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Validation of Numerical Modelling Techniques in Unsaturated Slope Behaviour

(Pengesahan Teknik Pemodelan Berangka dalam Tingkah Laku Cerun Tak Tepu)

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ABSTRACT

Knowledge in modelling unsaturated slope behaviour remains limited. Research findings have challenged the common assumption of fully saturated conditions for all soil problems thus widening the perspective of partially saturated states. The calibration of unsaturated soil parameters requires good understanding of the soil-water characteristic curve (SWCC) and the permeability functions. The modelling of unsaturated slope behaviour involves the setting out of the model geometry, boundary conditions and flux boundaries when it comes to rainfall. It is a norm where certain unobtainable data had to be assumed and the results are consequently under or over-estimated. Hence, this paper aims to validate the numerical techniques in modelling the groundwater flow and safety analyses for a slope model under the effect of typical rainfall in Hubei, China. The model is developed using Finite Element package; Plaxis and the results are compared to the field results and literature findings. The important parameters of hydrological and mechanical properties were gathered from the literature along with the boundary conditions. The flux boundaries are presented by simulated rainfall for a period of one month and the calculation is conducted in transient flow analysis. The results in terms of pore-water pressure are well validated with minor differences which can be explained by the unavailability of data for example the void ratio used and exact location of measurement taken in the field and literature findings. The analysis is also extended to calculate the factor of safety which contributes to familiarising the techniques in modelling by means of utilising the phi-c reduction method. In summary, the results demonstrated that the numerical modelling of unsaturated slope behaviour can be undertaken provided that all major information such as soil parameters, slope geometry and boundary conditions used are available and reliable.

Keywords: Unsaturated slope; groundwater flow; factor of safety; Plaxis

ABSTRAK

Pengetahuan mengenai pemodelan kelakuan cerun tak tepu masih terhad. Penemuan penyelidikan telah mencabar andaian umum bahawa semua masalah tanah adalah berkaitan dengan tanah berkeadaan tepu. Keadaan ini meluaskan kefahaman tentang perspektif keadaan tanah separa tepu. Penentukuran parameter tanah tak tepu memerlukan pemahaman yang baik tentang lengkung ciri air tanah (SWCC) dan fungsi kebolehtelapan. Pemodelan kelakuan cerun tak tepu melibatkan penentuan model geometri, keadaan sempadan dan sempadan fluks ketika berlakunya hujan. Adalah menjadi kebiasaan di mana terdapat data tertentu yang tidak dapat diperolehi telah diandaikan dan hasil keputusannya disalah anggarkan. Oleh itu, kertas kajian ini bertujuan untuk mengesahkan teknik-teknik berangka dalam memodelkan aliran air bawah tanah dan analisis keselamatan model cerun yang dipengaruhi kesan hujan tipikal di Hubei, China. Model ini dibina menggunakan pakej unsur terhingga; Plaxis dan keputusannya dibandingkan dengan hasil kerja lapangan dan penemuan literatur. Parameter penting bagi sifat hidrologi dan mekanikal telah dikumpulkan dari literatur terdahulu bersama dengan syarat sempadan. Batasan fluks dibentangkan oleh hujan simulasi untuk tempoh satu bulan dan pengiraan dijalankan dalam analisis aliran sementara. Keputusan dari segi tekanan air liang disahkan dengan perbezaan kecil yang dapat dijelaskan oleh ketiadaan data contohnya nisbah lowong yang digunakan dan lokasi pengukuran tepat yang diambil dari kerja lapangan dan hasil kajian literatur terdahulu. Analisis ini juga diperluaskan untuk mengira faktor keselamatan yang menyumbang bagi membiasakan teknik dalam pemodelan dengan menggunakan kaedah pengurangan phi-c. Secara ringkasnya, keputusan menunjukkan bahawa pemodelan numerik tingkah laku cerun tak tepu boleh dilakukan dengan syarat semua maklumat utama seperti parameter tanah, geometri cerun dan syarat sempadan yang digunakan boleh diperolehi dan dipercayai.

