The influence of rainfall sequences on negative pore-water pressures within slopes

Influence des précipitations sur les profils de succion dans les pentes

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ABSTRACT: The paper describes an investigation of the influence of rainfall infiltration on the negative pore-water pressures within residual soil slopes. Four research sites in Singapore were instrumented to measure rainfall, run-off and pore-water pressures/suctions. The results from one site are presented and show that when the initial pore-water pressures were already high (close to zero near the surface and positive at depth) that different rainfall events (86 mm and 13 mm in total) produced similar very small changes in the pore-water pressure. However, when the pore-water pressures were initially low then a very small rainfall event (1 mm in total) was able to produce much larger changes in pore-water pressure. Two other rainfall events (14 mm and 125 mm) during periods of low initial pore-water pressures produced similar large changes in the pore-water pressures. The pore-water pressure changes were not dependant only on the amount of rainfall but were significantly affected by the initial pore-water pressures. This shows the important role played by antecedent rainfall, as the rainfall that has fallen previously controls the initial pore-water pressures.

RÉSUMÉ: Le papier décrit une étude de l'influence de l'infiltration des précipitations sur les profils de succion dans un sol résiduel en pente. Quatre sites de recherche à Singapour ont été équipés d'instruments pour mesurer les précipitations, écoulements et profils de succion. Les résultats obtenus sur un des sites sont présentés. Ils montrent que quand le pression intersitielle initial est important (proche de zéro en surface et positif en profondeur) les différentes précipitations (86 mm et 13 mm au total) ont produit de très petits changements des profils de succion. Par contre, quand ces derniers sont initialement petits, alors une faible précipitation (1 mm au total) peut leur produire des changements importants. Deux autres précipitations (14 mm et 125 mm au total) pendant des périodes de faible pression intersitielle ont produit des changements importants à ces derniers. Les variations des profils de succion ne dépendent pas seulement du volume des précipitations mais sont aussi affectées d'une façon significative par les profils de succion initiaux. Ceci montre le rôle important des précipitations précédentes en l'occurence la dernière précipitation contrôle les profils de succion initiaux.

1 INTRODUCTION

Rainfall-induced landslides are a common occurrence in many tropical regions of the world. Many slopes are sustained by the presence of suctions (or negative pore-water pressures) and reductions in suction due to rainfall infiltration can result in failures. Such slope failures create difficulties in maintaining the transportation infrastructure of tropical countries, as failures of cut slopes and embankments cause significant disruption to road and rail networks.

Although the correlation between rainfall and landslides is widely recognised (e.g. Brand, 1984), there has been some debate as to the relative roles of antecedent rainfall (i.e. rain that falls in the days immediately preceding a landslide event) and the triggering rainfall (i.e. rain that falls at the time that the landslide occurs). Experiences from different regions of the world have resulted in different conclusions as to the significance of antecedent rainfall for slope instability.

The paper describes an investigation of the influence of rainfall patterns on the pore-water pressures within a typical residual soil slope. The study is divided in three parts: (i) presentation of the observations of pore-water pressures in a instrumented slope in Singapore due to natural rainfall events for 12 continuous months (ii) observations of pore-water pressure changes during specific rainfall events when the initial pore-water pressures were different (iii) observing the antecedent rainfall and how that correlates with the initial pore-water pressures.

2 FIELD MEASUREMENTS

Four research sites in Singapore were instrumented as part of a major study of rainfall-induced landslides in Singapore (Rahardjo et al, 2000). Measurements were made of rainfall, run-off and pore-water pressures/suctions. Only one of those sites will be discussed in this paper. This was on the Nanyang Technological University (NTU) campus. The location of the NTU campus is shown in Fig. 1. The site was adjacent to the School of Civil and Structural Engineering (CSE) and was known as NTU-CSE.

