Effect of Rainfall on Matric Suction and Stability of a Residual Granite Soil Slope

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ABSTRACT

Field instrument program was carried out to monitor in-situ matric suction in a granite residual soil slope. The variation in matric suction due to changes in climatic condition was investigated and to study its effect on slope stability. Matric suction in the soil increased during dry periods and decreased during wet periods. Maximum change in matric suction occurred near the ground surface and the magnitude of matric suction change decreased with depth. The amount of decrease in matric suction after a rainfall was observed to be a function of the initial matric suction just prior to the rainfall. Effect of matric suction on the slope stability is also investigated.

Keywords: **Matric suction, slope Stability, Granite soil.**

1. INTRODUCTION

Land slides in steep residual soil slopes are common in tropical and semitropical region. The occurrence of landslides in residual soil slopes is attributed to many factors. Rainfall has been considered to be the main causes of the majority of landslides that occurs in regions experiencing high seasonal rainfall [1]. Most of the rainfall-induced landslides in residual soils consist of relatively shallow slip failure above the groundwater table [2]. The mechanism of failure is that water infiltration causes a reduction of matric suction in the unsaturated soil, resulting in a decrease in the effective stress reflected in a decrease in the soil strength to a point where equilibrium can no longer be sustained in the slope. The soil suction and the water content, how these vary with time are often the most important variables in geotechnical engineering design. Field monitoring of in-situ matric suction in slopes has been conducted by a number of researchers, e. g. Krahn et. al. [3], Affendi and Faisal [4], Lim et. al. [5] and Low et. al. **[6]**. In most of the studies, Tensiometers are commonly used in the field instrumentation to measure matric suction in soil, as long as the suctions are less than 100 kPa. A granite residual soil slope at Hospital Universiti Kebangsaan Malaysia (HUKM) was instrumented. To study the change in matric suction in the slope due to changes in climatic condition and its effect on slope stability.

2. SOIL PROPERTIES

The instrumented slope is located in a granite soil formation at HUKM in Cheras, just 8 km south of Kuala Lumpur from the capital city of Malaysia. To study the geotechnical properties of the residual granite soil, block samples were obtained from trenches that were dug into the slope during the rainy season, when the soil was moist. The mean dry density obtained from field tests was 13.6 kN/m^3 and natural moisture content of about 31%. The specific gravity of this soil is 2.61. The liquid and plastic limits of the soil are 69% and 39% respectively. The fines content (i. e., percent finer than U. S. 200 sieve size) of the residual granite soil varies between 42 to 46%. Optimum moisture content and maximum dry density were found to be 23% and 14.7 kN/m^3, respectively. Based on Unified Soil Classification System (USCS), the soil was grouped as “clay with high plasticity” (CH). It was also classified in the “A-7-6” group according to the AASHTO classification system. The shear strength parameters obtained from consolidated drained triaxial test on saturated and unsaturated specimens are effective cohesion $c' = 40$ kPa, effective angle of internal friction $\phi' = 26.5^o$ and angle associated with matric suction $\phi^b = 17.8^o$.

3. INSTRUMENTATION

A field instrumentation program was carried out to monitor in-situ matric suction in the slope. Fig. 1 shows a cross section of the slope along with location and layout of the instruments installed in the slope. The slope has an average inclination angle of 50^o to the horizontal and a maximum height of 18 m. Three standpipe piezometers, P1, P2 and P3 were installed.

Piezometer was located at ground level near the bottom of the slope with its porous tip embedded at depth 6.5 m below the ground surface. Piezometer P2 was located at the bottom of berm 2 of the slope and embedded at the depth of 10.5 m. Piezometer P3 was located at the bottom of the berm 3 to depth of 10.5 m. Three piezometers were installed to monitor the fluctuation of the groundwater table below the instrumented slope. A rain gauge was also installed at the bottom of the slope to record the intensity of rainfall on the slope. A total of 9 jet-filled tensiometers were installed in 3 groups of 3 tensiometers per group to monitor the matric suction changes at berm-1, berm-2 and berm-3 of the slope. The three tensiometers in each group were placed at 0.5 m and were embedded vertically in the slope down to depth of 0.33, 0.95, and 1.7 m respectively. A total of 9 pressure transducers were connected to the jet-filled tensiometers for recording the matric suction. The transducers were installed together with the vacuum gauge using T-joints. The advantage of having both the transducer and the vacuum gauge is that the matric suction in the tensiometer can be recorded automatically and continuously using transducers as well as through direct manual reading using the vacuum gauge. All pressure transducers were connected to a data logger. The data were scanned and stored in the memory units of the data logger at a specific interval.