Kata kunci: Cerun tak tepu; aliran air bawah tanah; faktor keselamatan; Plaxis

INTRODUCTION

The numerical modelling of unsaturated soil slope has developed fast and many research can be found in literature promoting the advanced solutions of slope boundary problems. The general concept in conducting the numerical modelling remains vital to ensure accurate results are calculated especially when employing finite element codes. In fact, the implementation of finite element in several cross-disciplinary subjects enhanced the development of robust numerical models such as the studies of the effect of damping on bridges by Hwa and Osman (2015) and dynamic behaviour of concrete by Yong et al. (2017). Finite element modelling utilises approximate solutions of ordinary and differential equations to describe the distribution of stresses and strains in soil (Ungureanu et al. 2017). In soil, finite element modelling has facilitated the understanding of unsaturated behaviour tremendously over the last decades. This study lengthens the literature for finite element modelling of unsaturated soil mechanics by validating the techniques of numerical modelling in unsaturated slope behaviour.

For soil mechanics in unsaturated states, the flow is determined by the soil-water characteristic curve (SWCC) and the hydraulic functions. The Darcy's Law which commonly used to describe the flow in saturated soils can also be used to model the unsaturated flow (Zhao et al. 2017; Kristo et al. 2017; Childs & Collis-George 1950). One of the famous models such as the Van Genuchten (1980) described the hydraulic behaviour of unsaturated soils by establishing the relationship between the relative permeability and effective saturation. The SWCC and permeability equations are employed in association with relative permeability, k_r to effective degree of saturation, S_e as shown in Equations (1) and (2) (Van Genuchten 1980; Van Genuchten & Nielsen,1985; Le et al. 2013).

$$S_e = \frac{S - S_r}{S_s - S_r} = \left[1 + \left(\frac{S}{S_e} \right)^{1/(1-m)} \right]^{-m} \tag{1}$$

$$k_r = \sqrt{S_e} \left[1 - (S_e^{1/m})^m \right]^2 \tag{2}$$

Model parameter, m determines the shape of the SWCC and permeability function. Parameter s_e and k_e as in Equation (3) and (4) respectively are related to soil porosity, ϕ by the parameters of η, ϕ_0, s_{e0} and k_{s0} .

$$S_e = S_{e0} \exp[\eta(\phi_0 - \phi)] \tag{3}$$

$$k_s = k_{s0} \frac{\phi^3}{(1-\phi)^2} \frac{(1-\phi_0)^2}{\phi_0^3} \tag{4}$$

Parameter η controls the rate at which s_e changes from its reference value, s_{e0} when ϕ deviates from its reference value ϕ_0 (Le et al. 2013). Therefore, the unsaturated flow, q is computed based on the generalized Darcy Law equation as shown in Equation (5).

$$q = -k_s k_r \nabla \left(\frac{u_w}{\rho_w g} \right) + z \tag{5}$$

The parameters of u_w, ρ_w g and z represent the pore-water pressure, water density, gravitational acceleration and the elevation coordinate respectively.

As the software; Plaxis (Plaxis 2012) had been selected to develop the unsaturated soil slope model in this study, the method of calculation provided is carefully analysed. In the beginning, the soil behaviour model is developed by generating the groundwater flow. The results of the flow analysis are presented in the generation of pore-water pressure. Many research have studied the behaviour of unsaturated slopes and extended their analyses to capture deformations such as the work conducted by Leung and Ng (2016), Osman and Barakbah (2006) and Tiwari et al. (2014). Several studies also adopted the coupled-flow deformation analysis for example the Villarraga et al. (2014), Hossain et al. (2013) and García-Aristizábal et al. (2012). These advances of adopting the coupled analysis involving groundwater flow and deformation lead the research of unsaturated soils to better understanding and incorporate advanced analyses. In recent years, other contributing factors for instance chemical and thermal effects also have been considered. However, the main focus to develop all these integrated models depends on the significant flow models that determine the initial changes in the slope behaviour.

