Numerical analysis of slope stability in expansive soil: a case study of field test in Henan province, China

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ABSTRACT
To investigate stability of expansive soil slope under the rainfall condition, a field study conducted by Zhang et al. (2010) in Henan Province, China, is analyzed using a comprehensive numerical procedure that involves the hydraulic Finite Element Analysis, followed by Factor of Safety (FS) calculation based on Limit Equilibrium Analysis. Several hydraulic properties functions; including the unimodal SWCC and permeability functions with increased saturated permeability and bimodal SWCC with its permeability functions are used to consider effects of cracks developed within the shallow layer. The results suggest that the bimodal hydraulic properties can better represent the hydraulic behavior of cracked expansive soils, and result a close match between the predicted and measured pore water pressure change over time. The calculated FSs illustrates the importance of selecting shear strength parameters under lower confining pressure from laboratory studies in the stability analysis of expansive soil surficial layer.

RÉSUMÉ
Pour étudier la stabilité de la pente d'un sol expansif sous des conditions de précipitations, une étude de terrain menée par Zhang et al. (2010) dans la province du Henan, en Chine, est analysée en utilisant une procédure numérique globale impliquant l'analyse hydraulique par éléments finis et le calcul du facteur de sécurité basé sur l'analyse d'équilibre limite. Plusieurs fonctions de propriétés hydrauliques, y compris le SWCC unimodal et les fonctions de perméabilité avec l'augmentation de la perméabilité saturée, ainsi que le SWCC bimodal avec ses fonctions de perméabilité, sont utilisées pour considérer l'effet des fissures développées au sein de la couche superficielle. Les résultats montrent que les propriétés hydrauliques bimodales représentent mieux le comportement hydraulique des sols expansifs fissurés et il en résulte une correspondance entre le changement de pression interstitielle prédit et mesuré au fil du temps. La FSs calculée illustre l'importance de la sélection des paramètres de résistance au cisaillement sous une pression de confinement basse en laboratoire dans l'analyse de la stabilité de la couche superficielle d'un sol expansif.

1 INTRODUCTION

Expansive soils that swell significantly upon wetting and shrink during drying are found on every continent. Instability of slopes constructed of expansive soils are frequently reported in many countries around the world. The key triggering factor of expansive slopes failure can be attributed to the water infiltration, including the water from snow melting or the storm during wetting season. Although the infiltration-induced failures usually have a shallow slip surface, it still can cause distress to the nearby infrastructures and contribute to extensive economic losses. Maintaining the stability of expansive soil slopes remain one of greatest challenges to both the researchers and the practitioners (Ng et al. 2003; Bao and Ng 2000).

For example, in China, hundreds and thousands of expansive soil slopes are formed from the natural terrain or new slopes are constructed as infrastructure for supporting the growing needs of the increasing population in recent years. In recent years, several field tests were conducted to study the fundamental behaviour and failure mechanism of expansive soil slopes under rainfall conditions in China (Zhang et al. 2010, Cheng et al. 2011). Lessons learnt from these field tests are used as guidelines in the design of a giant water transfer project (South-to-North Water Transfer Project) which involves many canals in expansive soil areas, (i.e. Ng et al 2003, Zhan et al 2007. Zhang et al. 2010). The slopes are usually well instrumented to monitor the changes in pore water pressure, suction, soil heave, stress regime, and rainwater infiltration intensity, etc. The suction loss and engineering property degradations (i.e. strength loss and increase in permeability) of expansive soil resulting from environmental changes are attributed to be the key factors that contribute to expansive soil slopes failure.

Conducting in situ tests are costly and requires a long period of time. Comparatively, numerical analysis form a cheaper and convenient way to reproduce the response of expansive soil slopes to different infiltration conditions. Several researchers (Hamdhan and Schweiger (2012), Alonso et al. 2003, Rouainia et al. 2009 used the advanced numerical techniques to simulate the field studies from the literature, based on saturated-unsaturated seepage analyses. These results highlight the importance of selecting proper hydraulic properties of the soil to achieve a good match between predictions and measurements, especially the soil permeability. More recently, Qi and Vanapalli, 2015 (a, b) studies suggest that the hydraulic behaviour of cracked expansive soils can be well described using the bimodal soil-water characteristic curve (SWCC) along with a bimodal permeability function. The saturated coefficient of permeability of cracked soils is suggested to be 2-3 orders higher than that of intact specimens. In the present study, the hydraulic behaviour of an expansive soil slope under an artificial rainfall condition at an in situ test presented by Zhang et al. (2010) is modeled using commercial software, SEEP/W (Geo-slope international Ltd. 2007a). The results of suction (negative pore water pressure) using unimodal and bimodal SWCCs and their respective permeability functions are compared with the measurements. The factors of safety calculated based on the hydraulic analysis using the Limit Equilibrium Method are also presented and discussed.

