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Stability analysis of an unsaturated expansive soil slope subjected to rainfall infiltration

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Abstract. Shallow failures occur frequently in both engineered and natural slopes in expansive soils. Rainfall infiltration is the most predominant triggering factor that contributes to slope failures in both expansive soils and clayey soils. However, slope failures in expansive soils have some distinct characteristics in comparison to slopes in conventional clayey soils. They typically undergo shallow failures with gentle sliding retrogression characteristics. The shallow sliding mass near the slope surface is typically in a state of unsaturated condition and will exhibit significant volume changes with increasing water content during rainfall periods. Many other properties or characteristics change such as the shear strength, matric suction including stress distribution change with respect to depth and time. All these parameters have a significant contribution to the expansive soil slopes instability and are difficult to take into consideration in slope stability analysis using traditional slope stability analysis methods based on principles of saturated soil mechanics. In this paper, commercial software VADOSE/W that can account for climatic factors is used to predict variation of matric suction with respect to time for an expansive soil cut slope in China, which is reported in the literature. The variation of factor of safety with respect to time for this slope is computed using SLOPE/W by taking account of shear strength reduction associated with loss of matric suction extending state-of-the art understanding of the mechanics of unsaturated soils.

Keywords: expansive soils; slope stability; unsaturated soils mechanics; case study

1. Introduction

More than four decades ago, Chen (1975) suggested that there will not only be a significant increase in infrastructure construction activities in regions with expansive soils deposits, but they will also offer challenges to the geotechnical engineers for their design and construction in this direction due to their complicated hydro-mechanical behaviors (Alonso 1999). This prediction turned out to be true across different countries worldwide (Widger and Fredlund 1979, Hou *et al.* 2013, Xu *et al.* 2014, Alonso *et al.* 2003, Azañón *et al.* 2010, Day 1994, etc.). Different types of civil infrastructures which include bridges, highways, slopes, retaining walls and foundations are being constructed in expansive soils which are previously considered as problematic soils and were avoided as much as possible. Numerous man-made soil slopes are formed either by compaction of expansive soils or by cutting in natural expansive soil deposits (Widger and Fredlund 1979). It is known that the failures of slopes are likely to occur in the surficial layer due to the influence of climatic factors (Cho and Lee 2002, Ali *et al.* 2014, Cho 2014, Lu and Godt 2008, Tsai 2011). Field investigations (e.g., Bittelli *et al.* 2012) shows that the safety of the slope, in particular, the stability of the surficial layer, in expansive soils are extremely sensitive to local climatic changes.

However, the response of expansive soil slopes to climatic factors (e.g., rainfall or evaporation, etc.) could be significantly different from that of conventional clayey soils due to the presence of highly active clay minerals such as the montmorillonite or illite. Expansive soils typically exhibit considerable swelling upon wetting and shrinkage on drying, as shown by the laboratory experimental data (Fourie 1989, Windal and Shahrour 2002, Boyd and Sivakumar 2011, Richards and Kurzeme 1973, Brackley and Sanders 1992). As such, several hydraulic and mechanical characteristics of expansive soils that are distinct from the clayey soils might include (1) the more significant deformation-dependent water retention behavior and its effect on the hydraulic conductivity; (2) the substantial deformation magnitudes and the associated changes of stress regime; (3) the possible mechanical softening (stiffness reduction associated with matric suction loss and/or strength reduction associated significant straining), (4) the cracking behavior due to drying and its influence on the behavior of water flow through the cracked soil matrix. Most of these characteristic behaviors of expansive soils have negative influences on the slope stability, for example, the cracks and fissures that develop due to desiccation effects in the surface layers can act as channels during the rainfall infiltration process and significantly soften the top layer due to swelling and contribute to loss of shear strength which is associated with

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an increase in the water content (and reduction of matric suction). The significant complexity of expansive soils response to climatic factors and corresponding fundamental mechanisms of retrogressive landslides have been pointed out by many researchers (Flury *et al.* 1994, Hillel *et al.* 1998, Zhou *et al.* 2016). However, the failure characteristics of slopes in expansive soils are not well understood. For this reason, several investigators in recent years have undertaken studies on expansive soil slopes; some of these studies include in situ tests (Ng *et al.* 2003, Zhan *et al.* 2007) and centrifugal tests (Xu e*t al.* 2006, Cheng *et al.* 2011). These studies provide valuable data to better our understanding of fundamental mechanisms of expansive soil slope failures. Based on the measured data, it was found that the response of various parameters (e.g., water content, stress distribution, horizontal and vertical displacement) in sloping surface layers to climatic changes were generally consistent with the observed variation of positive or negative pore water pressures (i.e., matric suction). More specifically, the loss of soil suction is one of the most critical factors that contributes to slope failures in the surficial failures of expansive soil slopes during rainfall periods.