UNSATURATED SOIL BEHAVIOUR

Numerous studies have been undertaken to apply the concept of effective stress in unsaturated soils. Bishop's effective stress includes the effect of suction on the Terzaghi's theory of stress state variables. By understanding that suction is highly significant in unsaturated soils behaviour, the application of Bishop's theory is well established in the calculations by Plaxis. The effective stress formulation is given as in Equation (6) which involves the net stress; $\sigma - u_a$ and suction; $u_a - u_w$, u_a and u_w, are the pore air pressure and pore water pressure respectively. In addition, X is the coefficient factor taken as the saturation degree where full saturation value is 1 and dry is zero.

$$\sigma' = \sigma - u_a + X.(u_a - u_w) \tag{6}$$

Theoretically, Fredlund and Morgenstern (1977) suggested that the unsaturated soil deformation can be calculated using Bishop's theory and have been used in several research work such as studies by Hamdhan and Schweiger (2013) and Abed and Vermeer (2009). The current version of Plaxis can compute both the Bishop and Terzaghi theories that represent the advanced and conventional methods by taking into account the effect of tensile stresses. Moreover, a number of advanced constitutive models in unsaturated

states have been established in literature. The Barcelona Basic Model (BBM) has been recognized by a few as the most advanced and robust (Abed & Vermeer 2006) and popular elastoplastic constitutive model to describe the behaviour of unsaturated soils (D'Onza et al. 2012; Hoyos & Pérez-Ruiz 2012). The formulation of the model has been carefully reviewed and numerous comments are given to improve the model such as the work by Wheeler et al. (2002). Alonso et al. (1990) were one of the many to develop and presented the completed model. Many other researchers have continued to refurbish the model by adding other important variables. These example of advanced constitutive models paved the research roadmap of unsaturated soils to progressive and definitive level.

SLOPE PROFILE AND BOUNDARY CONDITION

The slope profile is taken similarly as plotted in the case study of Zaoyang, Hubei, China model and the slope profile is shown in Figure 1. Three tensiometers and thermal conductivity sensors are placed about 5 meters from the crest and toe of the slope. The centre equipment is placed on a flat berm at (24.6, 14.8). The location of initial groundwater level is plotted based on the measurement taken in the case study. Mesh is applied to the slope profile with very fine global coarseness for higher accuracy calculations. The surface of the slope profile is refined to perform better calculations over the high working area.

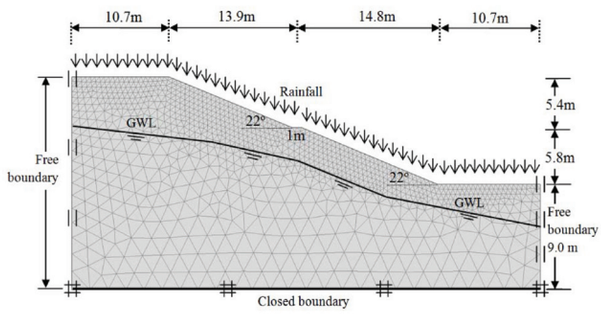

FIGURE 1. Slope geometry and boundary conditions (Hamdhan & Schweiger 2013)

The boundary condition is assigned by free-flow layer to both vertical sides and impervious layer to lower horizontal lines. The initial groundwater level is based on the monitoring data and plotted as in the slope profile. The minimum pore pressure head was set to -0.5 m and the maximum as 0.1 m during infiltration which explains the allowable depth for evaporation and water runoff respectively. A rainfall intensity chart as plotted in Figure 2 shows the precipitation amount of a 31-days duration. Continuous rainfall sessions are applied twice starting on the 6th and the 27th day. Infiltration is one of the most important factors in determining the unsaturated soil behaviour towards the changing weather, therefore, the use of typical rainfall realistically essential for the study.

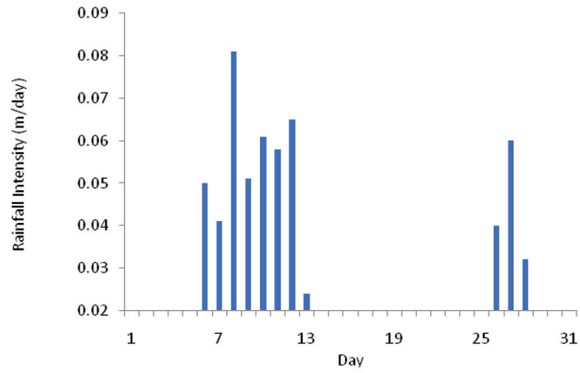

FIGURE 2. Typical rainfall in Hubei, China (Hamdhan & Schweiger 2013)

