International Journal of the Physical Sciences Vol. 7(3), pp. 508 - 518, 16 January, 2012
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS11.1651
ISSN 1992 - 1950 © 2012 Academic Journals

Full Length Research Paper

Influence of evaporation on transient suction distribution in unsaturated soil

Gambo Haruna Yunusa* and Nurly Gofar

Department of Geotechnics and Transportation, Faculty of Civil Engineering, Universiti Teknologi Malaysia.

Accepted 16 December, 2011

This paper presents the results of numerical analysis on influence of evaporation process on the transient suction distribution induced by rainfall infiltration in unsaturated soil. Transient seepage and slope stability analyses were carried out using commercial software SEEP/W and SLOPE/W (Geo-Slope International, 2007a, b) on 1-year data representing a site at Johor Bahru, Malaysia. Soil samples were collected and relevant data, that is, soil water characteristics curve (SWCC), hydraulic conductivity curve, and shear strength parameters were gained through interpretation of laboratory test results. The study was performed for two typical periods: dry period and wet period, that is, March and June, and two conditions: Rainfall alone and combination of rainfall and evaporation. Residual water content was assigned at the beginning of all analyses. The results show that evaporation gives a positive effect on slope stability by reducing the effect of rainfall on suction distribution. Consideration of evaporation in transient seepage analysis gives a better prediction of suction distribution in soil and slope stability.

Key words: Infiltration, evaporation, unsaturated soil, suction, transient seepage analyses.

INTRODUCTION

The problem slope failure pose major geotechnical hazards in tropical and subtropical countries where the ground surface is covered by residual soil and ground water table is at a great depth. The most important triggering factor in transient suction variation is rainfall infiltration (Lee et al., 2009). Au (1998) stated that more than 80% of rainfall induced slope failures in the tropical region were due to loss in suction. The suction contributes to the shear strength of the soil, but rainfall infiltration leads to decrease in suction and increase in pore water pressure effectively decreases shear strength of the soil making it more susceptible to failure (Rahardjo et al., 2000). The effect of rainfall infiltration on suction variation has been studied by many researchers such as Rahardjo et al. (2001) and Gofar and Lee (2008).

The amount of rainfall infiltration into the soil mass depends on external factors as well as intrinsic parameters of the soil. The intrinsic factors include water retention characteristics and the hydraulic conductivity (Mukhlisin et al., 2008) while the external factors comprise the rainfall intensity and duration and surface cover. Surface cover control the amount of water that flow on the surface as runoff. Gofar and Lee (2008) suggested that only 70% of rainfall penetrates into soil as infiltration. However, they also suggested that the ratio of rainfall intensity (I) to the saturated hydraulic conductivity (k_{sat}) plays a more dominant role. The rate of infiltration into soil is usually high at the beginning of the event but it eventually decreases as rainfall continues until it reaches a value equal to the saturated coefficient of permeability (k_{sat}) of the soil. Moreover, the soil moisture condition prior to rainfall event is also important to determine the depth of wetting front.

The role of rainfall infiltration in changing the suction in soil was studied extensively by Gofar and Lee (2008). However, it is known that the suction variation is also affected by other factors such as evaporation and transpiration. Both processes have the effect of increasing suction in the near surface soil mass through gradual drying of the soil mass and water uptake by plant respectively. The effect of transpiration or tree induced suction was studied by Rees and Ali (2006) while study on the effect of evaporation was attempted by Gofar et al.

*Corresponding author. E-mail: ghyunusa@gmail.com.

(2006). Through numerical analysis on the mechanism of water flow in a soil column model, they found that evaporation plays a role in the suction variation due to rainfall infiltration. Furthermore, they found that the evaporation process is affected by relative humidity and ambient temperature if the temperature is lower that the soil temperature which is common in tropical area. Another attempt has been made by Kassim (2011) to include the effect of evaporation on the numerical prediction of suction distribution in soil mass by constant evaporation rate of 5 mm/day. He concluded that the inclusion of evaporation in numerical analysis gives a better prediction of suction distribution in soil especially in wet condition.

The current study is aimed at investigating the effect of evaporation process during rainfall on the suction distribution in unsaturated soil using 1-year data representing a site at Johor Bahru Malaysia. A finite element seepage analysis program SEEP/W (Geo-Slope International Ltd., 2007b) was used for transient seepage analysis while slope stability analysis was performed by SLOPE/W (Geo-Slope International Ltd., 2007a) on the slope with negative pore-water pressure generated from the seepage analyses. The possibility of tension crack developing at the surface due to suction is not considered in this study.

TRANSIENT SEEPAGE AND SLOPE STABILITY ANALYSIS

Transient seepage analysis is time dependent analysis with regard to spatial and temporal changes in environmental condition (Lu and Likos, 2004). The analysis can be performed to evaluate the change in suction due to continuous change in moisture content. The transient water flow is usually governs by Richard's equation which takes care of change of volumetric water content with time in two dimension as:

$$\frac{\partial \theta_w}{\partial t} = \frac{\partial}{\partial x}(k_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(k_y \frac{\partial h}{\partial y}) + Q = m_w^2 \rho_w g \frac{\partial h}{\partial t} \quad (1)$$

where; θ_w is the volumetric water content, h is the hydraulic head, k_x *and* k_y are the coefficients of permeability of the soil along the x and y coordinates, and Q is the applied unit flux while on the right side of equation, m_w^2 is the coefficient of volumetric water change with respect to a change in negative pore–water pressure (u_a-u_w) and is equal to the slope of the soil–water characteristic curve, ρ_w is the density of water and g is gravitational acceleration.

The analysis requires the establishment of soil's hydraulic parameters, that is, soil water characteristic curve (SWCC) and hydraulic conductivity curve. Soil water characteristic curve (SWCC) is a fundamental hydraulic property of unsaturated soil relating the volumetric water content (θ) to matric suction (ψ). The parameter m_w is the slope of the curve. The hydraulic conductivity curve of unsaturated soil can be predicted empirically from the SWCC and the saturated hydraulic conductivity through Fredlund and Xing (1994) model.

The initial failures for most of the unsaturated soil slopes have small depth-to-length ratios and form the failure planes parallel to the slope surface; hence, the use of infinite slope analysis for stability evaluation is thus justified (Collins and Znidarcic, 2004). The factor of safety of the slope is calculated by using a modified Mohr-Coulomb failure criterion (Fredlund et al., 1978; Fredlund and Rahardjo, 1993):

$$\tau = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \quad (2)$$

Where *c'* is effective cohesion, ϕ' is effective frictional angle, $(\sigma_n - u_a)$ is net normal stress, u_a is pore-air pressure, u_w is pore-water pressure, (u_a – u_w) is matric suction, ϕ^b is internal friction angle due to matric suction. The unsaturated friction angle (ϕ^b) depicts the increment rate of shear strength due increase in suction and it can be obtained by performing a series of triaxial compression test under various matric suction conditions where the pore air pressure (u_a) control and transducer are install to measure the matric suction (u_a - u_w). Input for matric suction was the negative pore water pressure generated by transient seepage analysis. For infinite slope analysis, the factor of safety (FOS) of an unsaturated slope is expressed as:

$$FOS = \frac{c' + \sigma\tan\phi' + (u_a - u_w)\tan\phi^b}{W\sin\beta\cos\beta} \quad (3)$$

where W is the weight of slice which is the product of γ (the total unit weight) and h (vertical depth of the assumed slip surface) and β is slope angle.

