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Slope stability analysis considering soil suction using finite element method

Analyse de la stabilité des pentes en tenant compte de l'aspiration du sol en utilisant la méthode des éléments finis

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ABSTRACT: Unusual rainfall is one of the characteristics of climate change, and heavy rainfall is usually a major triggering factor of landslides in some areas. Moreover, seasonal changes in the groundwater table and the effect of soil suction are important factors to consider in slope stability analysis. However, in many cases, the effective stress and the shear strength of soils subjected to unsaturated conditions are not considered properly in such analysis. This paper presents a finite element method that incorporates the soil water characteristic curve in slope stability analysis wherein the degree of saturation varies according to the distance above the phreatic line. In the entire partially saturated zone of a slope, the actual shear strength and hydraulic conductivity of the soil are not uniform. Using ABAQUS/CAE, the two degree saturation-dependent parameters, i.e., matric suction pressure (u_a-u_w) and the hydraulic conductivity of soil (*k*), can be included in the computation. The proposed slope stability analysis also incorporates a strength reduction method. Consequently, the effects of the groundwater table, slope failure mode, and the contribution of partially saturated soil are addressed in the proposed slope stability analysis.

RÉSUMÉ: Les précipitations inhabituelles sont l'une des caractéristiques du changement climatique, et les fortes pluies sont généralement un facteur déclencheur majeur des glissements de terrain dans certaines régions. En outre, les variations saisonnières de la nappe phréatique et l'effet de l'aspiration du sol sont des facteurs importants à prendre en compte dans l'analyse de la stabilité de la pente. Cependant, dans de nombreux cas, la contrainte efficace et la résistance au cisaillement des sols soumis à des conditions insaturées ne sont pas considérées comme convenables dans une telle analyse. Cet article présente une méthode d 'éléments finis qui intègre la courbe caractéristique de l' eau du sol dans l 'analyse de stabilité des pentes où le degré de saturation varie selon la distance au - dessus de la ligne phréatique. Dans toute la zone partiellement saturée d'une pente, la résistance au cisaillement réelle et la conductivité hydraulique du sol ne sont pas uniformes. En utilisant ABAQUS / CAE, les paramètres à deux degrés dépendants de la saturation, c'est-à-dire la pression d'aspiration matricielle (ua-uw) et la conductivité hydraulique du sol (k), peuvent être inclus dans le calcul. L'analyse de stabilité des pentes proposée comprend également une méthode de réduction de la résistance. Par conséquent, les effets de la nappe phréatique, du mode de défaillance de la pente et de la contribution du sol partiellement saturé sont traités dans l'analyse de stabilité des pentes proposée.

KEYWORDS: Landslides, soil suction, finite element method, soil water characteristic curve, strength reduction method.

1 INTRODUCTION

The effects of rainfall and the location of the groundwater table on the stability of a slope are significant factors to consider in slope stability analysis (Rahardjo et al. 2010, Cho 2016). However, most traditional analysis procedures that employ limit equilibrium methods either ignore the effects of partially saturated zones or consider only the effects of saturated soils below the groundwater table and assume the pore water pressure to be zero above the groundwater table. In other words, most slope stability analyses are based on saturated soil mechanics. In practical engineering, however, landslides and other slope failures can involve both saturated and unsaturated soils. Given the recent development of concepts associated with unsaturated soil mechanics, the partially saturated zone above the phreatic line also is thought to play a significant role in slope stability.

It is reasonable to assume that the major portion of a slip surface passes through the saturated zone of a slope. However, for cases where the groundwater table is deep or water is not present in the slope, it is necessary to consider the effects of partially saturated soil. According to unsaturated soil mechanics theory and effective stress concepts for partially saturated soil, the shear strength of the soil in a partially saturated zone should increase and make a positive contribution to the stability of a slope (Fredlund and Rahardjo 1993, Rahardjo et al. 2010, Fredlund et al. 2012). Due to the resultant fluctuations of the groundwater table in a slope, the effect of the soil in partially saturated zones needs to be addressed in terms of slope stability. To this end, this study investigated a soil slope based on the principles of unsaturated soil mechanics and the empirical estimation for the soil water characteristic curve (SWCC) for partially saturated soils. This paper shows the importance of considering the groundwater table and addresses the contribution of soil suction in partially saturated soil to slope stability analysis.

