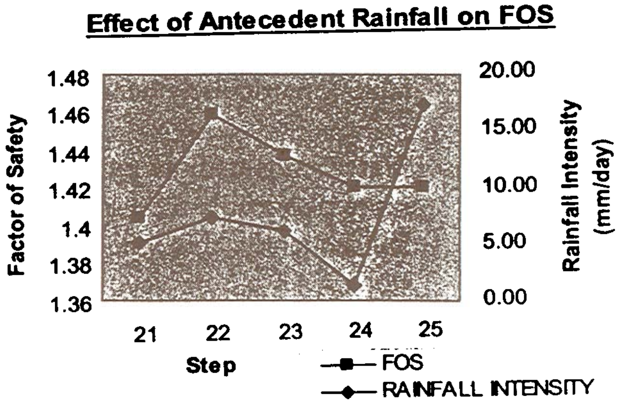
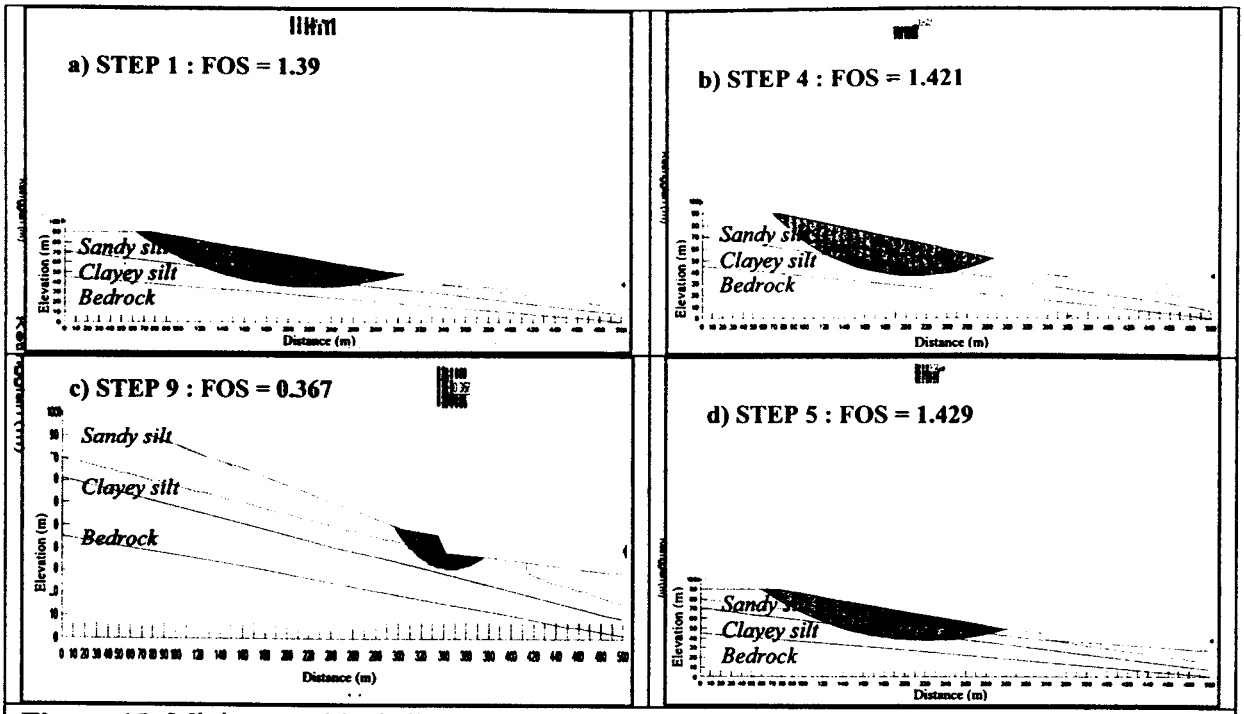


Figure 11: Rainfall intensity and FOS for Condition I
Figure 12: Rainfall intensity and FOS for Condition II


a) STEP 1 : FOS = 1.39

b) STEP 4 : FOS = 1.421

c) STEP 9 : FOS = 0.367

d) STEP 5 : FOS = 1.429

Figure 15: Minimum critical slip surface for (a) Condition I, (b) Condition II, (c) Condition III, and (d) Condition IV

4.0 Conclusions

The slope failure for the case study was initiated by the build-up of pore-water pressure at the toe of the slope, causing reduction in the soils shear strength and hence failure at the toe of the slope. The development of pore-water pressure was triggered by two heavy rainfall events occurred on 5th December and 11th December 1999. Based on the present results, the following conclusions can be drawn:

1. Rainfall penetrates into the surface of the slope, causing the loss in matric suctions, and eventually leads to positive pore–water pressure build up (i.e perched water tables), particularly near the surface.

2. Water tends to flow parallel along the interface of two soils layers (with upper layer more permeable than lower layer), instead of seeps vertically into the second layer. Subsequently, this will lead to the pore-water pressure accumulation at the toe of slope.

3. The increase in pore-water pressure effectively decreases the shear strength of the soil, making it more susceptible to failure. Thus, pore-water pressure distribution is an important factor to be considered when assessing the stability of a slope against rainfall induced slope failure.

4. Rainfall patterns have significant effect on the development of pore-water pressure, and hence on slope stability. Rainfall pattern refers to the rainfall

intensity, rainfall duration, and its occurrences but not depends solely on the amount of rainfall.

5. Both continuous rainfall and antecedent rainfall are important triggering factors for the occurrence of the slope failures. However, the soil properties such as permeability, shear strength are the controlling parameters as well.

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