METHODOLOGY

The rainfall and evaporation data used in this study were provided by Department of Irrigation and Drainage (2010) Malaysia for a station at Johor Bahru, Malaysia (Figure 1). One year data of January to December 2009 (Figure 2) was selected for the analysis. Samples were collected at the site to obtain relevant soil parameters for transient seepage analyses that is, soil water characteristic curve (SWCC) and hydraulic conductivity curve. Particle size distribution analysis was performed to identify the soil classification (BS EN 1997-2: 2007). The SWCC was obtained from the results of pressure plate extractor test. The hydraulic conductivity curve for unsaturated soil was predicted using Fredlund and Xing (1994) model incorporated in the software based on SWCC. Three parameters are required to predict the hydraulic conductivity curve: The saturated hydraulic conductivity, air entry

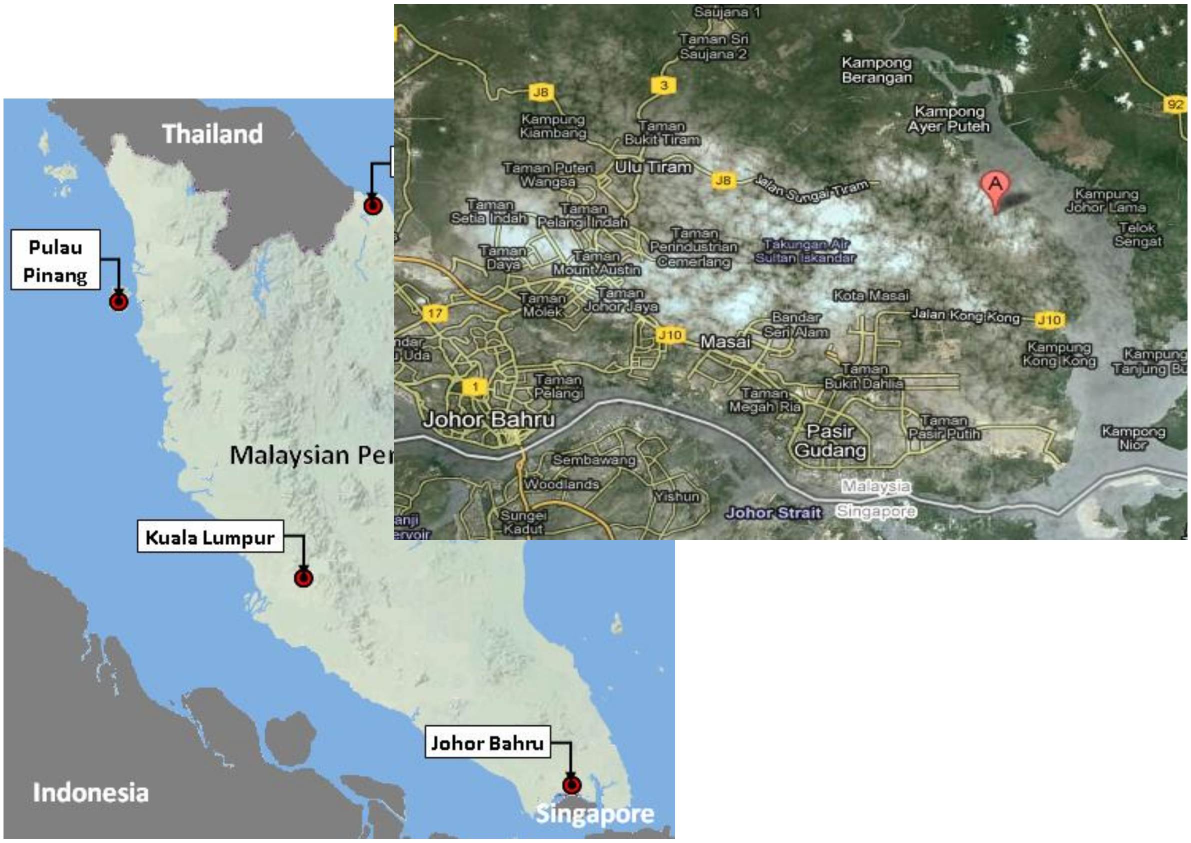

Figure 1. Location of study area.

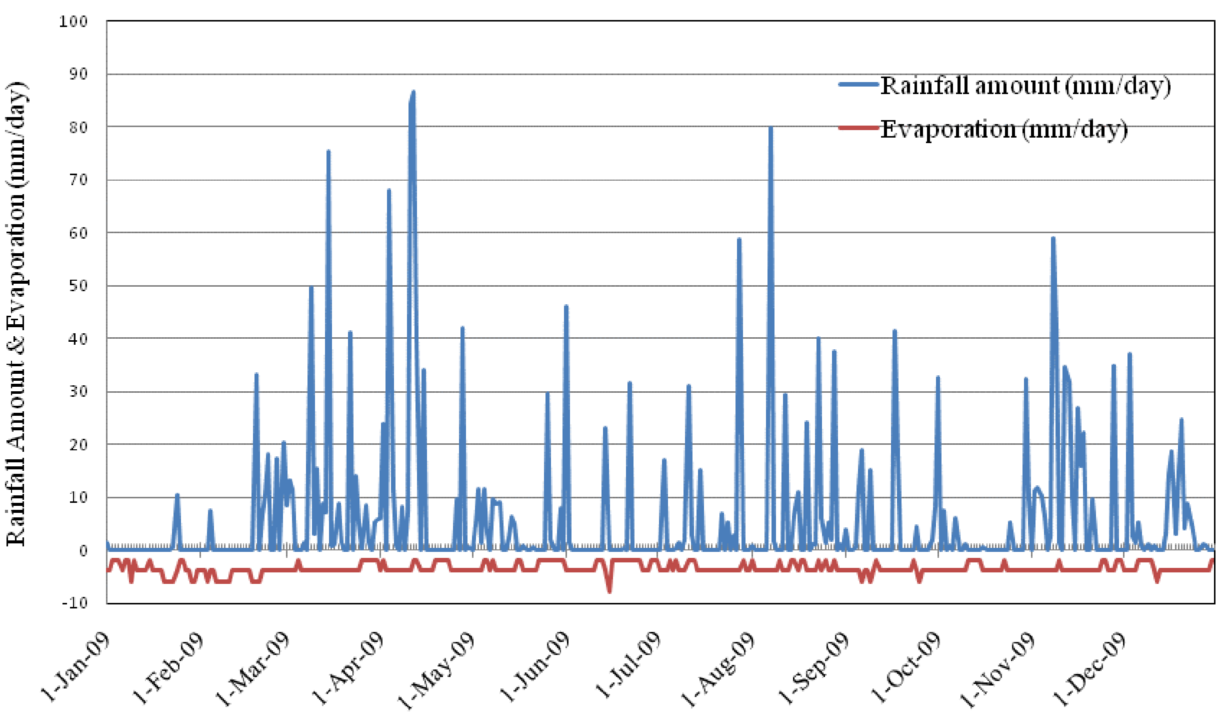

Figure 2. Rainfall (precipitation) and evaporation data from Sungai Layang Sta. for year 2009.