The effect of rainfall on stability and deformation of slope was studied using numerical analysis by several researchers (for example, Alonso *et al.* 2003, Potts *et al.* 1997, Cho 2009, Rahardjo *et al.* 2013, Hou *et al.* 2017, Yang *et al.* 2018, Kim and Jeong 2017, Tran *et al.* 2019). The numerical findings are essential and also specific for given slopes of particular case. For example, based on the pore-water-pressure distribution obtained from finite element analysis, the variation of local safety factors was computed following the classical expression for infinite slope as a ratio of available shear strength and shear stress by Alonso *et al.* (2003). The results showed that a perched water table developed over the interphase between upper two layers due to a significant transition in the coefficient of permeability values between these layers. The minimum factor of safety consistently approached a value close to unity in many of the similar scenarios at the interphase layer.

It is, however, found that slope stability and failure mechanism in natural unsaturated expansive soil areas is a rather complicated problem. There are various interior and exterior factors that can individually or combinedly influence the stability and/or trigger the failures/collapses of a slope. It is essential and necessary to single out the effect of each factor before establishment of a complete numerical model that can accommodate all these factors altogether. To better understand the particular effect of each important factor, the authors have conducted several works, e.g. the effect of expansion-induced degradation of mechanical properties was investigated in Qi and Vanapalli (2016), where decreasing in the mechanical properties (e.g., both the modulus of elasticity and shear strength) with gradual saturation was considered and the associated negative effects on the slope stability were quantified. In the previous works (Qi and Vanapalli 2015, 2016), the climate factors (soil-atmospheric interaction) are not well simulated. The results from Rahardjo *et al.* (2013) suggested that the computed pore water pressure distribution in slope stability analysis showed a better agreement with those from field measurements when the climate factors were taken into consideration in seepage analysis.

In this paper, to get a better understanding of the hydraulic response of expansive soil slope under unsaturated conditions to the climate factors and its influence on the slope stability, , VADOSE/W (Geo-Slope International Ltd. 2007) that can model soil water interaction accounting for climatic factors (e.g., the infiltration and evaporation) was used to predict variation of matric suction with respect to time in an expansive soil cut slope. Subsequently, the variation of factor of safety with time for the same slope model is computed using the SLOPE/W (Geo-Slope International Ltd. 2007) by taking into consideration shear strength reduction due to loss of matric suction associated with rainfall infiltration. The present work is conducted on the field case carried out by Ng *et al.* (2003). Good agreements in pore water pressure between predictions and measurements show the capabilities of the established numerical model, based on which the possible failure modes are also discussed.

2. Flow analysis using VADOSE/W

2.1 Model establishment

A field study performed by Ng *et al.* (2003) on an expansive soil cut slope in Zaoyang from Hubei province in China is used for establishing the finite element computational model. The investigations showed that abundant cracks and fissures developed near the ground surface that provided open channels for the rain water to infiltrate at a faster rate. From field reconnaissance studies it was found that the cracks reduced at a depth of about 1.5m under the ground surface. The sudden transition of the coefficient of permeability between the upper cracked soils layers of 1.5 m and denser soil layer that followed below it led to accumulation of water at their interface in the form of a perched water table during simulated rainfall periods of the in situ tests. To model these hydraulic characteristics of the slope and reproduce hydraulic response of the slope to simulated rainfall infiltration, a model with two soil layers was established as shown in Fig. 1.

The surface cracked layer having a thickness of 1.5m was set to a relatively high coefficient of permeability, while a lower coefficient of permeability was assigned to the dense intact soils below the depth of 1.5m. More details about the hydraulic properties used in the modelling are discussed in a later section. The slope model extends 50 m horizontally; the top and toe of the slope model have elevations of 107.2 m and 93 m, respectively. The computational domain used in the present study extends