The site comprised residual soils derived from the Jurong Sedimentary formation. These residual soils exist as interbedded layers of predominantly medium plasticity clayey silt, sandy clay and clayey to silty sand materials (Chang, 1988). The soil conditions at the NTU-CSE site (at the mid-height of the slope) consist of about 2m thickness of low plasticity silt and clay overlying a hard silty sand (Rahardjo et al, 2000). Saturated permeabilities to water (k_s) ranged from 2×10^{-7} to 8×10^{-7}m/s in the upper layer and were 3×10^{-9}m/s in the harder underlying layer (Gasmo et al, 1999; Agus et al, 1999).

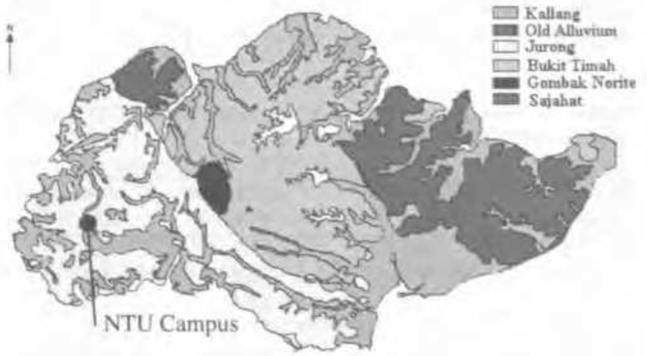

Figure 1. Geological map of Singapore (After Pitts, 1984) showing the site location.

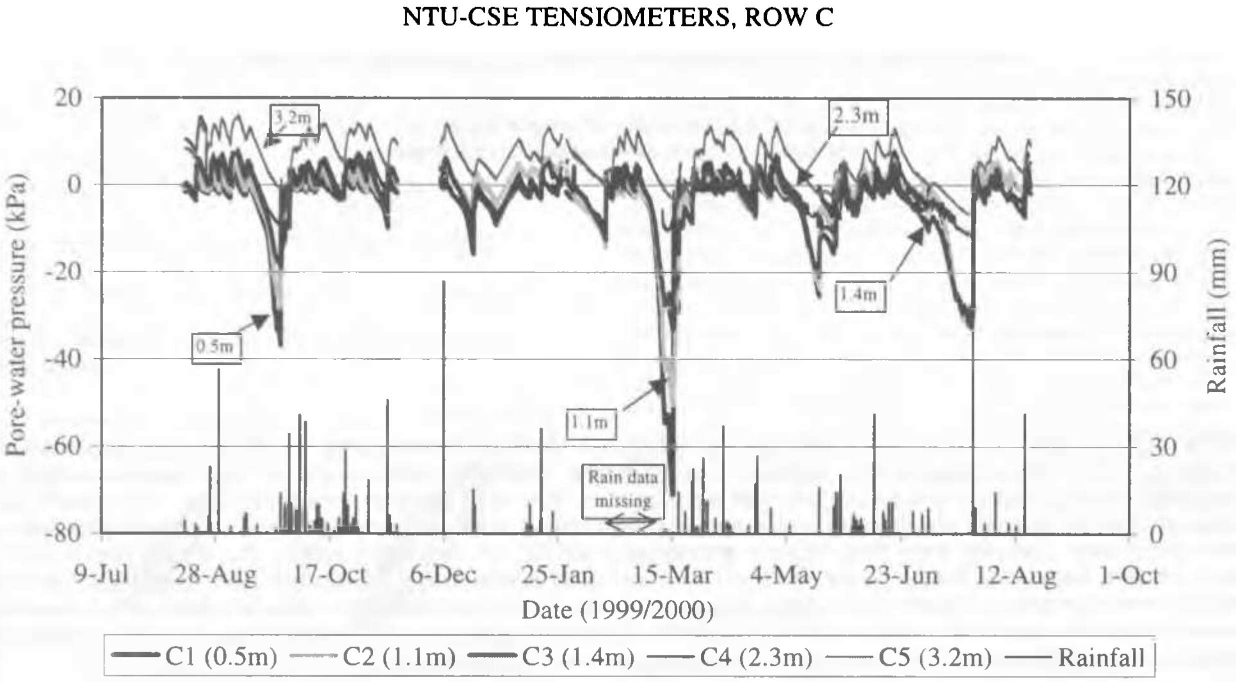

Figure 2: Pore-water pressure and rainfall measurements for the NTU-CSE slope.