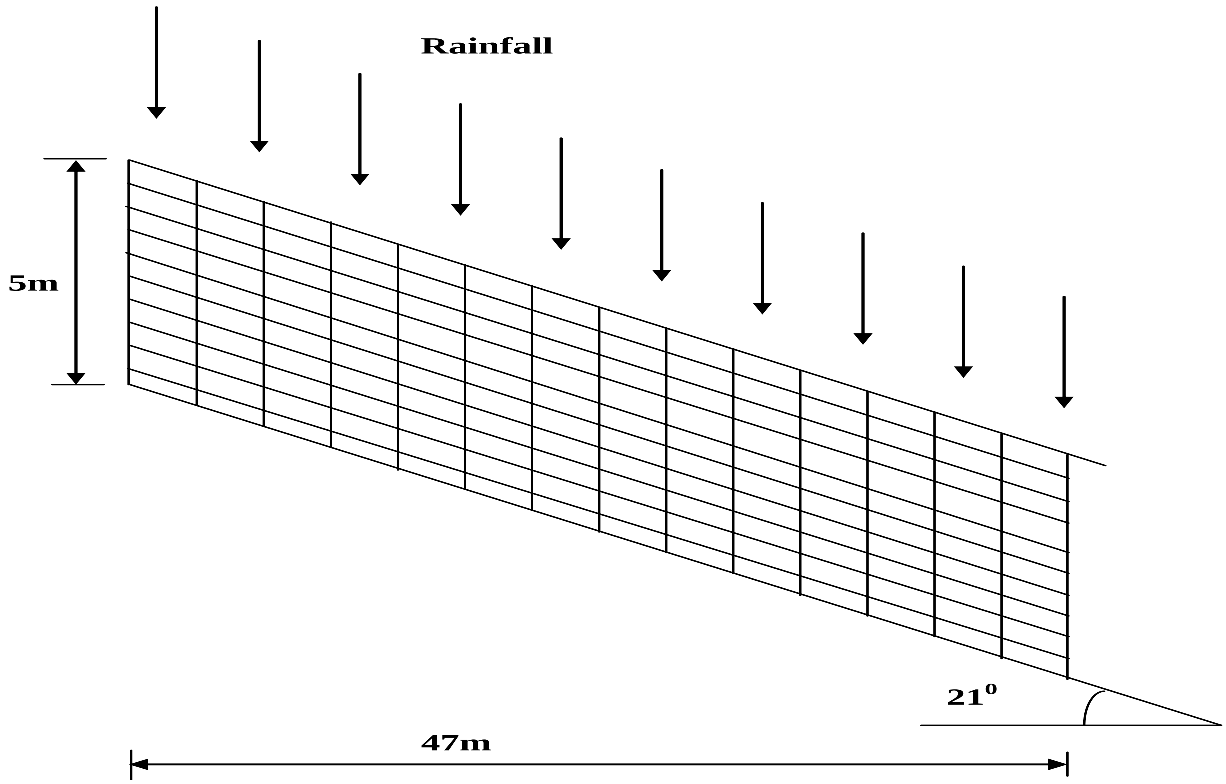

Figure 3. Finite element mesh for transient seepage analysis by SEEP/W (Geo-Slope International, 2007b).

value (*AEV*) and residual water content (*RWC*). The saturated hydraulic conductivity was obtained by carrying out falling head permeability test (Fratta et al., 2007). Air entry value and residual water content were obtained from the SWCC. Prior to the transient seepage analyses, steady state seepage analyses were performed using hydraulic conductivity function to serve as initial conditon for the transient seepage analyses. Soil density and unsaturated shear strength paramaters are required for slope stability analysis using SLOPE/W (Geo-Slope International, 2007a) using the pore-water pressure generated from the transient seepage analyses. The effective cohesion (c') and effective frictional angle (ϕ') were obtaned by triaxial test in consolidated drained condition while the unsaturated frictional angle (ϕ^b) was estimated as 2/3 of the internal friction angle (Geo-Slope International, 2007a).

Numerical analyses were carried out using finite element seepage analysis program SEEP/W (Geo-Slope International, 2007b). Geometry of the slope and finite element mesh used in this study is shown in Figure 3. The slope model is 47 m long with slope angle of 21°. The gentle slope angle is selected because it is the typical slope at the area and the study is focused on rainfall infiltration rather than slope stability. As many as 140 element meshes comprising of 142 nodes were designed to represent the slope profile. The bottom boundary condition was assumed to be potential seepage face, the left and right boundaries were assigned as constant total head boudaries and were given values of 18 and 2 m, respectively, based on the orientation of the modelled slope in the SEEP/W. The slope surface was treated as flux boundary conditions with varying rainfall infiltration intensity and difference between rainfall infiltration and evaporation intensity as the case may be. Slope stability analyses were conducted using SLOPE/W on slope with pore water pressure imported from transient seepage analysis. Morgenstern price method with entry and exit point was used to specify the critical slip surface and calculate the minimum factor of safety.

PRELIMINARY DATA AND ANALYSIS

Observation of the data presented in Figure 2 indicates that the month of March have the most number of days with rain and highest rainfall amount while the months of June has the least amount of rainfall. Thus, these two months were selected as the wettest and driest months respectively. The maximum daily rainfall in 2009 is 86.5 mm occurred on March 15th. The month of March had 22 days of rainfall while June only has four days of rainfall. Observation on the evaporation data reveals that evaporation normally range between 2 and 4 mm per day. It seems that temperature regulates evaporation rate. There is also a degree of dependency between rainfall and evaporation. The average evaporation in 2009 was 3.6 mm, with maximum evaporation of 8 mm occurred in June 14th. The seepage analysis was performed for two conditions, that is, effect of rainfall infiltration only and combination of rainfall infiltration and evaporation. Based on the previous study by Gofar et al. (2008), only 70% of precipitation is considered as infiltration while the rest contributes to runoff. Therefore, this study uses 70% of precipitation as input into the numerical transient analysis. Figure 4 shows the actual infiltration and evaporation data adopted in the seepage analysis. Observation of the data plotted in Figure 4 indicates that 15th March and 14th June are the wettest and driest days, respectively.