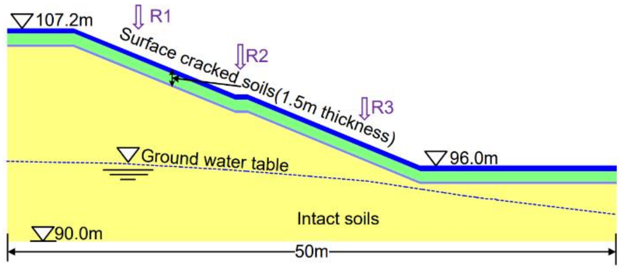


Fig. 1 Soil profile used for the model

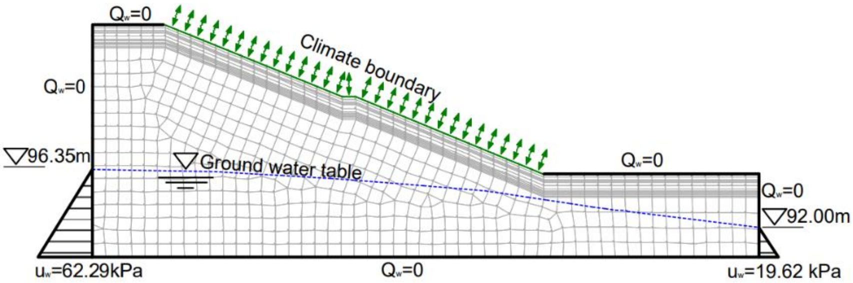
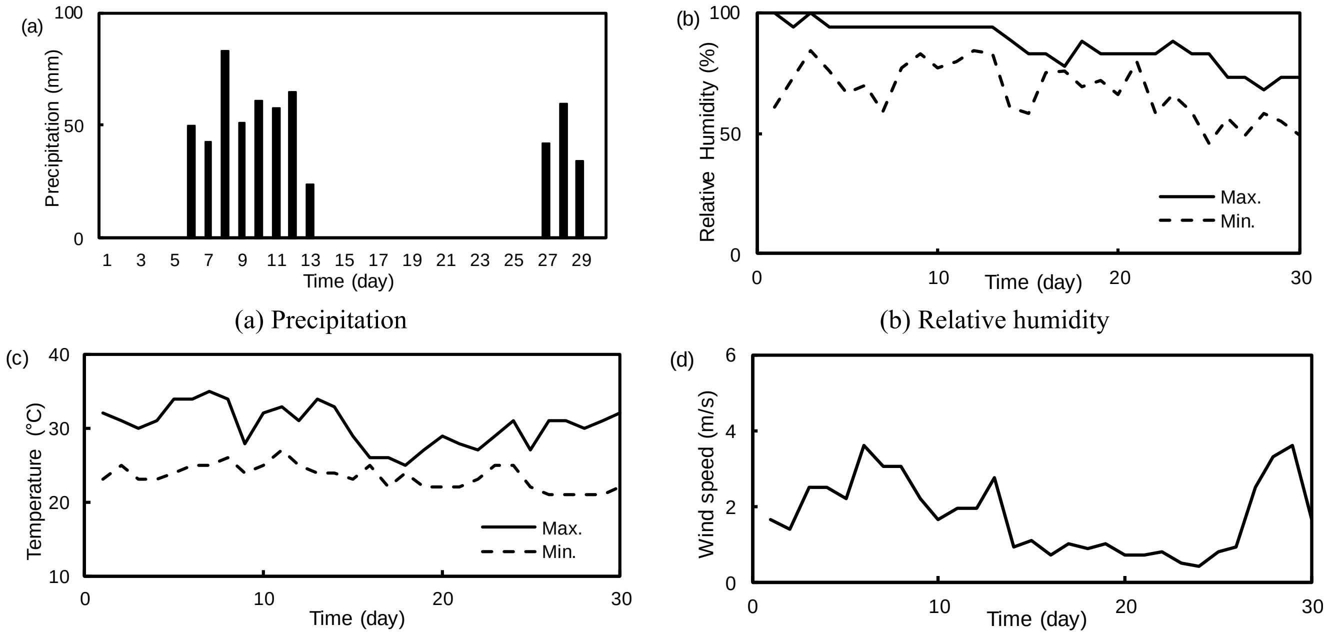