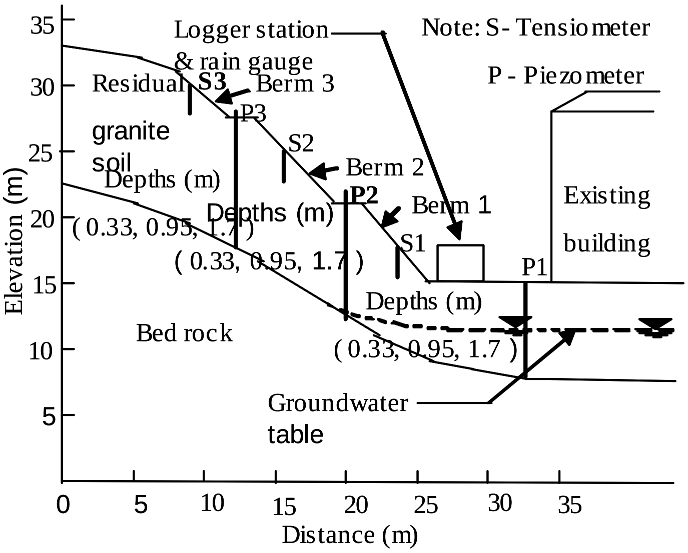


Fig. 1: Cross section of the instrumented slope showing instrumentation details.

4. SLOPE STABILITY

The study of the stability of a slope with matric suction involves the following steps: (i) survey of the elevation of the ground surface on a selected section perpendicular to the slope, (ii) advancement of several boreholes to identify the stratigraphy and obtain undisturbed soil samples, (iii) laboratory testing of the undisturbed soil specimens to obtain suitable shear strength parameters for each stratigraphic unit (i.e., c', ϕ' and ϕ^b parameters), and (iv) measurement of negative matric suction above groundwater table. Numerous assumed slip surfaces are analyzed by comparing their resisting to their actuating forces or moments using the limit equilibrium method of slices. The slip surface which has the lowest factor of safety is consider the critical slip surface. The following formulation are the revised derivations for the factor of safety equations that directly incorporate the shear strength contribution from matric suction. The mobilized shear force is used throughout the derivation. For most analysis the pore-air pressure is assumed atmospheric (i.e., $u_a = 0$)

Two independent factors of safety equations can be derived; one with respect to moment equilibrium and the other with respect to horizontal force equilibrium. The moment equilibrium factor of safety for a composite slip surface with respect to the centre of rotation of the circular portion can be written as follows:

$$F_m = \frac{\sum [c'\beta R + \{N - u_w \beta \frac{\tan\phi^b}{\tan\phi'}\} R \tan\phi']}{A_L a_L + \sum Wx - \sum Nf}$$

where W = total weight of the slice of width b and height h, N = total normal force on the base of the slice, R = radius for a circle slip surface, x = horizontal distance from the centerline of each slice of the centre of rotation, f = perpendicular offset of the normal force from the centre of rotation, a = perpendicular distance from the resultant external water forces to the centre of rotation, A = resultant external water forces, α = angle between the tangent to the centre of the base of each slice and the horizontal and β = sloping distance across the base of a slice.

The factor of safety with respect to force equilibrium is derived from the summation of forces in the horizontal direction for all slices:

$$F_f = \frac{\sum [c'\beta \cos\alpha + \{N - u_w \beta \frac{\tan\phi^b}{\tan\phi'}\} \tan\phi' \cos\alpha]}{A_L + \sum N \sin\alpha}$$

5. RESULTS AND DISCUSSION

Field Matric Suction Measurement

The results of field matric suction measurements for the months of March through May, 1999 are presented here. This period falls in the later part of the wet season and first part of dry season. The typical daily variation of the in situ matric suction in the slope with respect to rainfall for Berm 1, Berm 2 and Berm 3, are shown in Fig. 2 to Fig. 4.