SOIL PROPERTIES

The parametric study used the soil properties of mechanical and hydraulic parameters as provided in the case study by Hamdhan and Schweiger (2013). The basic soil properties used in the analysis are shown in Table 1. The unsaturated parameters are given as g_a, g_n and g_l. According to the low soil permeability given, the soil material used is considered clayey as indicated by USCS classification, therefore, it is best that the soil is applied in undrained behaviour. In Plaxis, the undrained behaviour for effective stress analysis can be conducted by using the model parameters. For this analysis, an option of Undrained (A) in Plaxis is used specifying the undrained analysis with effective angle of friction and cohesion. In addition, the soil is modelled with Mohr-Coulomb failure criterion under the perfectly plastic behaviour.

TABLE 1. Basic soil properties for mechanical and hydraulic conductivity (Hamdhan & Schweiger 2013)

Soil Properties	Value
Mechanical	
Unit weight, γ	15.6 kN/m^3
Elastic modulus, E'	10000 kPa
Effective Poisson's ratio, ν'	0.35
Effective cohesion, c'	16.67 kPa
Effective angle of friction, φ'	28.7°
Hydraulic	
Saturated permeability, k_{sat}	5.5×10^{-7} m/s
g_a	0.80 1/m
g_n	1.09
g_l	0.50

SIMULATIONS CALCULATIONS

Initial condition: The groundwater flow analysis is selected as the initial phase of calculation in this study. The analysis is a steady-state calculation. A constant value of small amount of rainfall is applied to develop the initial pore-water pressure at the beginning of the simulation. Also, the location of groundwater table is shown as in Figure 1. Due to the

fact that this study is a slope stability where the ground is a non-horizontal surface, the initial stresses applied is gravity loading instead of K_0-procedure.

Fully coupled flow-deformation analysis: By conducting the study with coupled analysis, the calculation provides both deformation and flow analysis. The deformation analysis allows the displacement to be computed for example in vertical and horizontal directions. On the other hand, the flow provides the analysis of pore water pressure by means of active pore-pressure. The rainfall intensity is included in the analysis based on the chart shown in Figure 2. On the day that has no rainfall, the intensity is assigned to zero values while during rainfall, the maximum and minimum pore pressure head limits are assigned at 0.1 m and -0.5 m respectively.

Nil Phase: A nil phase is included between the coupled analysis and the calculation of safety analysis. This calculation of plastic phase is required and reliable to reduce any inaccuracy and overestimation of the safety factor due to the effects of suction and gravity loading.

Safety analysis: Safety analysis is undertaken for selected days to evaluate the stability of the slope under the effect of rainfall. This calculation is based on phi-c reduction where the calculation converges when the slope stability reaches failure (i.e. Factor of Safety is less than 1.0).

The models developed in this study are presented in terms of pore-water pressure and factor of safety. These results are compared to the field work as conducted by Ng et al. (2003) and the numerical results achieved by Hamdhan and Schweiger (2013). Three tensiometers were installed in the actual field work to measure the pore-water pressure. However, the reading for tensiometers discussed in this paper is focused on the middle-height slope location only with different depths (i.e. 0.6, 1.2, 1.4 and 1.6 m). The factor of safety presents the lowest ratio computed within the slope model geometry.

RESULTS AND DISCUSSION

RESPONSE OF PORE-WATER PRESSURE

The results of these analyses for different depths of the tensiometer reading are shown in Figure 3 (a), (b), (c) and (d). During a short period of dry days in the early part of the simulation, the pore water pressure shows a negative value indicating the suction. The field data result displays increasing value of the negative pore-water pressure compared to both numerical analyses. For instant at location (a) in Figure 3, the field data recorded -47 kPa while the author calculated -27 kPa using Plaxis. At the field, it can be explained that the evapotranspiration of water from the soil continued to take place whereas in the numerical analysis, the effect of evapotranspiration was not applied. The calculation in the initial phase was conducted in steady state therefore, mild increase of suction can be observed. On day 6, rainfall was applied and it can be seen that the pore-water pressure abruptly increased. The rapid changes indicated the loss of suctions due to rainfall infiltration into the soil. The reduction of suctions continued and fluctuated gradually until the rainfall has ended.