Fig. 2 Finite element mesh and boundary condition for water flow



(a) Precipitation (b) Relative humidity

(c) Atmospheric temperature (d) Wind speed

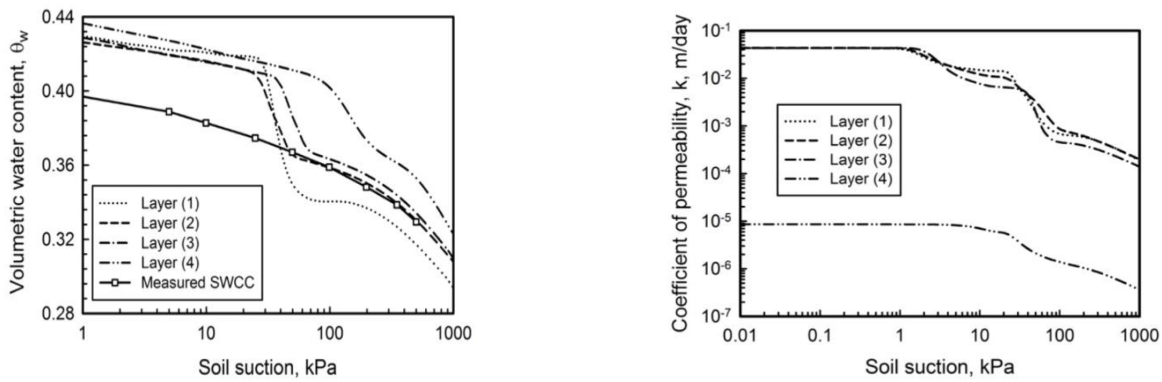
Fig. 3 The information of climate factors

to the depth of 6 m below the slope toe, where the lower horizontal boundary is defined. The ground water table for the deep flow regime that is essentially constant in both wet and dry seasons was detected at depths ranging from 2 to 11 m under the ground surface (Fig. 1). The computational domain used for the present study is discretized with 1075 quadrilateral or triangular elements in total; the mesh is finer in the surface cracked layer for dealing with the rapid changes in response to the climatic factors that could change dramatically over short periods of time, as shown in Fig. 2.

Fig. 2 also shows the various boundary conditions established for the discretized geometry of the slope. The measured pore water pressures at the lateral boundaries increased linearly with depth below the ground water table, which essentially represents the actual deep flow regime since the fluctuation of the ground water table can be negligible during the simulated periods. Similar results were also derived from numerical simulations that are discussed in a later section. The daily climate data gathered from the local weather station during the simulated periods was applied as a climate boundary at the sloping surface layer along with the two artificial rainfall events. The recorded time histories of temperature, wind speed, relative humidity, together with the two artificial events, over the simulation period are illustrated in Fig. 3. The other boundaries of the considered domain for water flow had a zero flux. As the daily variation of atmosphere temperature was not so significant, a simplified isothermal model was adopted to model the soil slope. In other words, the thermal properties of the slope soil were assumed to remain constant (i.e., the temperature = 27°C; the thermal conductivity = 400 kJ/days/m/°C; the volumetric heat capacity = 1875 kJ/m³/°C). In addition, an initial condition must be defined properly prior to calculation of varying hydraulic properties in the slope by performing the coupled transient analysis. The Draw Initial Water Table Command available in VADOSE/W is used for specifying the initial condition in the analysis since it is particularly useful when the actual position of ground water table is known. With this option, the initial pore water pressure in the considered domain varies hydrostatically with distance above and below the water table; a negative pore water pressure (i.e., matric suction) of 40kPa was set to the maximum limit for the pressure distribution in the unsaturated zone above the ground water table.