1.1 *Unsaturated Soil Mechanics*

The mechanical behavior and theories that underlie unsaturated soils are well documented. According to Bishop (1959), the effective stress in a partially saturated soil depends on three variables: net normal stress $(\sigma - u_a)$, matric suction$(u_a - u_w)$, and the effective stress parameter χ, which is a material variable. The relationship between the effective stress and the air-water phase in a partially saturated soil can be written as Equation (1):

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \quad (1)$$

where σ' =effective stress; σ = total stress; u_a = pore air pressure; u_w = pore water pressure; χ = a soil parameter that is related to the degree of saturation and ranges from 0 to 1; σ-u_a= net stress; u_a-u_w = matric suction; and $\chi(u_a - u_w)$ is part of the effective stress that is attributed to the saturation state.

1.1.1 *Suction Stress*

For partially saturated soil, the material parameter χ is a function of the degree of saturation or matric suction (Lu and Likos 2004). According to Vanapalli and Fredlund (2000), for matric suction values ranging between 0 kPa and 1500 kPa, the following two forms, i.e., Equations (2) and (3), show good agreement with the experimental results obtained from laboratory tests.

$$\chi = S^{\kappa} = \left(\frac{\theta}{\theta_s}\right)^{\kappa} \quad (2)$$

where S = the degree of saturation; θ = the volumetric water content; θs = the saturated volumetric water content; and κ = a fitting parameter that is optimized to obtain the best fit between the measured and predicted values, and

$$\chi = \frac{S-S_r}{1-S_r} = \frac{\theta-\theta_r}{\theta_s-\theta_r} \quad (3)$$

According to van Genuchten et al. (1980), the model for the relationship between the effective degree of saturation, S_e, and matric suction can be expressed by Equation (4).

$$S_e = \frac{S-S_r}{1-S_r} = \left\{\frac{1}{1+\left(\alpha(u_a-u_w)\right)^n}\right\}^{1-1/n} \quad (4)$$

where α and n = fitting parameters; and S_r = the residual degree of saturation. The α parameter typically falls within the range $0 < \alpha < 0.5$ kPa - 1. The n parameter is related to the breadth of the soil's pore size distribution. In general, the range of n is between 1.1 and 8.5 for most natural soil types, according to van Genuchten (1980).

Based on Equations (2), (3), and (4), the relationship between the effective stress parameter χ (e.g., Lu and Likos 2004) and the effective degree of saturation can be written as Equation (5):

$$\chi = S_e = \frac{S-S_r}{1-S_r} = \left\{\frac{1}{1+\left(\alpha(u_a-u_w)\right)^n}\right\}^{1-1/n} \quad (5)$$

Lu et al. (2010) introduced the so-called 'suction stress', which is a function of matric suction and the effective degree of saturation. The concept of suction stress unifies the effective stress under both saturated and unsaturated conditions as expressed in Equation (6) (Li et al. 2015):

$$\sigma' = (\sigma - u_a) - \sigma^s \quad (6)$$

where σ^s= suction stress. Lu et al. (2010) showed that suction stress can be described as shown in Equation (7):

$$\sigma^s = -(u_a - u_w)S_e \quad (7)$$

Thus, the closed-form solutions derived by Lu et al. (2010) for suction stress in the full range of degree of saturation can be written as Equation (8):

$$\sigma^s = -\frac{S_e}{\alpha}\left(S_e^{n/(1-n)} - 1\right)^{1/n} \qquad 0 \le S_e \le 1 \quad (8)$$

1.1.2 *Hydraulic Conductivity*

The hydraulic conductivity of partially saturated soils also varies depending on the change in saturation. van Genuchten (1980) proposed a closed-form equation to estimate the coefficient of permeability, k, for partially to fully saturated soils. The form of the equation for hydraulic conductivity, k for partially saturated soils, can be correlated to the hydraulic conductivity for saturated soil. The relationship can be written as Equation (9):

$$k = k_{sat}\left[\frac{\left\{1-\left(\alpha(u_a-u_w)\right)^{nm}\left[1+\left(\alpha(u_a-u_w)\right)^n\right]^{-m}\right\}^2}{\left[1+\left(\alpha(u_a-u_w)\right)^n\right]^{m/2}}\right] \quad (9)$$

where k = the hydraulic conductivity of the water phase (m/sec); k_{sat} = the saturated hydraulic conductivity of the water phase; and α, n, and m = the van Genuchten (1980) SWCC fitting parameter, m = 1-1/n.

2. PARAMETRIC STUDY

Soil was sampled from a depth of 15 feet in Jamestown, North Dakota for the parametric study. Mechanical analysis and Atterberg limits tests were carried out in the laboratory to determine the engineering classification using the Unified Soil Classification System (USCS). The characteristics of this soil are described herein.