Maximum change in matric suction occurred near the ground surfaces (i.e., at a depth 0.33 m), and the matric suction change decreased with depth. Similar behavior was also found in the studies conducted by Affendi and Faisal [4] and Lim et. al. [5]. Matric suctions near the ground surface were the first to be affected by changes in climatic condition and some delays in matric suction changes were exhibited at greater depths. Similar conclusion was also shown by Lim et. al. [5].

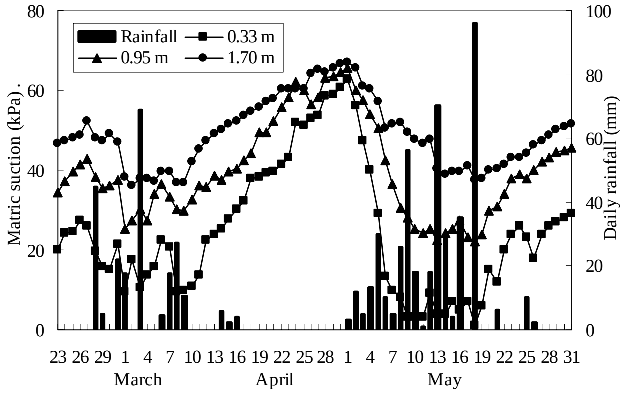


Fig. 2: Matric suction variation for Berm 1.

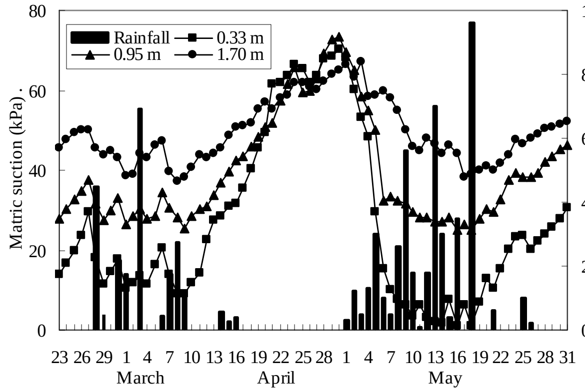


Fig. 3: Matric suction variation for Berm 2.

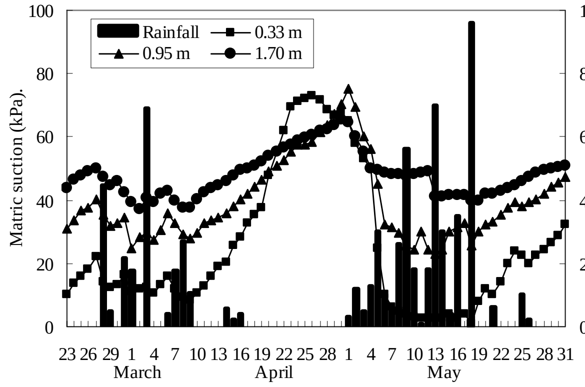


Fig. 4: Matric suction variation for Berm 3.

The magnitude of decrease in matric suction during a particular rainstorm period appears to be a function of the matric suction profile just prior to the rainstorm. For example, the rainfall on May 5 led to a more significant decrease in matric suction than the rainfall on May 18 (Fig. 2), although the amount of precipitation of the former was less than the later. This difference in response can be attributed to the different matric suction profile exist near the ground surface prior to each rainfall event. The higher suction in the slope on May 5 resulted in a higher infiltration rate into the soil. Similar observation was found for Berm 2 and Berm 3. Rainstorms with larger precipitation volumes (such as those on March 28, April 3 and May 18) have affected the matric suction values at greater depths (i.e., 0.95 m and 1.7 m). A small amount of precipitation (i.e., less than 4 mm) did not affect significantly the in situ matric suction at depth. This is shown in the observations made on the days of April 14, April 15, and May 15 (Fig. 2 to Fig. 4).

Change in matric suction due to rainfall also depends on the ground surface covers. Lim et. al. [5] reported that considerable fluctuations in matric suction caused by the rainfall when the slope surface is unprotected (i.e., bare) and matric suction fluctuation is less pronounced for the slope surface protect by grass or a canvas when subjected to the same rainfall pattern. Lim's study results show the importance of surface protection on a slope in minimizing the matric suction changes due to the infiltration of rainwater.