2.2 Model calibration

A procedure similar to those adopted by Overton *et al.*



(a) Soil-water characteristic curves (b) Coefficient of permeability functions

Fig. 4 Key soil properties of the 4-layers considered for the research slope

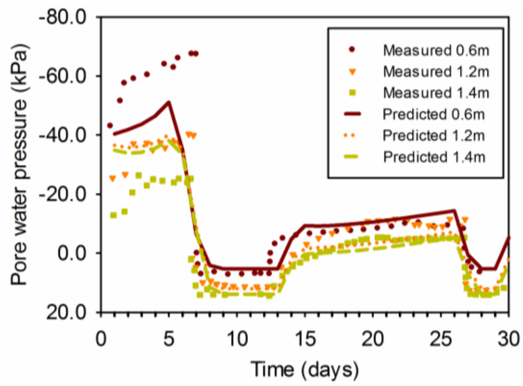


Fig. 5 Comparison of the predicted PWP and the measured PWP

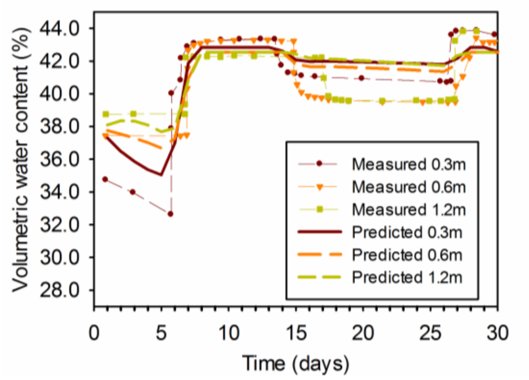


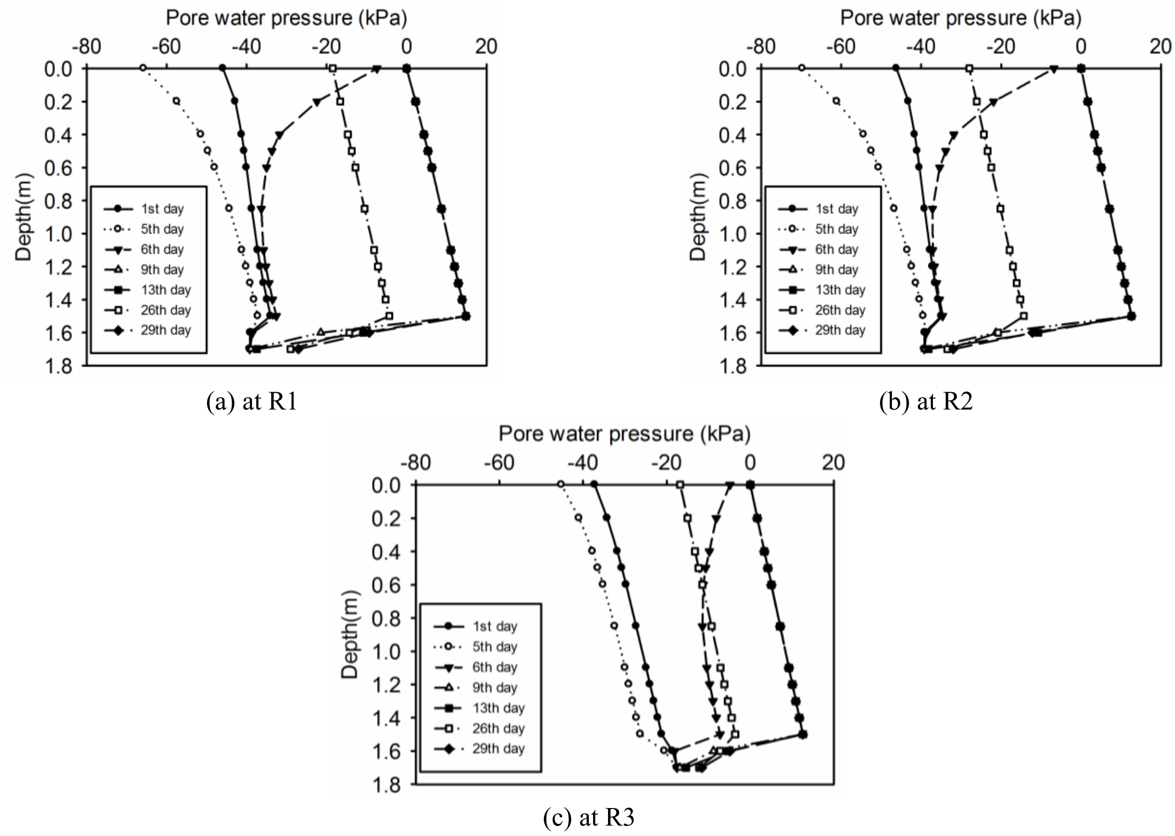
Fig. 6 Comparison of the predicted VWC and the measured VWC during rainfall events at R2

(2006) and Diewald *et al.* (2003) was used in the present study for VADOSE/W model calibration. In model calibration, some reasonable assumptions have to be made with regard to boundary conditions and some soil properties because of lack of data. When the hydraulic properties of interest were predicted based on these assumptions show a good agreement with the measured values, the model can be regarded as calibrated and can be used for further numerical simulations with confidence.