2.1 Soil Classification and Index Properties

Figure 1 presents a particle size distribution curve. The liquid limit (LL) = 29 and the plastic limit (PL) = 13. According to the USCS, the soil is classified as sandy clay (CL). The other properties of the soil include the undrained shear strength, S_u = 25 kPa, internal friction angle, ϕ = 15°, and dry unit weight, γ = 18.2 kN/m^3.

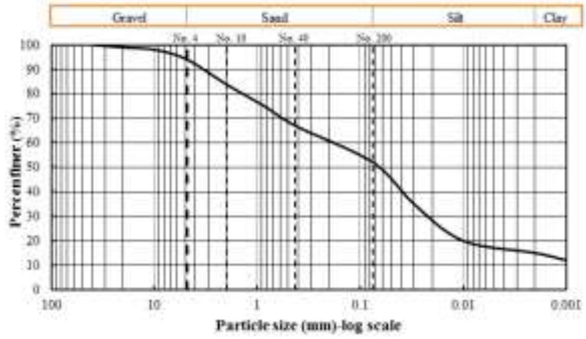

Figure 1. Particle size distribution curve

2 Hydraulic Conductivity of Unsaturated Soils

In addition to suction stress, the permeability of a partially saturated soil is dependent on the degree of saturation. The hydraulic conductivity formula for partially saturated soil can be rewritten by introducing a so-called permeability reduction factor, R. The mathematical expression is shown as Equation (10):

$$k = R \times k_{sat} \quad (10)$$

$$\text{where } R = \left[\frac{\left\{1-\left(\alpha(u_a-u_w)\right)^{nm}\left[1+\left(\alpha(u_a-u_w)\right)^n\right]^{-m}\right\}^2}{\left[1+\left(\alpha(u_a-u_w)\right)^n\right]^{m/2}}\right]$$

A permeability reduction factor R, which is dependent on the degree of saturation, is introduced and defined for the finite element analysis (FEA) used in this study.

3. NUMERICAL ANALYSIS

According to the required parameters for partially saturated soil that have been defined previously, the FEA along with a strength reduction method (SRM) were employed in this study to conduct the slope stability analysis. The Abaqus/CAE 6.14 finite element package was used to carry out a series of numerical analyses.

3.1 Slope Stability Analysis

For the FEA, a 2:1 slope (horizontal to vertical) underlain by a 0.5-H (H = slope height) thick foundation was created. The slope was assumed to be composed of clayey homogeneous soil. The Mohr-Coulomb failure criterion was employed to account for the plastic behavior of the soil. In addition to elasticity and plasticity, the permeability and soil suction data, which are two saturation-dependent parameters, were included in the analysis. Three boundary conditions for the groundwater table were assumed in the FEA. Sections 3.1.1 and 3.1.2 present details about the FEA using Abaqus/CAE.

3.1.1 Matric Suction and Permeability

Figure 2 shows the matric suction curve used in the FEA. The relationship between the degree of saturation and matric suction was derived using Equation (5) by assuming n = 2.0, S_r= 0.1, and α = 0.005 kPa^{-1}. Figure 3 shows the resulting permeability curve in terms of degree of saturation versus different levels of matric suction. The permeability of saturated soil is 5 × 10^{-6} m/s. Thus, the relationship between the permeability and the degree of saturation can be calculated by combining Equations (5) and (10).

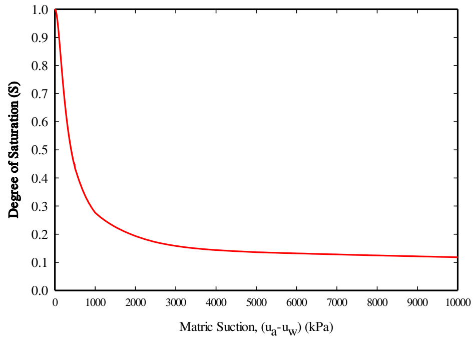

Figure 2. Matric suction curve

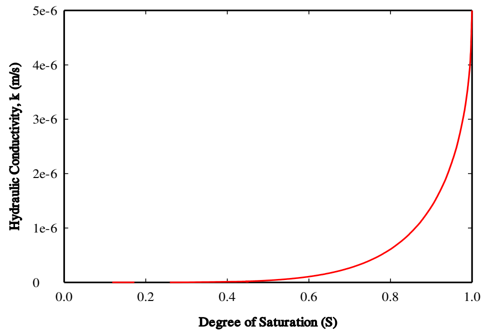

Figure 3. Permeability versus saturation

3.1.2 Finite Element Analysis

The model for the slope stability analysis was created using Abaqus/CAE and that was used for slope stability analysis with strength reduction method (SRM) by HO (2014). This model includes the suction curve and hydraulic conductivity that are dependent on the degree of saturation. The other soil parameters for the Mohr-Coulomb failure criterion must be defined for the model as well. Young's modulus (*E*) and Poisson's ratio (ν) are 100 MPa and 0.35, respectively.