Figure 5 shows the particle size distribution of the soil at the study area. The soil can be classified as sandy SILT. The SWCC

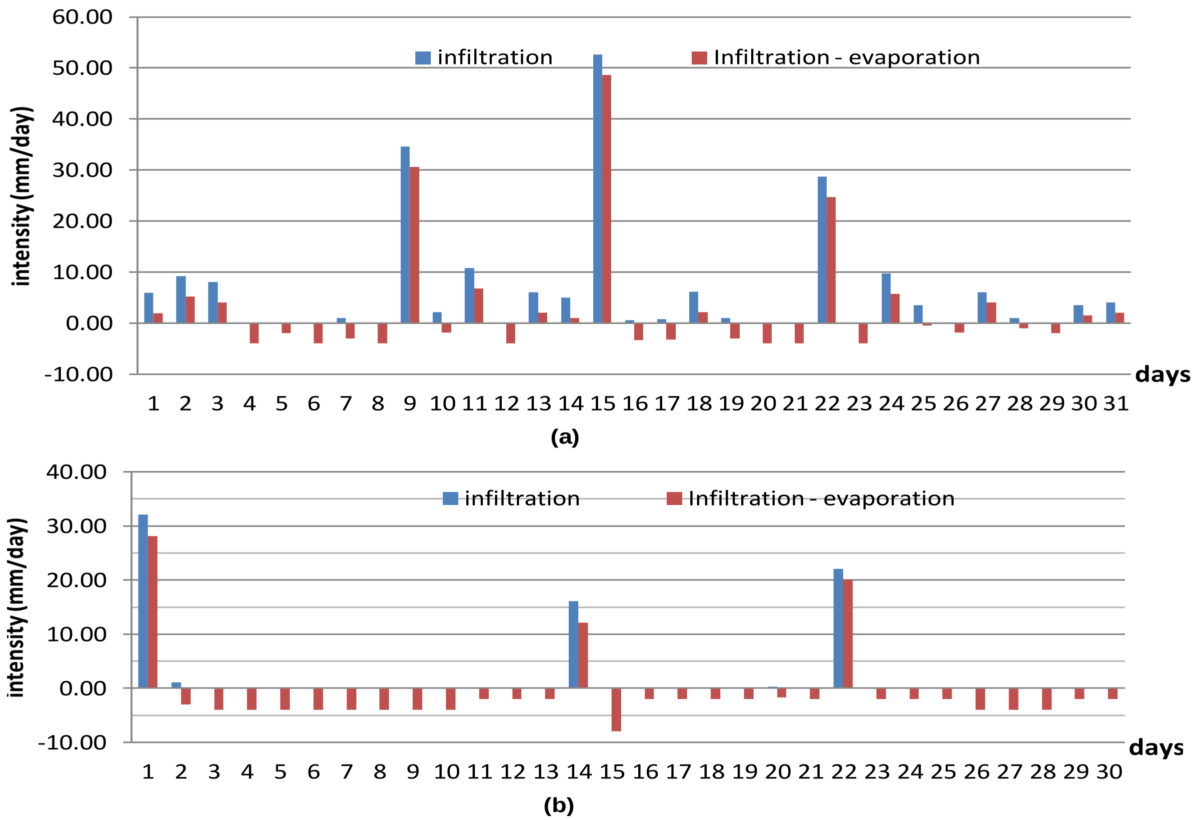

Figure 4. Rainfall and evaporation data adopted in seepage analysis; (a) wettest month (March), and (b) driest month (June).

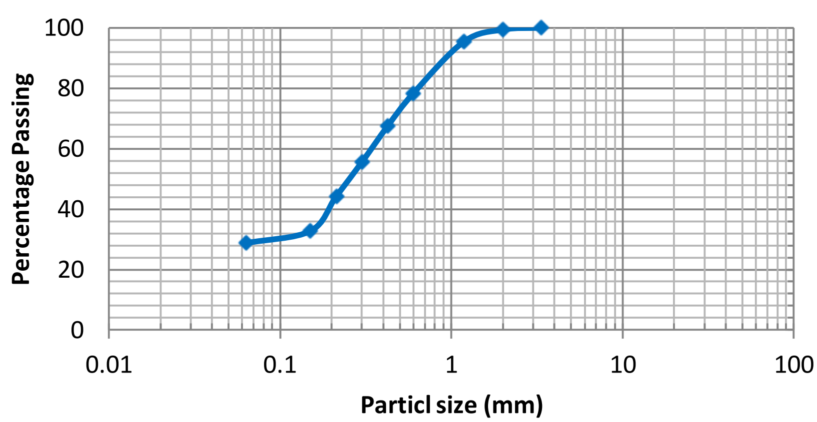

Figure 5. Particle size distribution.

and hydraulic conductivity curves required for the seepage analysis are presented in Figures 6 and 7. The hydraulic conductivity curve was predicted using Fredlund and Xing (1994) model which require several parameters, that is, k_{sat}, *AEV* and *RWC*. The saturated hydraulic conductivity (k_{sat}), measured by falling head permeability test is 4.50 × 10^{-7}m/s, while the *AEV* and *RWC* obtained from SWCC curve have the values of 12 kPa and 12.5%, respectively. The residual water content was also used as intial water content for each analysis. Shear strength parameters of unsaturated soil used for the slope stability analysis is presented in Table 1.

RESULTS AND DISCUSSION

The seepage pattern and pore-water head profile obtained from the transient seepage analyses on March 15th and June 14th due to combination of infiltration and evaporation are shown in Figure 8. General observation shows that soil suctions decreases with depth because the negative pore-water pressure approaches positive

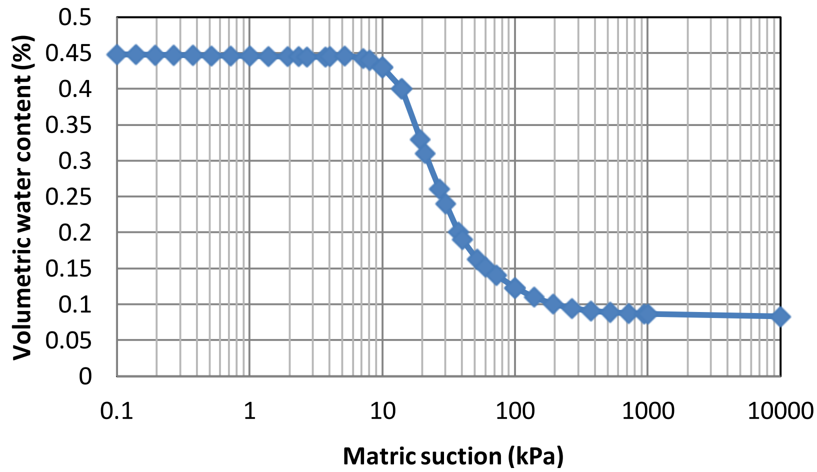

Figure 6. Soil water characteristics curve (SWCC).