In the present study, the primary interest is to estimate the variation of the negative pore water pressure (i.e., matric suction) in the surface of cracked soils as shallow failures occur mainly due to the loss of the matric suction which contributes to the reduction of shear strength. The hydraulic properties of the surface expansive soils with rich in cracks and fissures are essentially difficult to be measured, especially the soil water characteristic curve (SWCCs) and the coefficient of permeability. Moreover, the expansive soil layer has varying widths of cracks with depth and exhibits different hydraulic behaviours. For this reason, in the present model, the upper cracked soil layer was further subdivided into three layers. The calibration was performed by adjusting the SWCCs and coefficient of permeability functions for the surficial three layers and intact soil layer in order to obtain a good comparison between the predicted and measured values of the pore water pressure (PWP) at mid-slope (R2). The predicted PWPs within the surface layers are in close agreement with the measured PWP values (Fig. 5) when the hydraulic properties given in Fig. 4 are used in the VADOSE analysis.

2.3 Model validation

The calibrated model should be validated such that it can be extended with a greater degree confidence for further modeling tasks including estimation of matric suction and evaluation of safety factors. The model calibration can be performed by comparing the predicted and measured variation of soil properties that can reflect the hydraulic response of the slope to the climatic changes, including the changing pore water pressure, volumetric water content, temperature, etc. In the present study, the variation of volumetric water content within 1.5m depth was selected as the reference to validate the slope model. Fig. 6 demonstrates that the volumetric water content predicted using the calibrated models provide a reasonable agreement with the measured values. The predicted volumetric water content at all depths increased rapidly to a steady state condition after the two artificial rainfall events but reduced to a lower value during the evaporation periods. Note that the actual evaporation rate at the surface was predicted by VADOSE/W based on Penman-Wilson (1990) method for which the coupled heat and mass solution provided the necessary parameters (Geo-Slope International Ltd. 2007). These are generally consistent with the measured volumetric water contents as well as response of pore water pressure to climatic changes although slight differences can



(a) at R1 (b) at R2

(c) at R3

Fig. 7 Variation of matric suction profiles

be seen in Fig. 6. The slight inconsistency may be due to some variations in situ measurements of volumetric water contents due to influence of the cracks and fissures present in the surface layer. Moreover, it is difficult to model the effects of randomly distributed cracks and fissures accurately using the present computational model.

2.4 Pore water pressure variation with time

The surficial failures in expansive soil slopes are mainly due to the increase of pore water pressure or loss of matric suction in the active zone during the period when climatic changes are predominant. Fig. 7 demonstrates that the variation of PWP profiles in the upper part of slope at three locations, namely, R1, R2, R3, during the simulated periods. It can be seen from Fig. 7(a) that the pore water pressure decreased remarkably during the first five days (prior to first rainfall event) due to evaporation, especially at depth close to the ground surface. After the commencement of the first artificial rainfall, the pore water pressure within the depth of 0.4m under the slope surface increased dramatically in the 6th day. The pore water pressure at the deeper depths subsequently rise as the rainfall continued during the following week. A hydrostatic condition was formed in the pore water pressure profile in the upper 1.5 m depth by the end of first rainfall period. After experiencing a reduction due to evaporation effects for a certain period, the pore water pressure profile again reached a hydrostatic condition quickly during the second rainfall. Similar trends can be found in the variation of pore water pressures at the other two locations (Fig. 7(b) and (c)). The predicted formation of hydrostatic condition above the depth of 1.5m was consistent with measured results. This discussion provides a reasonably good explanation why most slip surfaces of rain induced slope failures in expansive soil appear to be shallow.

3. Slope stability analysis using SLOPE/W

3.1 Analysis method

The pore water pressure variation with time in the slope obtained using the VADOSE/W was used as a parent file (from where the input parameters are in the subsequent analysis) to conduct slope stability using SLOPE/W considering the effect of climatic changes. Various limit