The variations in matric suction in response of a heavy rainstorm that commenced at 15:07 and ended at 18:55 on March 28 were shown in Fig. 5. The rainstorms delivered a total of 44.8 mm of rainfall at Berm 2. The plots are extended to 14:00 on March 29 to study the characteristic of water movement in the soil during and after the rainstorms. Decrease in matric suction was observed after rainstorm. Maximum changes in matric suction occurred near the ground surface and the matric suction change decreased with depth. Lim et. al. [5] mentioned that equalization in matric suction occurred sooner at shallow depths. Such phenomenon was not observed from Fig. 5. As fluctuation in matric suction were still recorded at the various depths even after more than 30 hours after the beginning of the rainfall.

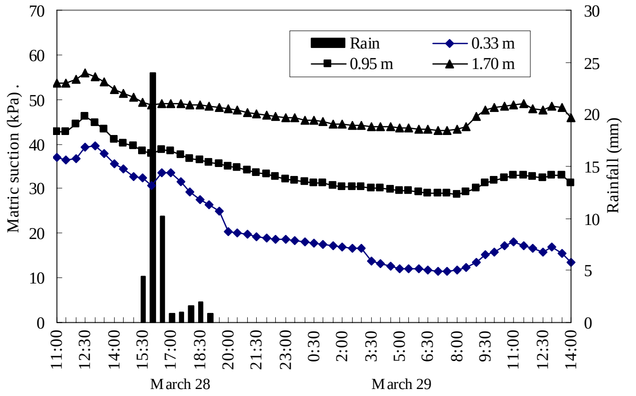
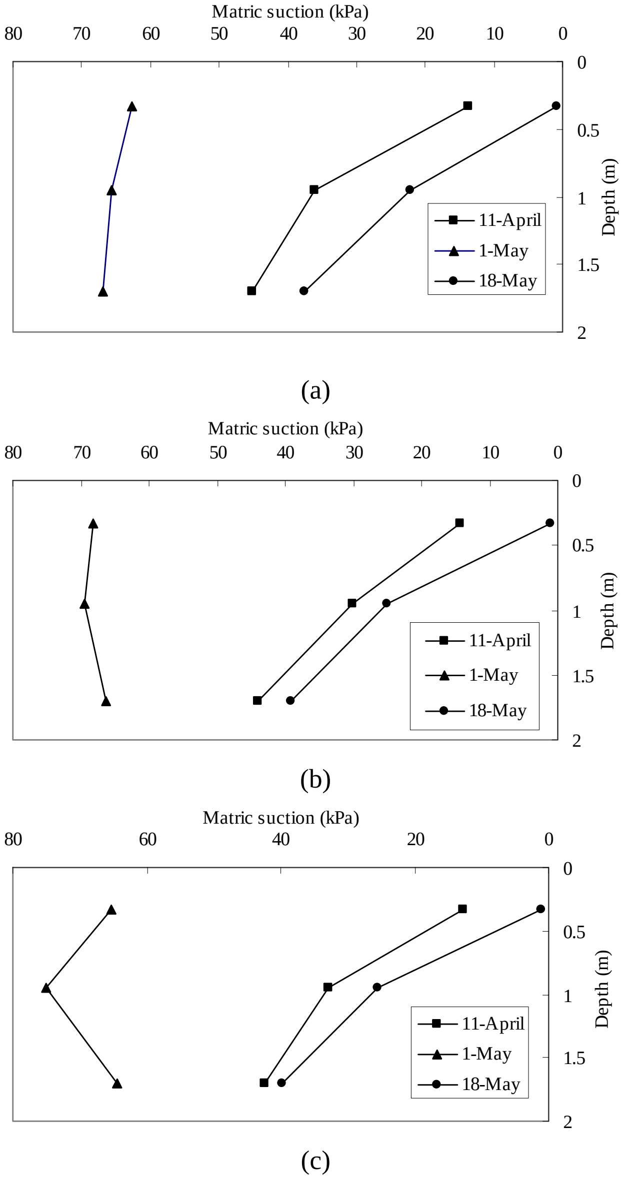


Fig. 5: Matric suction vs. elapsed time at different depths of Berm 2 during the rainstorm of March 28.