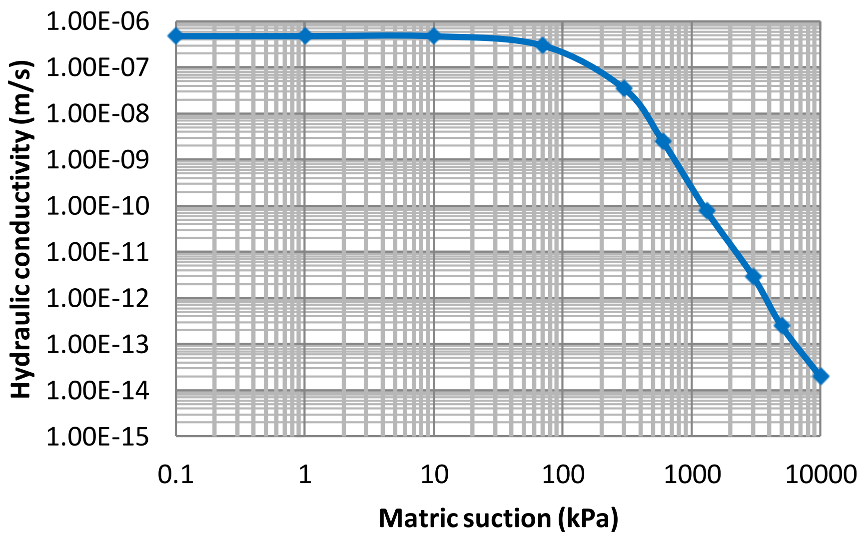

Figure 7. Hydraulic conductivity curve.

Table 1. Soil properties for slope stability analysis.

Soil property	
Unit weight of the soil (γ)	19 kN/m^3
Cohesion (c')	7 kPa
Angle of internal friction (ϕ ')	30°
ϕ^b	20°

value as the point approaches water table. The pressure heads show that the infiltration flows downward from the crest towards the toe. However, the pattern differs according to the input in infiltration and evaporation. Very high suction (-50 kPa) was monitored near the soil surface on June 14th due to high evaporation rate and the dry condition of the soil prior to the rainfall event. The minimum suction reached in this condition is only -20 kPa due to less water infiltrating into the soil mass. The water infiltrates deeper on March 15th due to high precipitation and near saturated condition was reached at the bottom boundary due to accumulation of water. The deeper penetration was also achieved due to initial condition of the soil due to several rainfall events prior to March 15th. The depth of wetting front is affected by either saturated hydraulic conductivity k_{sat} or rainfall intensity (q), the duration of rainfall, the initial water content, and the porosity of the soil while the influence of suction is more concentrated on the near surface soil. The magnitude of suction were observed at four different points, that is, at

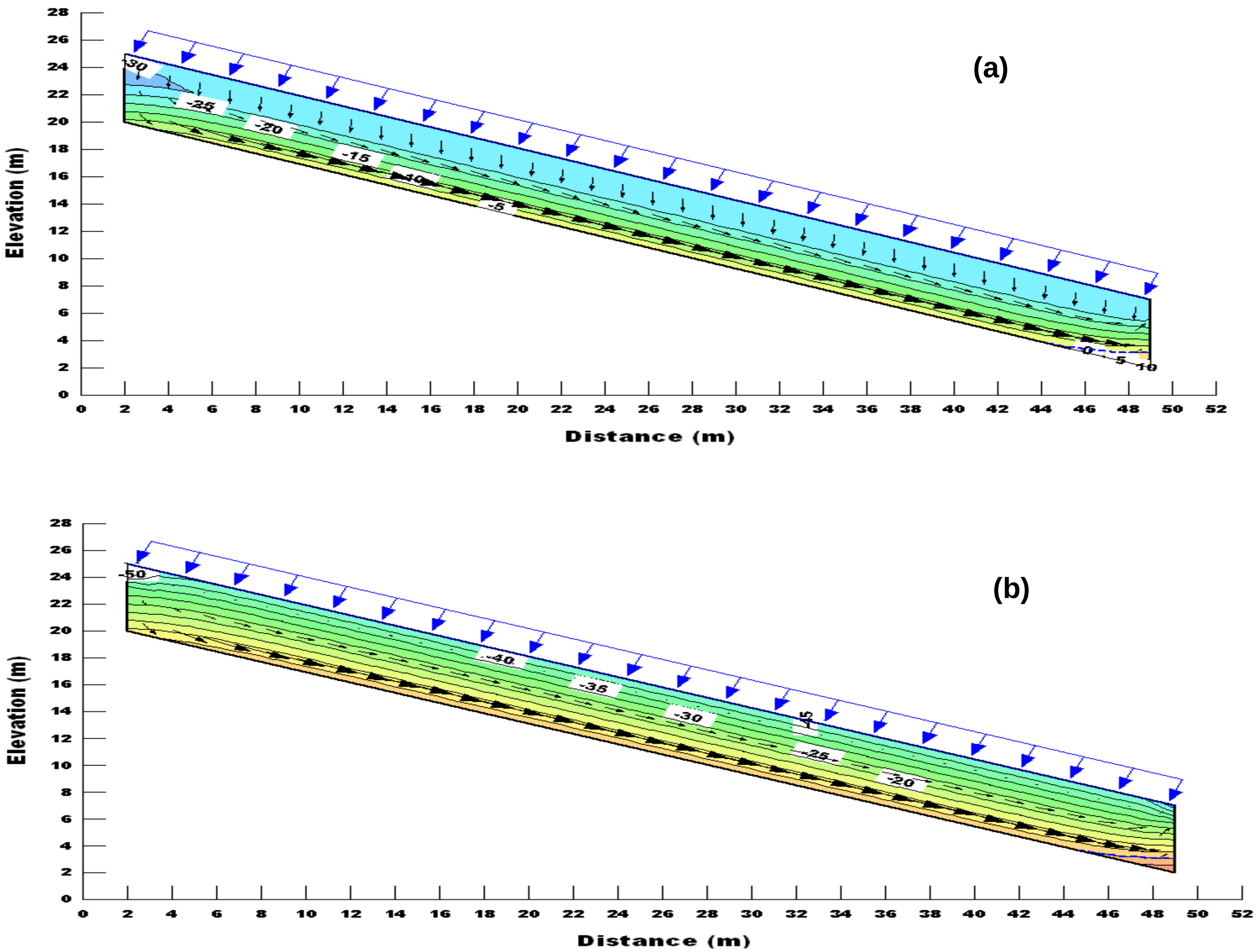

Figure 8. Seepage pattern on 15th March (a) and 14th June (b) due to rainfall infiltration – evaporation.

depths. The effect of evaporation on suction at depth of 0.5, 1.0, 1.7, 3.3 and 5.0 m from the surface of the slope.