Full details of the instrumentation regime are given by Rahardjo et al (2000). Negative pore-water pressures in the unsaturated zone above the water table were measured using jet-fill tensiometers. These were installed at depths of 0.5, 1.1, 1.4, 2.3 and 3.2 m at the NTU-CSE site. Piezometers were also installed at greater depth to monitor changes in groundwater levels. Rainfall gauges were installed on each slope to provide rainfall data specific to that site.

The pore-water pressures within the NTU-CSE slope were monitored from August 1999 until August 2000. Fig. 2 shows the pore-water pressures at the various measuring depths for a row of tensiometers installed near the mid-point of the slope (6m downslope from the crest). Tensiometer readings were taken every 20 minutes and the full set of readings are shown in Fig. 2. The daily rainfall is also shown as a bar graph in Fig. 2. At this site, piezometer data (Rahardjo et al, 2000) indicates that the groundwater table is 10 m below the ground surface.

It can be seen from Fig. 2 that the pore-water pressures within the NTU-CSE slope were, for a large part of the monitoring period, only slightly negative and at 3.2m depth were generally positive. However, there were six periods during the year when pore-water pressures reduced significantly following a drier period. During March 2000, pore-water pressures dropped to as low as –70 kPa near the surface (0.5 m depth). Table 1 presents a summary of the range of measured pore-water pressures at different depths for this particular row of tensiometers.

Table 1. Summary of the measured pore-water pressures at the mid-height of the NTU-CSE slope.

Depth (m)	Maximum (kPa)	Minimum (kPa)	Average (kPa)
0.5	4.6	-71.2	-3.8
1.1	7.2	-50.5	-2.8
1.4	7.4	-33.4	-2.9
2.3	15.7	-12.2	0.1
3.2	16.2	-7.8	6.4

3 ANALYSIS OF THE FIELD MEASUREMENTS

A closer look at specific periods within the year-long record shown in Fig. 2 shows that the effect of rainfall (in terms of producing a change in pore-water pressure) is heavily influenced by the pore-water pressures at the start of a rainfall event. This can be demonstrated by comparing five rainfall events that are shown in chronological order in Figs. 3 to 7. Figs. 3, 6 and 7 show the response to rainfall following dry periods when the pore-water pressures were initially low. Figs. 4 and 5 show rainfall events that follow wet periods when the pore-water pressures were generally positive.

The effect can most clearly be seen by comparing the result of a large rainfall event in December 1999 (when the pore-water pressures were already positive) to a small rainfall event after a dry spell in March 2000 (at a point where the pore-water pressures were at their most negative).

Fig. 5 shows the pore-water pressure response to the large rainfall event totalling 86 mm of rain that fell on 6th December 1999. The event lasted over 4 hours, but the majority of the rain fell in the first 1.5 h and achieved an intensity of over 120 mm/h. Prior to this event the pore-water pressures near the surface (0.5 m) were slightly negative. However, at depths of 1.1 to 2.3 m pore-water pressures were positive, around 5 kPa. At a depth of 3.2 m the pore-water pressure was over 10 kPa. It can be seen in Fig. 5 that during the rainfall event that the pore-water pressure at 0.5 m increased by about 5 kPa but then dropped away after the end of the rainfall to a value of around 2 kPa. At depths below 1 m the pore-water pressures increased more slowly and continued to increase after the rainfall event as water drained down from the surface with time. However, the changes were relatively small; a day after the start of the rainfall event the pore-water pressures showed an increase of less than 5 kPa compared to those prior to the rainfall event.