2 INSTRUMENTATION AND MONITORING

2.1 The monitoring area

The monitoring area is located near the city of Xinxiang, province of Henan, China, where a huge project transferring water from Southern to Northern China (i.e. the South-to-North Water Transfer Project) goes through. Design of safe and economical dimensions for canals constructed in expansive soils has become one of the major geotechnical problems in this area. The average annual rainfall in this region is about 800 mm, and 60 to 70% of the rainfall is distributed from June to August (Zhang et al. 2010), and numerous slope failures were triggered by the rainfalls with high intensity during the wetting seasons.

2.2 Field study

Several field tests were conducted in this area (Zhang et al. 2010) to investigate the sliding mechanisms of expansive slopes under artificial rainfalls. One of the field slope is selected for numerical simulation in the present study. The monitoring area affected by the artificial rainfall is 28m length and 16m width. The test slope formed by excavation has a height of 9m, and the slope following excavation was 1:2.5. The instrumentation included Tensiometer and ThetaProbe probe for measuring suction and volumetric water content respectively, and rain gauge. The layout and locations of the instrumentation along a section profile the slope are shown in Figure 1.

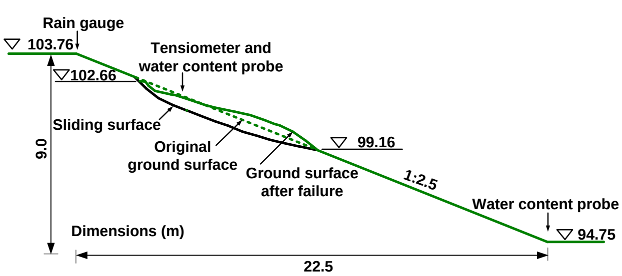

Figure 1. Cross section of studied slope (from Zhang et al. 2010)

In order to simulate the infiltration process, a sprinkler system was specially designed for artificial rainfall; which consists of 1 pump, 2 main water-supply pipes, 15 branches, and 75 sprinkler heads. This system was used to produce three periods of rainfall with a constant intensity of around 8mm/h. In the first two rainfalls, there sliding displacements were measured but no mass failure was observed. The collapse of a mass near the slope top occurred during the third rainfall period. Figure 1 shows the slip surface and ground surface after failure.

3 SEEPAGE ANALYSIS

3.1 Theory of water infiltration

The processes of water infiltration and flow through saturated and unsaturated soil system can be modeled analytically (Srivastava and Yeh 1991; Wu and Zhang 2009) or numerically (Alonso et al. 2003; Oh and Vanapalli, 2010). The analytical methods are able to provide reasonable solutions for infiltration problems with a regular geometry and simple boundary conditions. Comparatively, the numerical solutions can simulate various complicated saturated and unsaturated seepage processes. Both the solutions are based on conservation of flux that incorporates the Darcy's Law. Thus, the mathematical description is given by the following partial differential equation:

$$\frac{\partial \theta_w}{\partial t} = \nabla \cdot \left[k_{unsat} \nabla \left(\frac{u_w}{\gamma_w g} + y \right) \right] \qquad [1]$$

where, θ_w is volumetric water content, t is time, k_{unsat} is the permeability of soils under unsaturated condition, u_w is the value of pore water pressure, γ_w is the density of water, g is the gravitational acceleration, and y is the elevation. ∇ is the gradient operator and defined as:

$$\nabla = \frac{\partial}{\partial x} i + \frac{\partial}{\partial y} j + \frac{\partial}{\partial z} k \qquad [2]$$

From Equation [1] it can derived that the difference between the flow entering and leaving an elemental volume is equal to the rate of change of the volumetric water content with respect to time (Fredlund and Rahardjo, 1993). In order to solve Equation [1], a continuous relationship is required to link the volumetric water content and suction, which is defined as the soil-water characteristic curve (SWCC). An appropriate SWCC (either unimodal or bimodal) can be specified as a fundamental hydraulic parameter. In other words, the permeability of unsaturated soils, k_{unsat}, is no longer a constant, but a variable dependent on water content or suction. Usually, a permeability function relating the variation of the coefficient of permeability with respect to suction is specified for saturated and unsaturated seepage analysis. These two functional parameters (SWCC and the permeability function) make Equation [1] highly nonlinear. Analytical solution is not available for some cases with simple boundary conditions. Furthermore, bimodal SWCC and permeability function used in the present study will increase complexities associated with nonlinearity. For this reason, the solution of Equation [1] for a two dimensional slope has been numerically obtained using the commercial finite element based software SEEP/W.