Figure 9 shows the suction distribution with depth on the two days due to infiltration alone and combination of infiltration and evaporation. Figure 9 indicates that more noticeable difference was observed at depths of 0.5 and 1.0 m because these points are easily affected by both infiltration and evaporation. The effect of evaporation occurs only at shallower depth and becomes insignificant at deeper elevation. The suction at 1.7, 3.3 and 5.0 m remained relatively constant except in March where the rainfall infiltration was high and the changes occur at all 0.5 in the month of March and June is presented in Figure 10.

Figure 10 indicated that an average difference of 42.18 kPa of suction was identified in March due to evaporation. More significant effect was obtained in June due to less rainfall and higher evaporation rate. Maximum difference of 45.07 kPa was identified on 21st of June because there was no rain for about six days. However the rate of increase can be seen from 2nd to 13th of June in which the difference in suction increases from 34.45 to 43.37 kPa. The same thing happens from 23rd to 30th of June and 4th to 8th of March. This finding shows that the effect of evaporation becomes more significant as the number of days without rainfall increases may be due to the increase in the temperature of soil. After rainfall, the suction redistributes and increases gradually (Gofar and Lee, 2008) with time, and evaporation enhances the process of drying at the surface. This finding is in a good agreement with field observation performed previously at a location near the study area. The detail of the monitoring program can be referred to Gofar et al. (2008). In this study, monitoring of suction was carried out three times a day (morning, afternoon and evening) on a barren slope for a period of one year. The maximum and

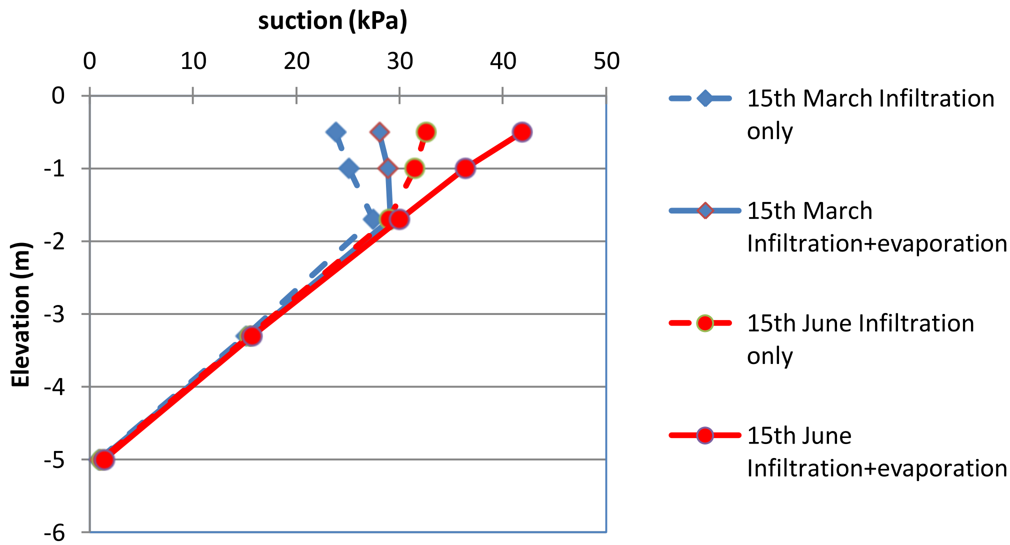

Figure 9. Suction distribution on 15th March and 14th June due to rainfall and combination of rainfall and evaporation.