In contrast, Fig. 6 shows the response to a rainfall event after a dry period in March 2000. The rainfall event in this case was only about 1mm in total (lasting for about 2.5 hours with a peak intensity of about 0.5 mm/h). It can be seen that the pore-water pressures near the surface (0.5 m) were below –70 kPa. Even at a depth of 3.2 m the pore-water pressures were negative, around –5 kPa. In this case the small rainfall event produce very large

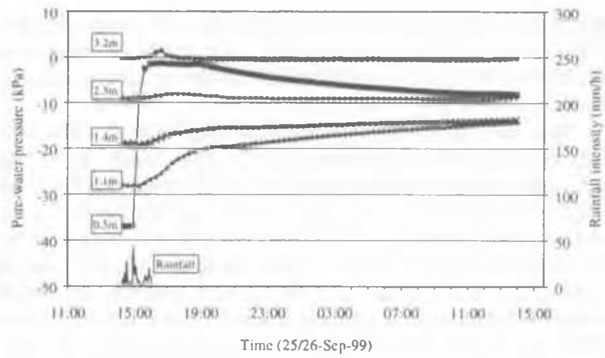

Figure 3. Changes in pore-water pressure due to rainfall after a dry period (25 September 1999)

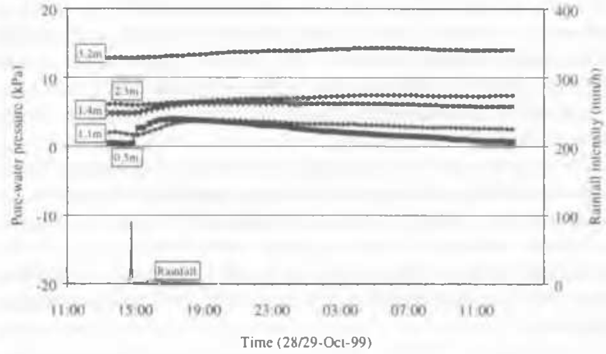

Figure 4. Changes in pore-water pressure due to rainfall after a wet period (28 October 1999).

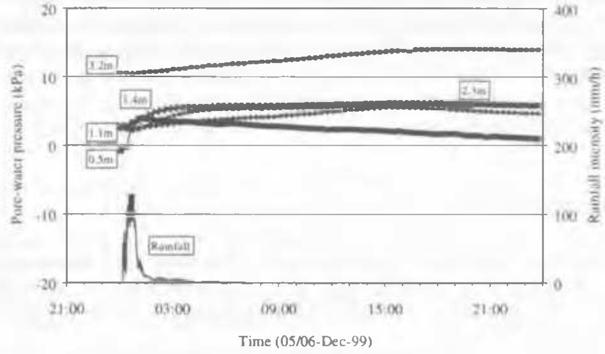

Figure 5. Changes in pore-water pressure due to rainfall after a wet period (6 December 1999)

changes in pore-water pressure at the shallower depths. Most affected was the pore-water pressure at 0.5 m depth. Here the pore-water pressure increased from –70 kPa to above –10 kPa during the rainfall event. The values then decreased after the rainfall (to around –30 kPa) as the water that had infiltrated at the surface gradually drained down to lower levels. This can be seen by the pore-water pressure response at a depth of 1.1 m. At this depth there is not a rapid jump during the rainfall event, but the pore-pressure steadily increases over the day and reach a value around –30 kPa by 24 h after the start of the rainfall event. Smaller changes can be seen at depths of 1.4 m and 2.3 m, but virtually no change at a depth of 3.2 m.

Therefore it can be seen that a very large rainfall event (86 mm in total) produced only small changes in pore-water pressure (less than 5 kPa) when it occurred during a period when initial pore-water pressures were already high. However, when the pore-water pressures were initially low then a very small rainfall event (1 mm in total) was able to produce much larger changes in pore-water pressure (of the order of 40 kPa).