A slow increment of suctions then was observed during the return of dry period. The field data recorded a slightly high increment compared to the numerical results. This situation can be explained by the same mechanism happened during the initial phase where the evapotranspiration continued to occur whereas normal evaporation of suction loss happened for the numerical calculations. Next, due to the second session of applied rainfall, the pore-water pressure increased in a three-day rainfall event. The loss of suction can be seen occurring drastically again. Upon reaching the 31st day of the simulation, the behaviour of unsaturated soils presented by the development of negative pore-water pressure suggests that the loss of suction can occur at a very fast rate.

The redevelopment of suctions can be said requires time and the gradual increment suggest the need to include the effect of hysteresis in future research. The soil which was predominantly contained water demonstrated to collect water easily compared to losing water. Other than that, the development of suction can also be related to the initial degree of saturation and the effect of soil permeability. Low permeability soils such as clayey material losses less amount of water compared to sandy materials. These propose a further complex model for better result comparisons. From the technical aspect, any unavailable data such as the exact locations of the pore-water pressure calculated, may be the reason for the small differences computed in the results.

SAFETY FACTOR ANALYSIS

The factor of safety (FOS) in this section was analysed by using the phi-c reduction method. The FOS calculated in the first stage of initial phase shows an intermediate safe value of 1.87 as presented in Figure 4. This value then dropped gradually to 1.72 during the applied rainfall. Next, the drying period allowed the FOS to increase slowly due to the effect of suction. The increment can be explained by the development of shear strength that increases when the water content of the soil reduces. Once the rainfall was being reapplied, the shear strength reduced and the FOS also decreased. In terms of the FOS, it can be observed that the increment did not happen in large values. Once the soil loses suction, it was uneasy for the soil to redevelop its shear strength. This situation may be in relation to the effect of hysteresis which was not considered in this analysis. In addition, the safety analysis shows a steady increment and reduction. At day 29, the FOS further reduced slowly due to the continuous session of rainfall in the second stage. It is understood that the effect of hysteresis will be highly essential if it was applied in this analysis considering both wetting and drying processes affect the slope behaviour. It is also one of the reason why the difference of pore-water pressure was calculated differently from the work by Hamdhan and Schweiger (2013). Moreover, since most of the obtainable parameters used in both numerical