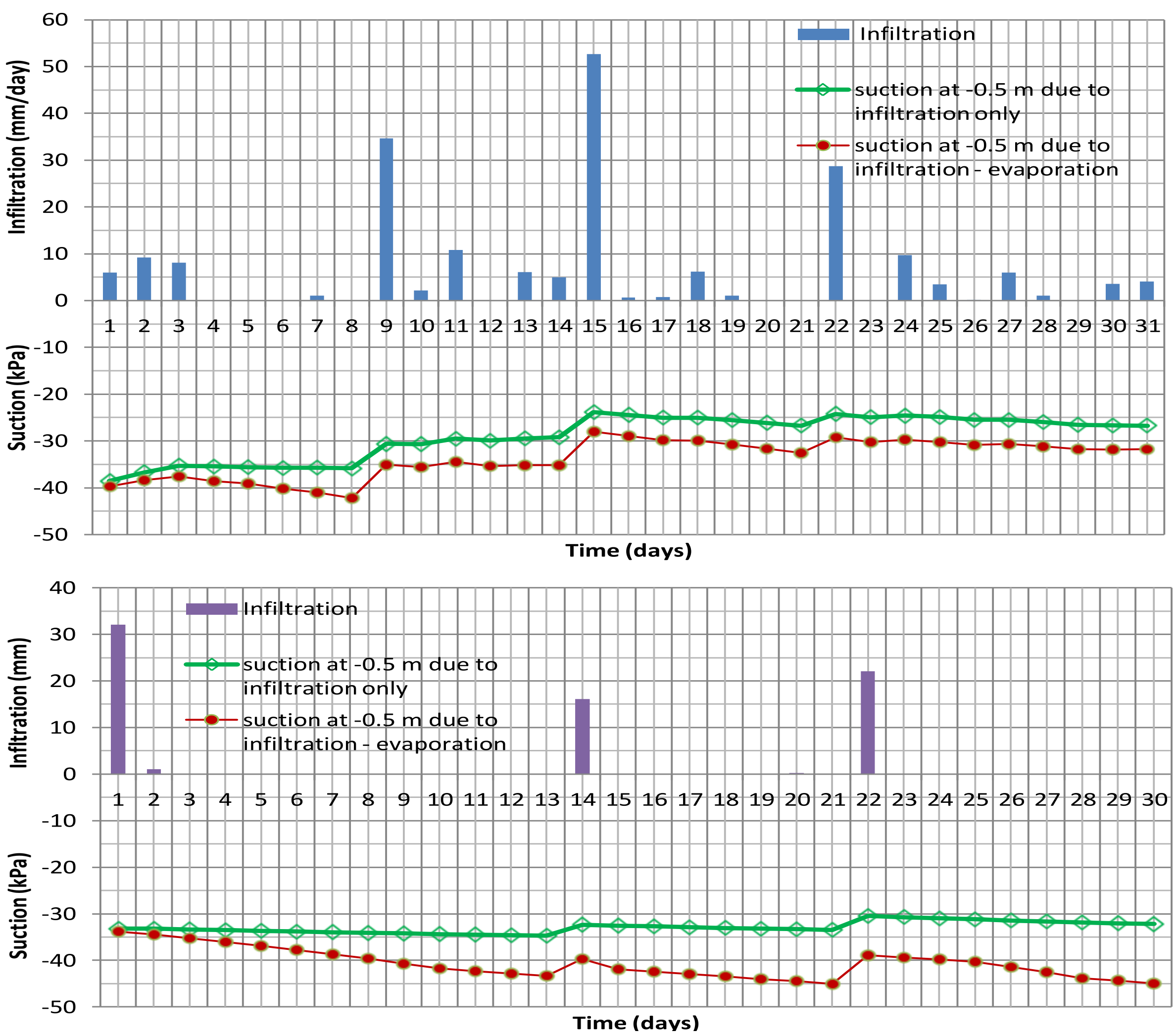

Figure 10. Effect of evaporation on suction at depth of 0.5 m with time; (a) March (b) June 2009.

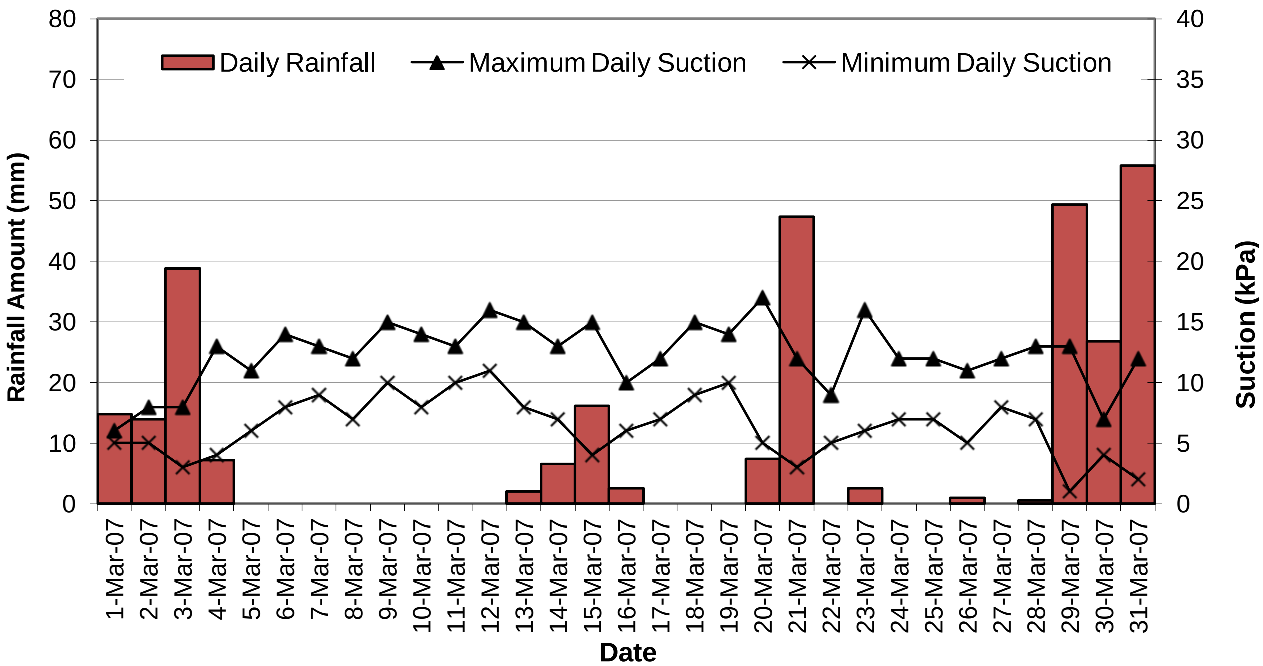

Figure 11. Measurement of daily suction in March 2007.

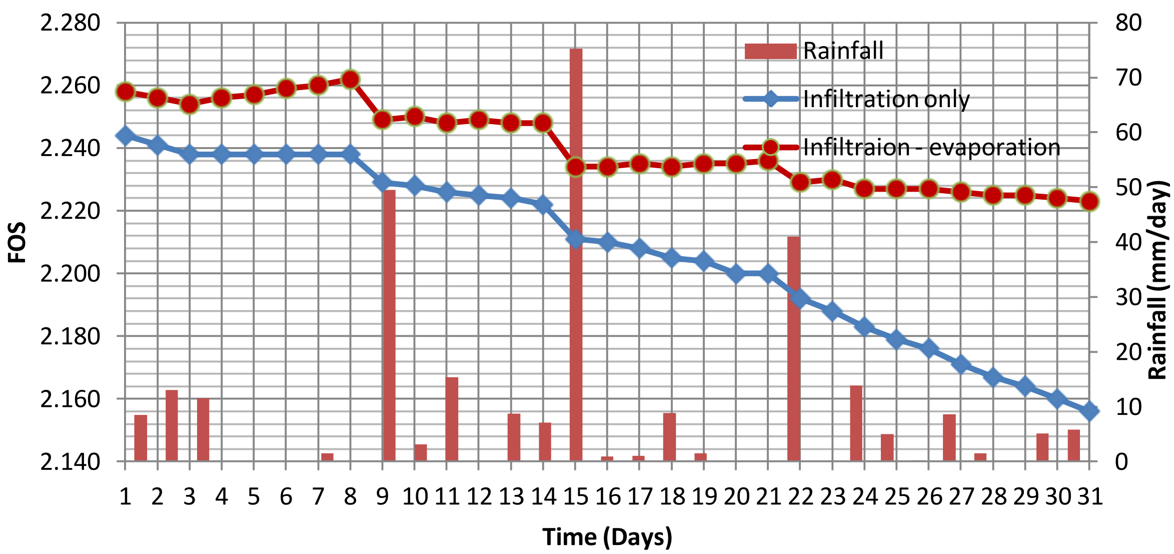

Figure 12. Variation of FOS with time in March 2009.

minimum suction measured every day on a typical dry month is presented in Figure 11. The difference between the maximum and minimum suction is almost equal to the average evaporation rate and bigger difference was observed in the days without rainfall.