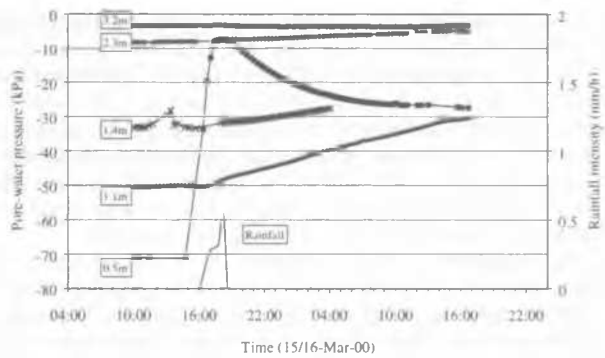

Figure 6. Changes in pore-water pressure due to rainfall after a dry period (15 March 2000)

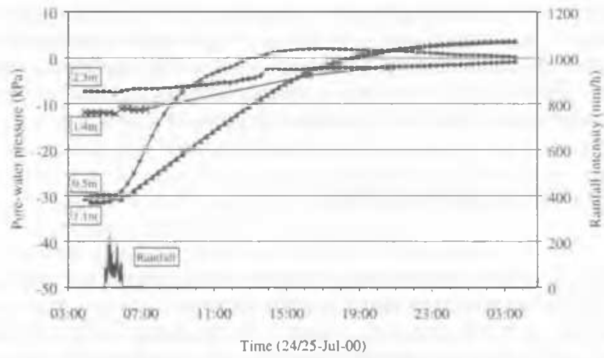

Figure 7. Changes in pore-water pressure due to rainfall after a dry period (24 July 2000)

The other events confirm this general pattern. If we consider another 'wet period' in 28th October 1999 (Fig. 4) we can see that the measurements at the various depths show high pore-water pressures. The rainfall event that occurred that day involved 13 mm of total rainfall distributed over nearly 4 hours, but most of the rainfall was precipitated during the first 0.5 h. The initial pore-water pressures at 0.5 m depth were less than 1 kPa and during the rainfall event reached a maximum value of 4 kPa. The increases in the pore-water pressures at depths greater than 1 m were more gradual and continued to increase for more than 24 hours, but were still small.

Comparing the two 'wet periods' of 6th December 1999 and 28th October 1999 we can see that the development of the pore-water pressures is very similar, even though the rainfall patterns of the two rainfall events are very different. In both cases the increase in pore-water pressure was very limited even though on 6th December 1999 a large rainfall event of 86 mm occurred and on 28th October 1999 only 13 mm of rainfall was precipitated.

Figs. 3 and 7 present the development of the pore-water pressures following two further 'dry periods'. They show rainfall events that occurred on 25th September 1999 (Fig. 3) and on 24th July 2000 (Fig. 7). The initial conditions in the slope at the start of these two rainfall events were very similar. On 25th September 1999, the pore-water pressures at 0.5 m depth at the start of the rainfall event were –36 kPa and on 24th July 2000 the initial pore-water pressures at 0.5m depth were –30 kPa. However, the amounts of precipitation were very different. On 25th September 1999 only 14 mm of rainfall was precipitated over about 2 hours, while on 24th July 2000 125 mm was precipitated over 8 hours. The rainfall event of 24th July 2000 was the largest during the monitoring period.

The development of the pore-water pressures near the ground surface, during the two rainfall events, do not differ enormously. During the rainfall event of 25th September 1999 the pore-water pressures at 0.5 m increased from –36 kPa to –1 kPa, but did fall away to –8 kPa about a day after the rainfall event. At 1.1 m and 1.4m depths the increase was 16 kPa and 5 kPa respectively, while at greater depths the changes were very limited. During the rainfall event of 24th July 2000 the pore-water pressures at 0.5 m deep increased from −30 kPa to 2 kPa. At 1.1 m deep the pore-water pressures increased from −31 kPa to 4 kPa after 24 hours. At greater depths the increase of the pore-water was more limited but the pore-water pressures at all depths reached a narrow band between −1 kPa and 2 kPa. Unfortunately due to technical problems the pore-water pressures at 3.2m deep could not be measured during the rainfall event of 24th July 2000.