3.2 Material and Model

There are many equations proposed in the literature to represent a unimodal SWCC (van Genuchten, 1980; Fredlund and Xing, 1994; Leong and Rahardjo, 1997). In the present study, the Fredlund and Xing (1994) equation with a correction factor equal to 1, is used:

$$\theta_w = \frac{\theta_s}{\left\{ \ln \left[e + \left(\frac{u_a - u_w}{2} \right)^n \right] \right\}^m} \quad [3]$$

where u_a - u_w is the soil suction (kPa), e is the natural logarithm (base 2.71828 …), θ_s is the saturated volumetric water content, a, n and m are three fitting parameters, which are related to the air-entry value of the soil (kPa), the slope at the inflection point in the SWCC and the residual water content of the soil, respectively. The parameters, a = 100 kPa, n = 0.888, m = 0.293, together with the saturated volumetric water content, θ_s = 41.8% are used to fit the date of volumetric water content and suction, provided by Zhang et al. (2010).

Figure 2 shows the SWCCs used in this study. It is well known that the permeability function of an unsaturated soil bears a strong relationship to the corresponding SWCC. Fredlund et al. (1994) proposed a procedure to estimate the permeability function by integrating along the SWCC. The Fredlund et al. (1994) permeability model is used to represent the unimodal permeability function in the present study. The permeability function used in this study is illustrated in Figure 3. The saturated coefficient permeability values of k_s = 10^{-3}, 10^{-4}, 10^{-5} m/h are used to generate the unimodal permeability functions using Fredlund et al. (1994) permeability model for the numerical exercise. Figure 2 and 3 also show the bimodal SWCC and bimodal permeability function, respectively. These two curves are represented by the spline functions built in the software which facilitate to generate continuous curve with any shape.

A finite element method-based computational model slope was established using SEEP/W as shown in Figure 4. The geometry of the slope is consistent with that of studied slope from Zhang et al. (2010). The model slope consists of two layers, i.e. the surficial cracked layer underlain by a relative intact layer. According to Zhang et al. (2010), the simulated artificial rainfall had a substantial influence on the hydraulic response of soils within the shallow layer, and negligible effect on that of soils under the depth of 1m or deeper. This is attributed to the fact that cyclic drying and wetting-induced cracks only develop within the soil near the ground surface. Thus, it is assumed that the surficial cracked layer has thickness of 0.8m for the model slope (see. Figure 4). The locations of PWP measurements at the depths of 0.5 and 1.0m conducted by Zhang et al. (2010) are also indicated in Figure 4. The quadrilateral elements with vertically oriented nodes are used to discretize the surficial cracked layer for dealing with the dramatic response where effect of artificial rainfall was predominant. For the other zone, the mixed regular quadrilateral and triangle elements are used.