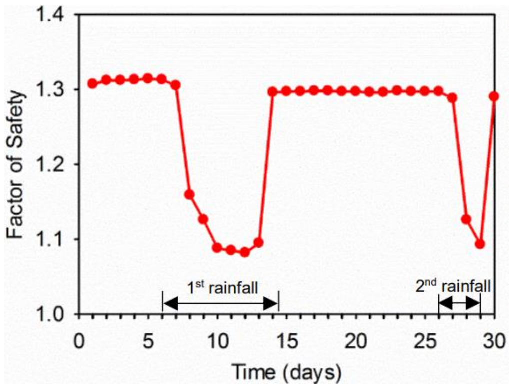
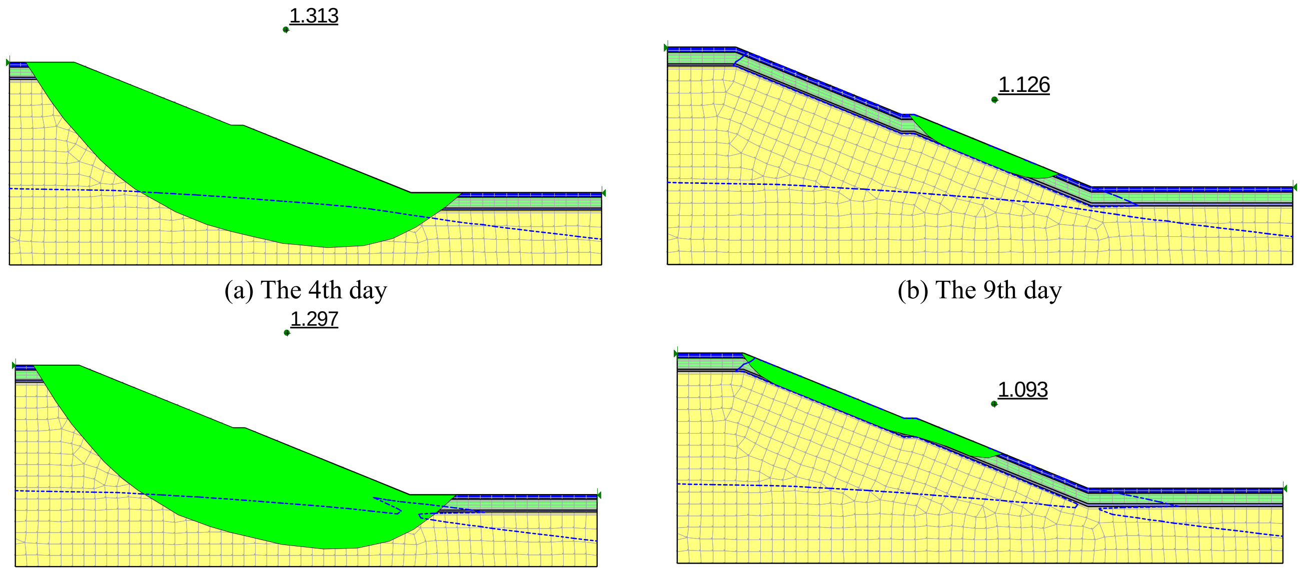


Fig. 8 Change of Factor of safety with respect to time



(a) The 4th day (b) The 9th day

(c) The 25th day (d) The 29th day

Fig. 9 Slip surfaces and factors of safety at different elapsed time

equilibrium methods, including ordinary method of slices, Bishop, Janbu's simplified, Spencer, Morgenstern and Price (M–P) and General Limit Equilibrium (GLE) method, are available in SLOPE/W for slope stability analysis. The fundamental theories of these slope stability analysis methods can be found elsewhere. Since the Morgenstern and Price method can satisfy all three equilibrium conditions for two-dimensional scenarios, it was utilised in the present study to compute the variation of factors of safety of the model slope with respect to time under varying environmental conditions.

The equation proposed by Vanapalli *et al.* (1996) that uses the soil water characteristic curve and effective shear strength parameters to predict the unsaturated soil shear strength with respect matric suction

$$\tau_f = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\left[\left(\frac{\theta_w - \theta_r}{\theta_s - \theta_r}\right)\tan\phi'\right] \qquad (1)$$

where τ_f= shear strength of unsaturated soil, c' and ϕ'= effective cohesion and internal friction angle for saturated condition, (σ-u_a) = net normal stress, (u_a-u_w) = matric suction, θ_w= volumetric water content, θ_s= saturated volumetric water content, θ_r= residual volumetric water content. The air pressure in unsaturated soils can be assumed to be atmospheric (i.e., u_a= 0). An average unit weight of 18 kN/m^3 was assigned to the entire soil layer in the slope, in other words, the slope model was considered to be homogeneous with respect to unit weight for simplicity reasons. Recalling the cracking feature in the surficial layer, whose effect on the water flow behaviour has been considered by using bimodal hydraulic functions, its development is also likely to decrease the apparent shear strength. In this work, the parameters (c' = 5 kPa and ϕ' = 17 deg.) derived by Ng *et al.* (2003) from the simple calculation of passive stress ratio based on theoretical limiting conditions, were assigned to the upper cracked soil matrix with a thickness of 1.5 m. While, for the underlying intact soil layer, the parameters (c' = 16.2 kPa and ϕ' = 28.7 deg.) measured by Zhan *et al.* (2007) on compacted sample taken from the same site of field study were utilized. Given the heterogeneity of the assigned shear strength parameters, together with the different distributions of pore water pressure, the shape and location of critical slip surface corresponding to the minimal computed factor of safety could be different. The auto-search technique built in Geo-slope was used to locate the critical slip surface at each elapsed time. Specifically, the built-in "Entry and Exit" option, which allows more flexibilities for the slip surface, is used in this study to approximate the shallow slip surface that are likely to occur for the considered case, as demonstrated in the results presented later.