The comparison of the developments of the pore-water pressures of the above two rainfall events show that although the total rainfall was very different the pore-water pressure changes near the ground surface were not as different as might have been expected. The larger rainfall event in July 2000 did produce pore-water pressures at all depths that were near zero a day after the event, whereas the smaller rainfall event in September left residual pore-water pressures between −15 kPa and −8 kPa. Nevertheless, the changes in pore-water pressure induced were of the same order, even though the amounts of rainfall were significantly different. This shows that the initial conditions have a major effect on the resulting pore-water pressure change. The changes cannot be simply related to the amount of rainfall.

4 ANTECEDENT RAINFALL

Table 2 presents the antecedent rainfall that was measured prior to the five rainfall events described earlier. Antecedent rainfall has been calculated for three periods: 1-day, 5-day and 15-day. It was suggested by Lumb (1975) that a 15-day period was appropriate for studying the effects of antecedent rainfall on landslides in Hong Kong. However, Chatterjea (1989) and Li (1995) have suggested that such a long period is inappropriate for the rainfall pattern in Singapore. They adopted periods of 5 and 6 days respectively.

Table 2. Summary of the antecedent rainfall prior to the rainfall events

Date of rainfall event	1-day antecedent rainfall (mm)	5-day antecedent rainfall (mm)	15-day antecedent rainfall (mm)
25 Sep 1999	0	2	20
28 Oct 1999	9	68	88
6 Dec 1999	0	98	107
15 Mar 2000	0	2	*
24 July 2000	1	2	2

* rainfall data missing for part of the 15 days preceding the event

It can be seen that for the 'wet periods' in October and December 1999 when the initial pore-water pressures were near zero at 0.5 m depth that the rainfall in the previous 5 and 15 day periods was high (>60 mm for 5 days and >80 mm for 15 days). On 28th October, 9 mm of rain had fallen on the previous day and hence the pore-water pressures were all positive.

For the 'dry periods' the 5-day antecedent rainfall was only 2 mm in all three cases and the 15-day antecedent rainfall was less than 20 mm. Unfortunately data is not available for the whole 15 day period for 15th March 2000 but since this is the period when the lowest pore-water pressure was recorded (-71 kPa) it is likely that the 15-day antecedent rainfall was lower than that for the other two 'dry periods'. However, the fact that 1 mm of rain fell on the day prior to the event of 24th July 2000 may well have had the effect of increasing pore-water pressures.

5 CONCLUSIONS

Measurements of pore-water pressures in slopes in Singapore show that antecedent rainfall is very important in controlling the pore-water pressure response during a rainfall event. It was seen that a very large rainfall event produced only small changes in pore-water pressure when it occurred during a period when initial pore-water pressures were already high. However, the field observations showed that when the pore-water pressures were initially low then a very small rainfall event was able to produce much larger changes in pore-water pressure.

It was also seen that two rainfall events with large differences in total rainfall, but both falling during 'wet periods' (with high initial pore-water pressures) produced very similar small changes in the pore-water pressures. Also, in 'dry periods' with low initial pore-water pressures, it was observed that two rainfall events with large differences in total rainfall produced similar changes in the pore-water pressures. This suggests that the pore-water pressure changes were not dependant only on the amount of rainfall but were significantly affected by the initial pore-water pressures.

The initial pore-water pressure conditions prior to a rainfall event are controlled by the antecedent rainfall. The 'wet periods' (where the pore-water pressures were near-zero and generally positive) were periods where the antecedent rainfall for a 5-day period was greater than 60 mm and for a 15-day period was greater than 80 mm. For the 'dry periods' (where pore-water pressures near the surface were below −30 kPa) the 5-day antecedent rainfall was only 2 mm and the 15-day antecedent rainfall was less than 20 mm.

This shows the important role played by antecedent rainfall, as the rainfall that has fallen previously controls the initial pore-water pressures. These results show that initial conditions within the slope, expressed either as antecedent rainfall or as initial pore-water pressure distribution within the slope is a controlling parameter for any changes in the pore-water pressures during infiltration.

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