The SRM was used to the slope stability analysis in this paper. When the computation is conducted, a strength reduction factor (SRF) is applied and keeps increasing in each iteration and in all fields in the model until the computation stops. The final SRF is regarded as the factor of safety that is used in limit equilibrium methods. The final SRF is a maximum value that will result in excessive distortion or plastic strain in the FEA. In terms of slope stability, the slope is considered to be failed. Also, the computation will stop because an unconverged solution appears (e.g., Griffiths and Lane 1999). The concepts behind the SRF can be expressed mathematically using Equations (11) and (12).

$$c'_f = \frac{c'}{\mathrm{SRF}} \qquad (11)$$

$$\phi'_f = \arctan\left(\frac{\tan\phi'}{\mathrm{SRF}}\right) \qquad (12)$$

where c' and ϕ' are the shear strength parameters of the soil; and c'_f and ϕ'_f are the shear strength parameters at failure.

In Abaqus/CAE, three case studies with different boundary conditions for the groundwater table and unsaturated zones were assumed and developed for this research: Case I – no groundwater; Case II – the groundwater table is consistent with the height of the foundation without considering soil suction in the partially saturated zone; and Case III – the groundwater table is consistent with the height of the foundation and soil suction is considered in the partially saturated zone. The analysis results of these case studies are discussed in Section 4.

4. CASE STUDIES

The slope is assumed to be homogeneous for all three case studies of the slope stability analyses using Abaqus/CAE discussed herein. Figure 4 presents the geometry of the slope created for the numerical analysis. The dimensions of the slope include the slope height, H = 40 m, and foundation, 0.5 H = 20 m.

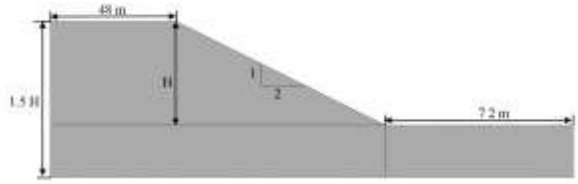

Figure 4. Geometry of a homogenous slope

4.1 Case I: No Groundwater

Case I assumes that no groundwater table exists or that the groundwater table is very deep and away from the slope foundation. For Case I, the calculated SRF is 1.02. The plastic strain at the SRF is 1.02, as shown in Figure 5. The excess plastic strain appears in the red band in the FEA. The excess plastic strain can be regarded as the potential slip surface of this slope. The potential failure mode of this slope is rotational failure.

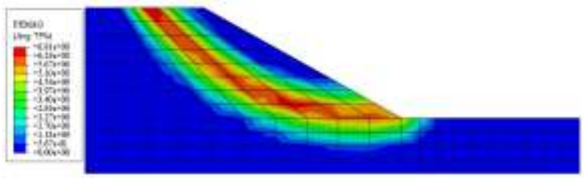

Figure 5. Contours of equivalent plastic strain using Abaqus.

4.2 Case II: Matric Suction Not Considered

Case II does not consider the negative pore pressure in the partially saturated zone. In this case, the groundwater table is assumed to be at the same height as the foundation underneath the slope. The soil below the groundwater table is assumed to be fully saturated and the pore water pressure above the groundwater table is assumed to be zero. Figure 6 presents the results of the pore pressure distribution for Case II. The highest pore pressure that appears in the model is about 200 kPa at the bottom and 0 at the surface of the foundation, which is consistent with the analytical results for the pore pressure in the saturated zone. In this Case II, the SRF was computed to be 0.97, which is slightly lower than the SRF for Case I without groundwater. Figure 7 shows the plastic strain that results when the slope fails and is regarded as the location of the slip surface.

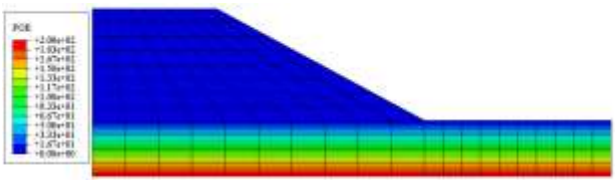

Figure 6. Pore water pressure distribution for Case II.