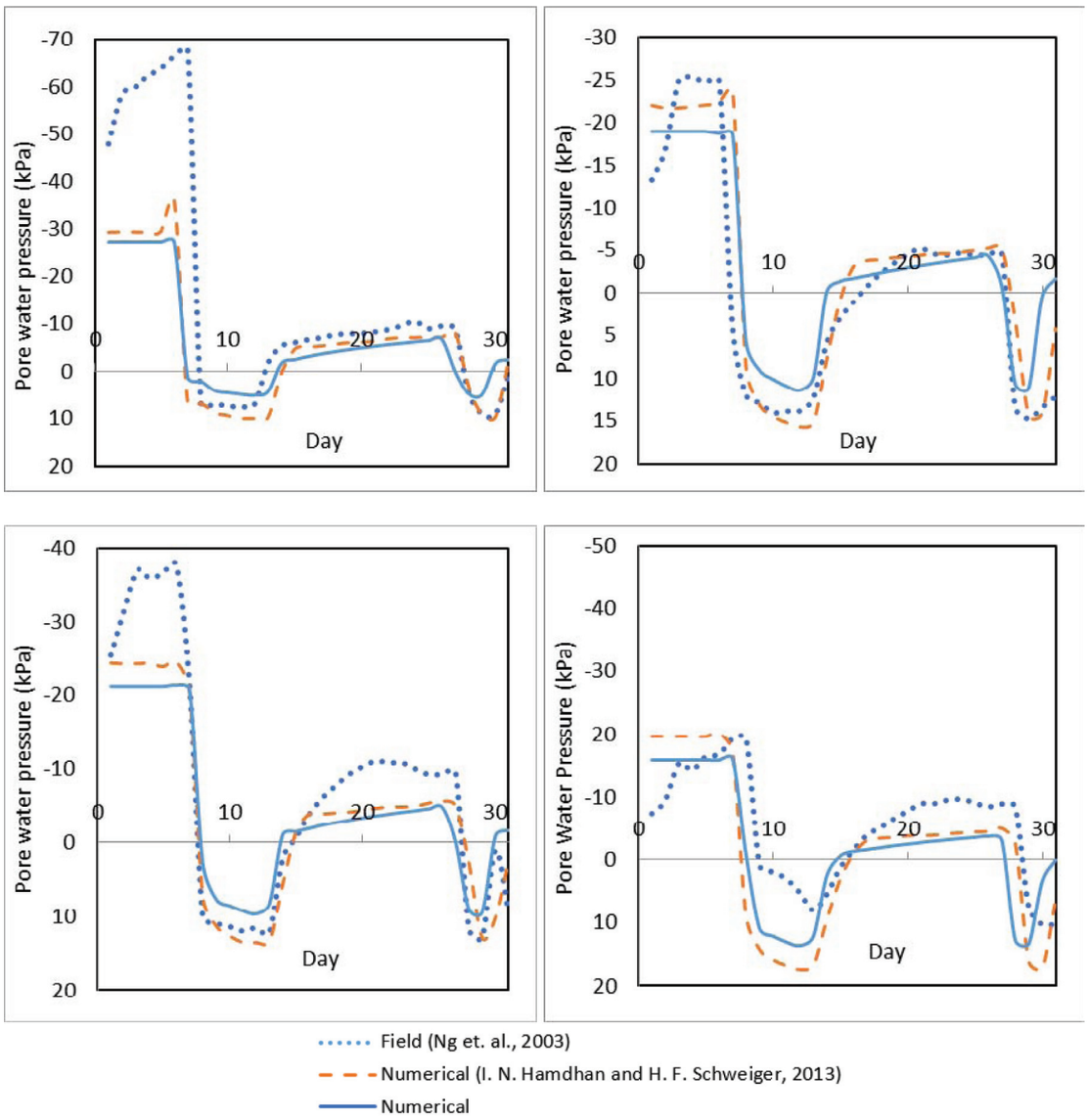

FIGURE 3. Generation of pore-water pressure for different depths (a) 0.6 m, (b) 1.2 m, (c) 1.4 m and (d) 1.6 m under the effect of typical rainfall

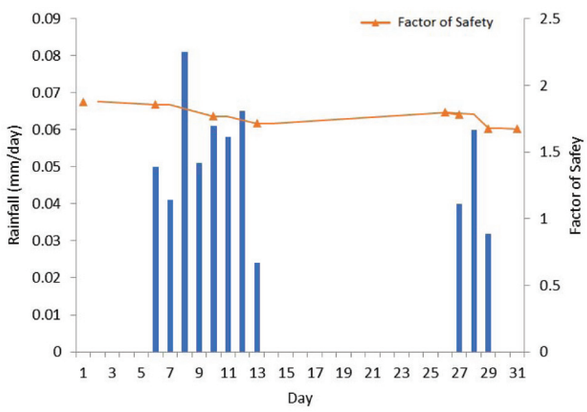

FIGURE 4. Factor of safety during the rainfall period

calculations were the same, the only reason of the different results that can be discussed here is the unavailable data in the literature. Careful considerations have to be undertaken to estimate these unavailable data so as not to under or overestimate the results.

CONCLUSION

This paper has successfully validated the numerical techniques in modelling the unsaturated slope behaviour under the effect of typical rainfall. The results were presented in terms of pore-water pressure and factor of safety. It is shown that a good comparison was found between the results calculated numerically and the field data and findings gathered in the literature. These consistencies of results can

be modelled provided that the slope geometry, soil properties, boundary conditions are available completely. Slight different results were observed due to minor information that had to be estimated within expected range of values such as the void ratio and exact location of results taken from the slope geometry. The extension of safety analysis also provided further information to the slope behaviour.

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