The ranges of matric suction and their variation with depth at all three berms during wet and dry seasons were also investigated. Observations made from April 10 to May 31 were selected for discussion. Figure 6 shows typical results from the field measurements which indicate the changes in matric suction profiles during wet and dry periods. A matric suction recovery observed on April 11 was due to the drier period commencing on April 10 (Fig. 1). Prior to the commencement of the rainy period on May 1, the matric suction profile showed higher matric suction in the slope.

The progressive reductions in matric suctions in the slope during the wet period (May 2 to May 18) are also depicted in Fig. 2. A matric suction recovery, observed on May 20, was due to the drier period commencing on May 19. The suction variation for different berms at 0.33 m depth is greater than for depth 0.95 m and 1.7 m. The fluctuation of suction values at 0.33 m depth is from below 1 kPa to above 70 kPa. For deeper that 0.95 m the suction variation is between 20 kPa and 70 kPa. Figure 6 also indicated that matric suction variation at 1.7 m depth was relatively low compare to the depth 0.33 m. Matric suction at greater depth remain 30-40 kPa on 18 May heavy rain. This may be due to very low permeability of the soil and steep slope gradient. In addition to duration of rainfall and rainfall intensity, Lumb [7] reported that changes in the matric suction also dependent on the soil properties and the slope morphology.



(a)

(b)

(c)

Fig. 6: Changes of in situ matric suction profile in response to rainfall in instrumented slope between April and May 1999; (a) Berm 1; (b) Berm 2 and (c) Berm 3.

Groundwater table at different location of the slope constructed based on an assumed datum 15 m depth below the level ground surface at the bottom of the slope. Fig.7 shows the groundwater table fluctuation at Berm-1 and Berm-2 due to variation in daily rainfall. No ground water table was detected from the piezometer (P3) at Berm 3. Variation of groundwater table level was observed less than one meter.

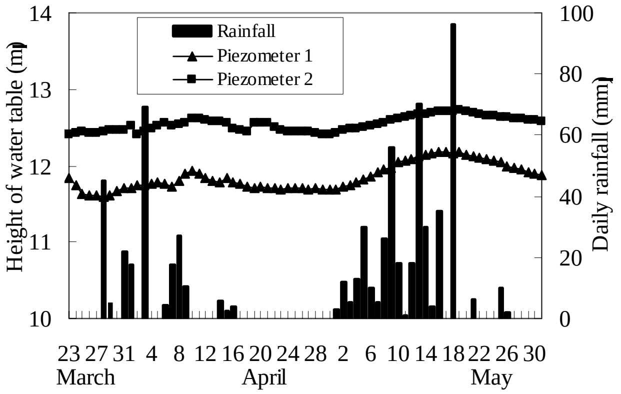


Fig. 7: Groundwater measurements from piezometers for the month of March through May, 1999.

Steep natural and cut slopes in residual soils have deep ground water table above which the soils are partially saturated. The partial saturation of the soil allows to develop matric suction. The apparent cohesion of the soil increases due to the matric suction and this increases the stability of the slope. The pore-water pressures in a slope are changing with climatic conditions. Matric suction exists in the slope because of moisture loss either through evaporation or evapo-transpiration. The rain initiates the adsorption of water by the surface layers causing the degree of saturation to increase. The saturation zone advances to greater depths. The advancing saturation front alters the matric suction profile.

Design of Slope Stability

Stability analyses of the instrumented slope were performed to assess the effect of matric suction changes on the factor of safety of the slope. Generally, the properties of residual soil vary with depth. For simplicity, it is assumed that residual soil layer is homogeneous and isotropic. The water table was located about 12 m below the slope foot. The fluctuation of this deep groundwater table was observed less than 1 m due to climate changes (Fig. 7) and it does not directly affect the slope stability analysis.

Shear strength parameters $c' = 40$ kPa and $\phi' = 26.5^{o}$ from saturated CD triaxial tests and $\phi^{b} = 17.8^{o}$ from unsaturated CD triaxial tests were used in the slope stability analysis. Ordinary (i. e., Fellenius), Bishop's simplified and Janbu's simplified methods were used for slope stability analyses. The analyses were performed using SLOPE/W software considering circular slip surface. For the first analysis, the effect of matric suction was ignored (i. e., assuming full saturation) and the lowest factor of safety was computed (Fig. 8).