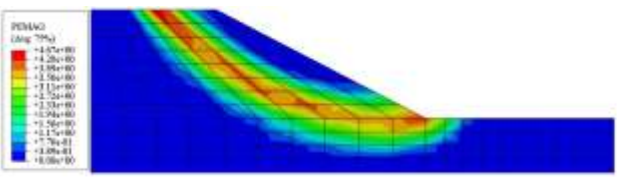

Figure 7. Contours of equivalent plastic strain for Case II

4.3 Case III: Matric Suction Considered

For Case III, the groundwater table is consistent with the height of the foundation, which is similar to the boundary conditions used in Case II. The soil below the groundwater table is assumed to be fully saturated, and the soil suction is considered in the partially saturated zone, which is above the groundwater table. The matric suction (u_a-u_w) is dependent on the degree of saturation of the soil. Moreover, the permeability of the partially saturated soil is also dependent on the degree of saturation. Thus, matric suction is taken into account in the FEA according to the curves shown in Figure 2 and Figure 3.

Figures 8, 9, and 10 present the Case III results for the degree of saturation, pore water pressure distribution, and equivalent plastic strain, respectively. Figure 8 shows the degree of saturation in the slope where the degree of saturation reduces to the residual degree of saturation, 0.1, at about 8 m above the groundwater table. Figure 9 shows the corresponding pore pressure where the pore pressure at the top of the slope is about -400 kPa. Figure 10 presents the potential slip surface in terms of excessive plastic strain. The SRF computed for Case III is 1.00.

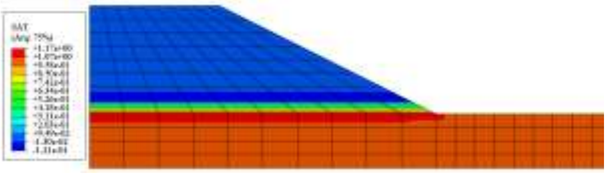

Figure 8. Degree of saturation for Case III

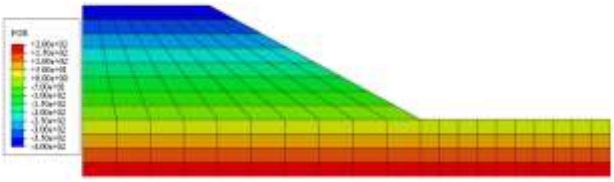

Figure 9. Pore water pressure distribution for Case III

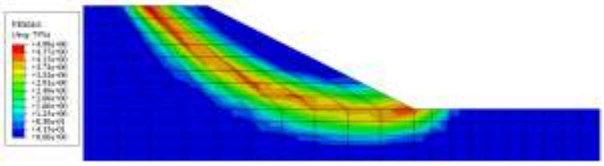

Figure 10. Contour of equivalent plastic strain for Case III

4.4 Results Discussion

The results of the FEA for the three case studies show that the type of soil in a slope is a very critical determining factor of safety for slope stability. Also, if groundwater is not present, the factor of safety is 1.02, which is right on the verge of slope failure. The factors of safety for the case studies that include and do not include the effect of soil suction in partially saturated soil are 1.00 (Case III) and 0.97 (Case II), respectively. These values are reasonable because the factor of safety varies due to the seasonal groundwater change. If no groundwater is present, the factor of safety could be higher. Because the groundwater is not present in the slope; thus, the effect of the groundwater table in slope stability analysis is negligible and the soil suction does not have to be considered.

Comparing Case II to Case III, if the groundwater table is located at the bottom of the slope, then Case III, which includes suction pressure in the analysis, has a higher factor of safety than Case II. Thus, the contribution of the negative pore water pressure for the partially saturated soil should not be excluded or ignored. In this study, the stability of a slope will be underestimated if the matric suction is ignored in the FEA.

The results of the FEA can be used to determine a strategy for mitigating slope-related hazards (landslides, e.g.). Taking advantage of soil suction to improve the shear strength of the soil can increase the stability of a soil slope.

5 CONCLUSIONS

This study presents a series of FEAs for slope stability. The SRM is included in the FEA to avoid the need to predefine a slip surface. In addition, the local soil provides insights into the effects of groundwater and soil suction for partially saturated soil. Several conclusions can be drawn from this study:

(1) The soil suction parameter for a slope that contains both fully saturated and partially saturated soil needs to be considered properly in slope stability analysis.
(2) The SWCC must be included in slope stability analysis when using a finite element technique, especially for those soils that have suction pressure that is sensitive to the degree of saturation, such as clayey soils.
(3) For practical slope engineering, the increase in the stability gained from negative pore water pressure should not be ignored to avoid the overdesign of engineered slopes or for landslide remediation.

6. ACKNOWLEDGEMENTS

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