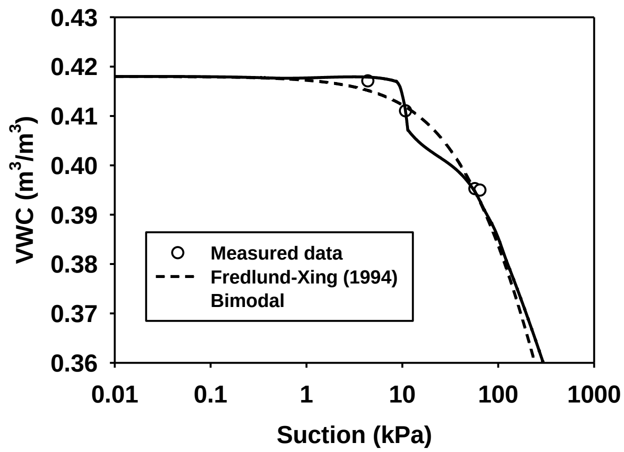

Figure 2. SWCCs used in the study

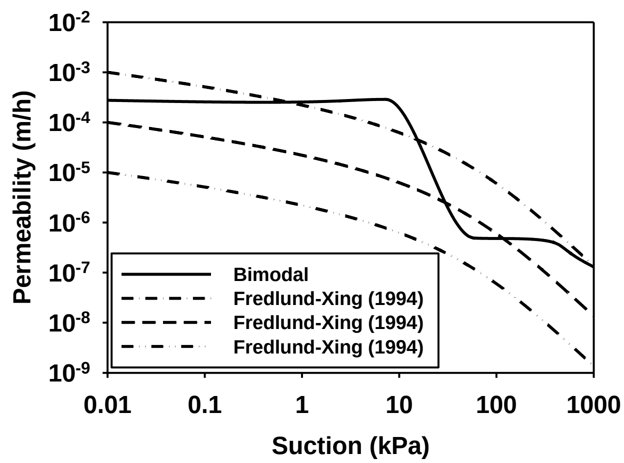

Figure 3. Permeability functions used in the study

The initial hydraulic condition for the slope model is generated using spatial function according to the measured pore-water pressures just before the commencement of the artificial rainfall. A spatial function is built in SEEP/W to assist the users in setting up the initial condition accurately since the pore water pressure may distribute nonlinearly or irregularly within the slope profile for most real cases. The consistent hydraulic heads are applied to the both the right and left lateral boundaries during rainfall infiltration. The bottom boundary of the computational domain for water flow has a zero flux. The infiltration from artificial rainfall is simulated using a constant influx with an intensity of 0.008 m/h for 28 hours during the first rainfall on slope ground surface without allowing any ponding.

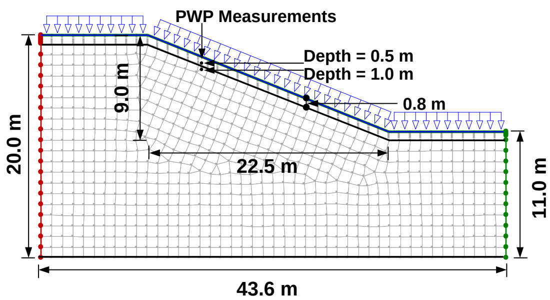

Figure 4. Model slope for numerical analysis

3.3 Numerical Results

Figure 5 compares the time history of PWPs predicted using seepage analysis within measured values at the depth of 0.5m near ground surface. It can be seen that there is a dramatic decrease in the measured suction (i.e. negative PWP) from around 60 kPa at the 7th hour to less than 10 kPa at the 12.5 depth. After that, the suction at the depth of 0.5m remains almost constant during the remaining period of rainfall. As explained by Zhang et al. (2010), the hydraulic regime near the ground surface was greatly affected by the artificial rainfall because of the presence of cracks that provide pathways for preferential flow. For numerical simulation using unimodal SWCC and permeability function, slight decreases in the suction are observed when using the relative lower saturated permeability (i.e. 10^{-4} or 10^{-5} m/hr), which do not match the measured values. When the saturated coefficient of permeability of unimodal permeability is increased to 10^{-3} m/hr, the predicted suction gradually decreases with respect to time. However, the discrepancy between the predictions and the suction measurements is still apparent. When the bimodal hydraulic properties are used, a good match is obtained between predicted and measured suction values. In other words, the dramatic decrease in the suction value at the depth of 0.5m is successfully reproduced in the numerical simulation by using bimodal hydraulic properties.

Figure 6 compares the time history of PWPs predicted using seepage analysis within measured values at the depth of 1.0m near ground surface. It can be seen that the measured value of suction (negative PWPs) remains essentially around 10 kPa. The PWP at this depth is not significantly affected by the rainfall, since the cracks are not developed at deeper depth as suggested by Zhang et al. (2010). For numerical simulation, when the unimodal SWCC and permeability function with a lower saturated coefficient of permeability for the intact layer is used, the predicted PWPs remain constant and show good agreements with the measured values, independent of the hydraulic properties assigned to the surficial cracked layer. Negligible decrease in the suction at the depth of 1.0m is, therefore, attributed to the low permeability of intact layer.