3.2 Factor of safety variation with time

Fig. 8 shows the factors of safety at each elapsed time (time step is one day for this case) computed using SLOPE/W. Before the commencement of the first rainfall, the factors of safety remains at a relatively high value slightly greater than 1.3, which indicates that the slope was in stable state during this period. However, the computed factor of safety decreases dramatically to a relatively low value after one day of rainfall. The response of factor of safety change to rainfall infiltration was essentially consistent to that of pore water pressure both predicted using VADOSE/W and measured in-situ (Ng *et al.* 2003). Immediately after the first rainfall stopped, the factor of safety increased quickly back to the magnitude of about 1.3 and remained at the same value even during the evaporation periods. The response of factor of safety to the second artificial rainfall showed a similar trend to that of the first one. At the end of 12th day, the factor of safety dropped to the lowest value of 1.082, which brought slope close to failure condition. This discussion provides a reasonable explanation of the significant increase in the down-slope displacements observed in situ of the study summarized in

Ng *et al.* (2003).

3.3 Failure modes

A closer examination at the factors of safety and corresponding potential failure modes at different elapsed time (Fig. 9) suggests that the types of potential failure modes during evaporation periods (Fig. 9(a) and 9(b)) differ from those during rainfall periods (Fig. 9(b) and 9(d)). The potential critical slip surfaces during evaporation periods appeared to be deep-seated, part of which go through the fully saturated zone (i.e., under the phreatic surface). This is because the various zones in the unsaturated soil zone have higher shear strength due to the contribution of matric suction, compared to the soils under the phreatic surface with lower shear strength because of the influence of the positive pore water pressure. A perched water table developed at the interface between the cracked and intact soils layers with the rainfall infiltrating. After a certain period of rainfall, the hydrostatic pore water pressure distribution formed in the surface cracked soil layer as explained in an earlier section. The shear strength within this cracked layer were dramatically reduced due to loss of matric suction as well as decrease in normal effective stress exhibiting the shallow failure modes. A large portion of potential slip surface located at the interface between the cracked and intact soils layers, as shown in Fig 9(b) and (d). The computed results show a good agreement with those obtained by Alonso *et al.* (2003) using numerical methods as well as in situ results observed by Ng *et al.* (2003).

4. Conclusions

The responses of expansive soils to climate change are rather complicated, so is the associated failure mechanism of slopes in expansive soils. To better out understanding of the effect of climate change on the stability of expansive soil slopes, the combination of VADOSE/W and SLOPE/W is used to numerically investigate the behavior and stability of a cut slope in expansive soils in Zaoyang of Hubei province in China (Ng *et al.* 2003). The interactions between the slope and climate factors that contain, in particular, two artificial rainfalls, are simulated by the VADOSE/W, from which the produced pore water pressure variation is incorporated into slope stability analysis where both FS and location of potential slip surface are calculated.

It is found that close agreements between the predicted hydraulic responses of the model slope and field measurements, in particular, the time histories of pore water pressures and water contents within the shallow layer, can be achieved by using the established two-layer models with properly calibrated hydraulic properties to account for the cracking effect on the shallower layer. This indicates the effectiveness of the calibrated the bi-model SWCC and permeability functions to describe the behavior of water flow through cracked soil matrix near the ground surface.

The results from the stability analysis show that the variation of stable/instable state of the slope is the consistent with change of flow regime within the slope. The slope is fairly stable during the evaporation stage, but is likely to fail with the failure mass located mainly surface layer during the rainfall periods. The switches between these two states is also as quick as the variation of pore water pressure. This results satisfactorily reflect the possible shallow sliding mechanism implied from the observed evolution of displacement (Ng *et al.*, 2003).

The capability of the established numerical model to simulate the complexities of expansive soil slopes under climate conditions, is not only attributed to the proper consideration of heterogeneity in hydraulic properties, but also the heterogeneity in shear strength parameters.

Acknowledgments

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