Slope stability analysis was performed on the slope with pore water pressure distribution imported from the results of transient analysis. Stability analysis performed for the whole period of transient analysis signify the effect of suction on the shear strength and the stability of slope, however; only the results performed at some points of critical suction is discussed herein. Figures 12 and 13 show the variation of factor of safety (FOS) during the months of March and June. The factor of safety at the beginning of the month was 2.245 but the rainfall infiltration has causes the factor to decrease to 2.155. When, evaporation is considered, the factor of safety only decreases to 2.223. In the beginning of June, the factor

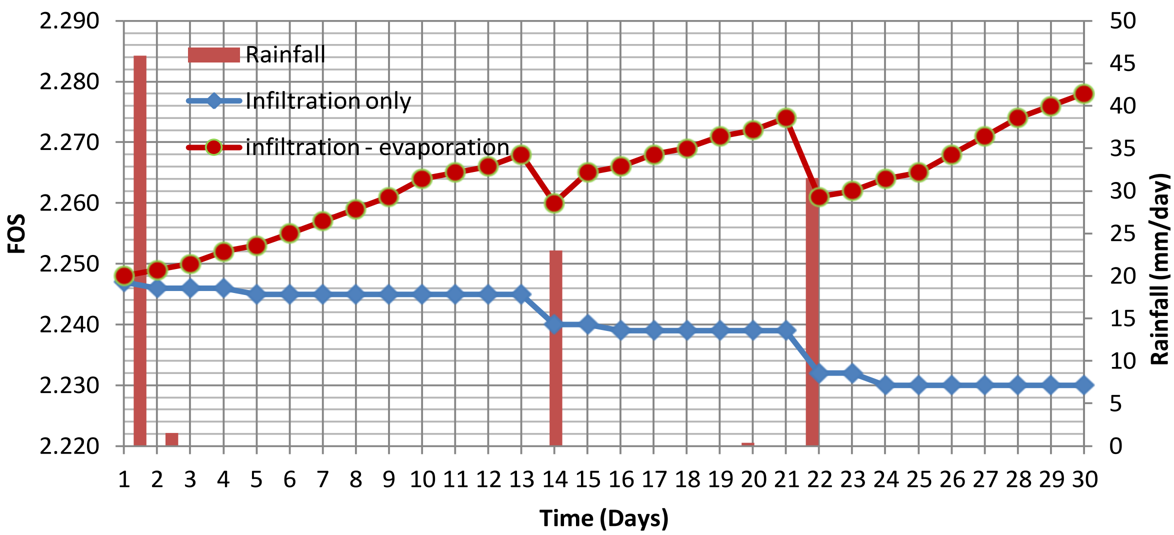

Figure 13. Variation of FOS with time in June 2009.

of safety of the slope was 2.247 and decreases slightly to 2.230 due to two rain events on 14th and 22nd of June. The stability of the slope increases to 2.279 when evaporation was considered. The maximum FOS of 2.354 was reached in February 18th 2009 while the lowest one is 2.155 in March 31st 2009. Consistently higher FOS was obtained when evaporation was considered in the analysis.

Conclusions

Evaporation is the process of water movement from soil surface back to the atmosphere due to temperature. This process induces suction in the near soil surface and has effect on the suction distribution in soil which invariably results in increase in slope stability. The following conclusion can be drawn from the analysis:

1. Consideration of evaporation in the transient seepage analysis provides a more realistic prediction of suction distribution induced by rainfall infiltration.
2. The influence of evaporation, though limited to the near surface soil, leads to the increase in suction within the soil profile and subsequently increases the slope stability.
3. The effect of evaporation in suction distribution is more significant as the number of days without rainfall increases.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the Department of Irrigation and Drainage Malaysia more especially Khairul Fadzilah bt. Muhammad Omar for supplying the rainfall and evaporation data. The first author thanks Assoc. Prof. Ir. Dr. Azman Kassim and Bimo Brata Adhitya for their help and encouragement.

REFERENCES

Au SWC 1998). *Rain-induced slope* instability in Hong Kong. Eng. Geol., 51: 1-36.
BS EN 1997-2:2007 Eurocode 7 — Geotechnical Design — Part 2: Ground Investigation and Testing p. 202.
Collins BD, Znidarcic D (2004). Stability Analyses of Rainfall Induced Landslides. *J. Geotech. Geoenviron. Eng. ASCE*. 130(4): 362-372.
Department of Drainage and Irrigation (2010). Rainfall and evaporation data of *Loji air* Sungai Layang station Johor Bahru Malaysia, 30p.
Fratta D, Aguettant J, Roussel-Smith L (2007). *Soil Mechanics Laboratory Testing*, CRC press, 248 p.
Fredlund DG, Morgenstern NR, Widger RA (1978). The Shear Strength of Unsaturated Soil. *Canadian. Geotechical. J.,* 15: 313–321.
Fredlund DG, Rahardjo H (1993). *Soil mechanics for unsaturated soils*, John Wiley and sons, Inc., New York, 517 pp.
Fredlund DG, Xing A (1994). Equations for the Soil-Water Characteristic Curve. *Canadian Geotechical J*., 31: 521–532.
Gofar N, Lee ML, Kassim A (2008). Response of Suction Distribution to Rainfall Infiltration in Soil Slope. Elect. J. Geotech. Eng., 13(E) 1-13.
Gofar N, Lee ML (2008). Extreme Rainfall Characteristics for Surface Slope Stability in the Malaysian Peninsular. *GEORISK: Assessment & Management Risk for Engineering Systems. Geohazards,* 2(2): 65-78
Gofar N, Lee ML, Kassim A (2006). *Effect of surface boundary condition on rainfall infiltration,* Jurnal Teknologi, (B) 44: 63-70
Geo-Slope International Ltd (2007a). *SEEP/W User's guide for finite element seepage analysis*, GEO-SLOPE International Ltd, Calgary, Alta.
Geo-Slope International Ltd (2007b). *SLOPE/W User's guide for slope stability analysis*, GEO-SLOPE International Ltd, Calgary, Alta.
Kassim A (2011). Modeling the Effect of Heterogeneities on Suction Distribution Behaviour in Tropical residual Soil. PhD Thesis Universiti Teknologi Malaysia, p. 315.
Lu N, Likos WJ (2004). *Unsaturated Soil Mechanics*. John Wiley and sons Inc.
Lee ML, Gofar N, Rahardjo H (2009). A simple model for preliminary evaluation of rainfall-induced slope instability. Eng Geol., 108(3-4): 272-285.

Mukhlisin M, Taha MR, Kosugi K (2008). Numerical analysis of effective soil porosity and soil thickness effects on slope stability at a hillslope of weathered granitic soil formation*, Geosci., J.,* 12 (4): 401–410.

Rahardjo H, Leong EC, Michael SD, Jason MG, Tang SK (2000). Rainfall Induced Slope Failures, *Geotechnical Engineering Monograph 3,* NTU-PWD Geotechnical Research Centre, NTU, Singapore, 86p.

Rahardjo H, Li XW, Toll DG, Leong EC (2001). The Effect of Antecedent Rainfall on Slope Stability. J. Geotech. Geolog. Eng. Netherl., 19: 371-399.

Rees SW, Ali N (2006). Seasonal water uptake near trees: A numerical and experimental study. *Geomechanics and Geoengineering*: An Int. J., 1(2): 129-138.