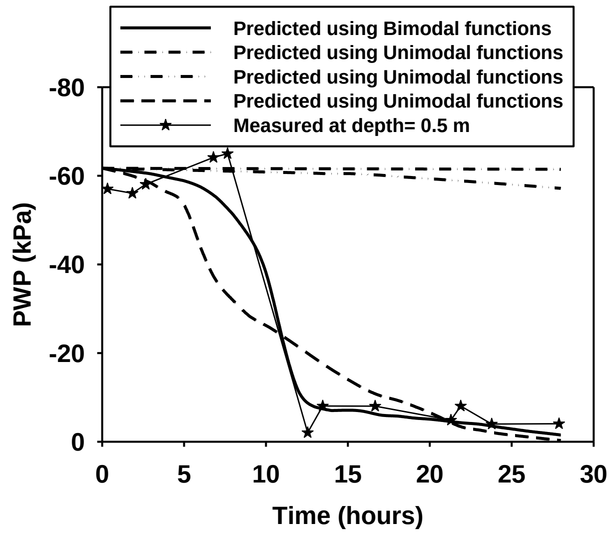

Figure 5. Comparison between measured PWP and predicted PWP at the depth of 0.5 m

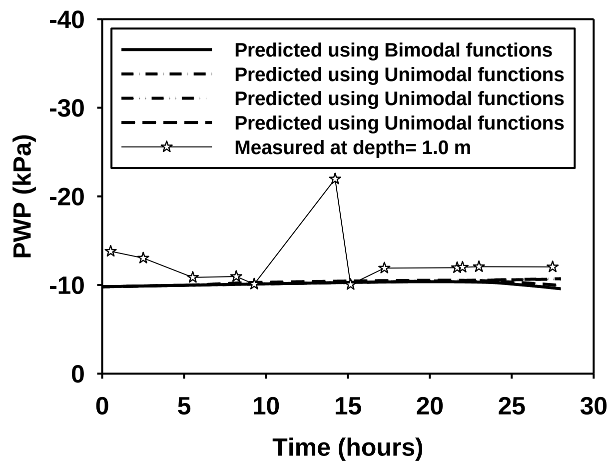

Figure 6. Comparison between measured PWP and predicted PWP at the depth of 1.0 m

4 SLOPE STABILITY ANALYSIS

4.1 Method for calculating FS

Deterministic methods are widely used in which a scalar, called factor of safety (FS) is used to evaluate the slope stability. There are dozens of methods proposed in the literature for determining the FS. These methods can be generally characterized into the following categories according to different theories they are based on; namely: (i) the limit equilibrium methods based on rigid block equilibrium analysis; (ii) the limit analysis methods based on upper bound plasticity theorem; (iii) finite element stress based method; (iv)finite element strength reduction method; (v) finite element gravity increase method. Among all these methods, the limit equilibrium methods are still the most preferable for practice applications due to its long history as well as simplicity.

There are several commonly used variants of limit equilibrium methods in the literature, such as the Bishop's simplified method (Bishop, 1955) satisfying only the moment equilibrium of failure mass, the Janbu's simplified method (Janbu, 1954) satisfying only the force equilibrium, and the Morgenstern-Price Method (Morgenstern and Price, 1965) satisfying both the force and moment equilibrium conditions. Although the methods that satisfy both equilibrium conditions appear to be able to provides most reliable FS, especially for complicated slopes, in some case they may encounter numerical non-convergence problems. In the present study, the slip surface detected in the field study by Zhang et al. (2010) is well defined and relative shallow, which puts this slope collapse into a typical translational type. For translational type of slope failure, the Janbu's simplified method (Janbu, 1954) may be able to produce a satisfactory result, and is therefore used here to calculate the FS.

For saturated soils, the basic procedures and formulation of Janbu's simplified method can be found elsewhere and are not detailed here. It should be noted that, for unsaturated soils, the shear strength contribution due to suction requires to be considered in the slope stability analysis formulation. The semi-empirical model proposed by Vanapalli et al. (1996) (Eq. 4) has been widely used in the literature, which quantifies the nonlinear behaviour of shear strength of unsaturated soil using the saturated effective shear strength parameters and the SWCC as tool.

$$\tau_f = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\left[\left(\frac{\theta_w - \theta_r}{\theta_s - \theta_r}\right)\tan\phi'\right] \quad [4]$$

where, c' = effective cohesion, ϕ' = effective internal friction angle, σ = normal stress acting on the slip surface, θ_w is volumetric water content, θ_s and θ_r are saturated and residual volumetric water content, respectively. Through simply replacing the c' by $c_a = (c' + (u_a - u_w)(\theta_w - \theta_r)/(\theta_s - \theta_r)\tan\phi')$ in any formulations of slope stability analysis for saturated soils, those existing limit equilibrium methods can be used to evaluate the slope stability for unsaturated soils, including the Janbu's simplified method.