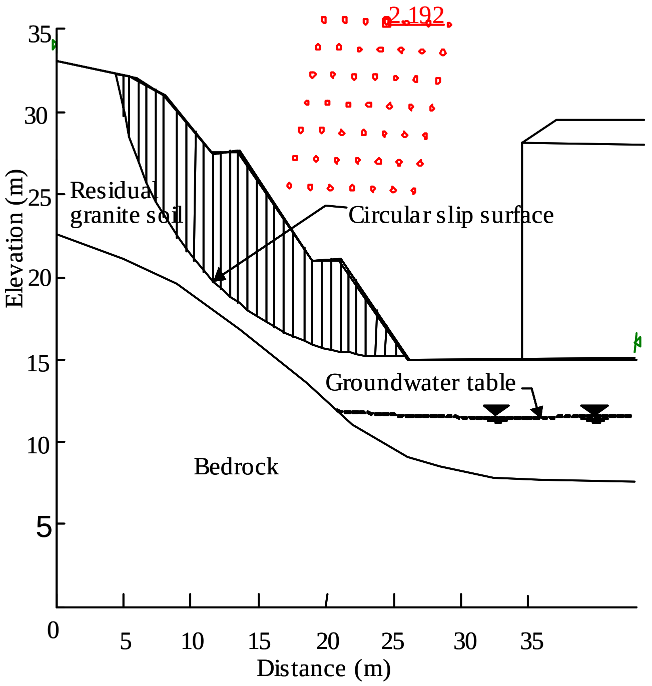


Fig. 8: Potential circular slip surface for zero matric suction.

For subsequent analysis, matric suction was taken into account as part of the cohesion. Fig. 9 shows that factor of safety increase as the suction increase. A suction of 30 kPa becomes equivalent to cohesion of 9.6 kPa. The associated change in the factor of safety is 2.14 to 2.48, an increase at about 16%. It was found from in-situ matric suction monitoring that the average matric suction for the slope remained 30 kPa after heavy rainfall. For dry condition, the average matric suction was monitored about 70 kPa. The factor of safety at this matric suction increases approximately 35%. This illustrates the dramatic influence of matric suction on the stability of slope. Krahn et al. [3] mentioned that the negative pore water pressures play important role in the stability of slope, particularly in the near surface stability. Ng & Shi [8] and Low et al. [9] have state that the decrease of factor of safety was attributed due to reduction of matric suction caused by the infiltration of rain water into the soil.

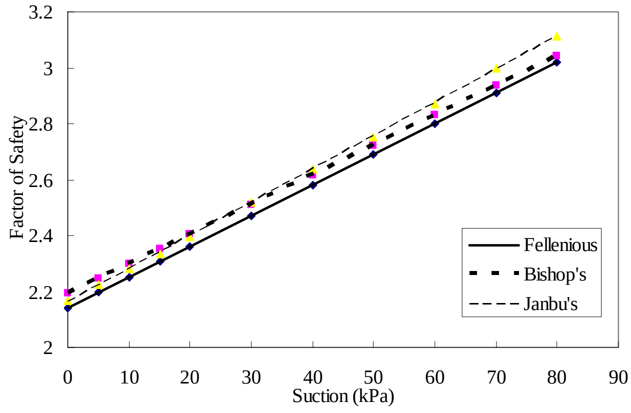


Fig. 9: Effect of matric suction on factor of safety of a residual granite soil slope.

6. CONCLUSIONS

The following conclusion can be drawn from this study

1. Matric suction near the ground surface is the first to be affected by rainfall, followed by those at greater depths. The amount of decrease in matric suction due to a particular rainfall event appears to be a function of the matric suction profile just prior to the rainfall.
2. Matric suction in the soil increases during dry season and decreases during wet season. Maximum change in matric suction occurs near the ground surface and the magnitude of matric suction change decrease with depth.
3. Matric suction increases the shear strength of the soil and therefore the factor of safety of the slope increases.
4. Higher matric suction values give higher factor of safety of the slope.

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