4.2 Factor of Safety (FS) results

Calculation of FS variation over time is performed using SLOPE/W (Geo-slope international Ltd. 2007b). The hydraulic response under the rainfall condition predicted using SEEP/W can be directly incorporated into SLOPE/W for stability analysis. The seepage analysis results using bimodal hydraulic properties and unimodal hydraulic properties with the saturated permeability of 10^{-3} m/hr. By using the semi-empirical model for shear strength of unsaturated soils, the input parameters only include the saturated cohesion and effective internal frictional angle. The values: c' = 5 kPa and ϕ' = 17 kPa suggested by Liu (1997) for cracked expansive soils was first used for the surficial layer in the stability analysis. The variation of FS with respect to time is show in Figure 7. It can be seen that the FS calculated using the bimodal hydraulic properties is initially higher than that obtained using unimodal hydraulic properties. However, the FS based on bimodal hydraulic properties decreases in a faster rate and becomes lower than that based on unimodal hydraulic properties after the 15th day of rainfall. This phenomenon is generally consistent with that observed in the suction variations over time illustrated in Figure 5.

The FS calculated using c' = 5 kPa and ϕ' = 17º at the end of rainfall condition is around 2.8, indicating a fairly stable slope. This value cannot reflect the actual condition that some sliding displacements occurred, although an entire collapse was not observed (Zhang et al. 2010). Some researchers (e.g. Lade, 2010) argued that the shear strength parameters for shallow slope stability analysis should be determined from the specimens under low confining stress conditions according to the actual ground condition, a nonlinear or linear strength model with a zero or extremely low cohesion is recommended to fit the measure shear strength data under low confining stress condition. In the present study, the strength parameters, c' = 0 kPa and ϕ' = 30º as a representative at low confining stress condition are used to repeat the FS calculation based on the same hydraulic condition outlined above. The results are shown in Figure 7. At the end of rainfall period, the FSs based on both bimodal and unimodal hydraulic properties decrease to values slight larger than one, which may better reflect the field observation by Zhang et al. (2010).

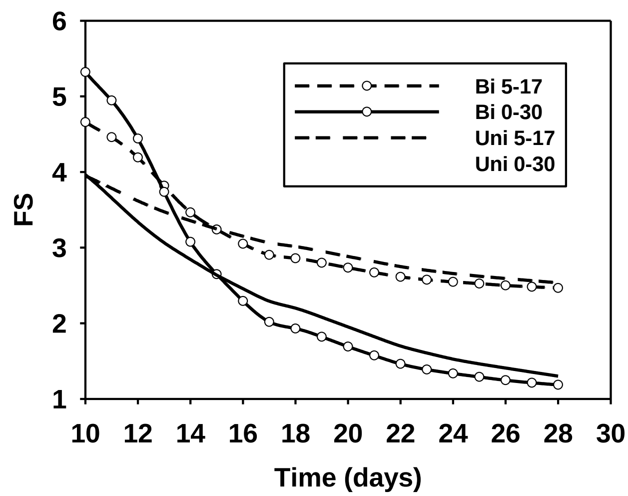

Figure 7. Factors of safety using the bimodal and unimodal hydraulic properties

5 CONCLUSION

The response of an expansive soil slope to an artificial rainfall infiltration in the in situ study conducted by Zhang et al. (2010) is numerically simulated in the present study. The hydraulic behaviour within the slope profile is reproduced using the Finite Element Method-based software SEEP/W, while the slope stability analysis is carried out using the Limit Equilibrium Method-based software SLOPE/W. In the hydraulic analysis, effort is put into selecting the proper SWCC and permeability functions to represent the effect of cracks. In the slope stability analysis, the simplified Janbu's method is selected to calculate the FS variation over time along a prescribed slip surface according to field study. The following conclusions can be derived from the results presented in this paper

(i) The cracks can significantly increase the permeability of surficial layer. However, it is difficult to reproduce the measured time history of PWP at shallow depth using the unimodal SWCC and the coefficient of permeability.

(ii) The dramatic decrease over time in the suction at the shallow depth is successfully predicted by using a bimodal SWCC and permeability function. This indicates bimodal SWCC and permeability function can better account for the effect of cracks on the hydraulic behaviour of surficial layer.

(iii) The FSs calculated based on bimodal hydraulic properties are initially higher, but become lower, than those based on unimodal hydraulic properties. This phenomena is consistent with suctions predicted in Finite Element Analysis.

(iv) Selection of appropriate shear strength parameters from laboratory tests under lower confining stress conditions are required for the slope stability analysis of expansive shallow layer during rainfall period.

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