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Effect of changes in matric suction on slope stability in natural unsaturated soil

Effet du changement de la succion matricielle sur la stabilité des pentes dans le sol naturel non saturé

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ABSTRACT Stability analyses were performed for a real engineering-geological cross-section of unsaturated Quaternary silt sediments. Unsaturated shear strength is a function of the two stress variables: net normal stress and matric suction. Constitutive equations (unsaturated shear strength – matric suction) and (angle φ^b – matric suction) were defined for these silty soils. These equations were established on the basis of primary constitutive relationships for unsaturated soils by soil-water characteristic curves (effective degree of saturation – matric suction). Soil-water characteristic curves were obtained from results of experimental tests on draining saturated soil samples under different pressures, performed for the first time in Serbia, in a 15 bar pressure plate extractor, according ASTM. Effective shear strength parameters c' and φ' were also experimentally obtained from direct shear tests. Stability analyses were performed using the GLE method for different climate conditions, before and after rainfall, i.e. for different values of matric suction. Stability analyses were performed for the same groundwater level, too. It was confirmed that rainfall decreases the angle φ^b and stability of natural unsaturated soil slopes. Decreasing the φ^b angle of unsaturated soil, due to rainfall, decreases the safety factor of the slope faster for coarse-grained soil than for fine-grained soil.

RÉSUMÉ Pour la coupe géotechnique réelle du terrain constitué de sédiments limoneux quaternaires non saturés, des analyses de stabilité ont été effectuées. La résistance au cisaillement du sol non saturé est fonction de deux variables de contrainte : contrainte normale et succion matricielle. Pour ces sols limoneux, des équations constitutives ont été déterminées, notamment : résistance au cisaillement non saturée – succion matricielle et angle φ^b- succion matricielle. Les équations sont déterminées sur la base de la dépendance constitutive primaire pour le sol non saturé – courbes caractéristiques humidité – succion (degré de saturation effectif – succion matricielle). Ces courbes ont été déterminées expérimentalement, pour la première fois en Serbie, par drainage des échantillons saturés du sol sous différentes pressions, avec l'extracteur de 15 bars. Les paramètres effectifs de la résistance au cisaillement c' et φ' ont été déterminés également expérimentalement, avec l'essai de cisaillement direct. Les analyses de stabilité sont réalisées la méthode générale d'équilibre limite, pour les différentes conditions climatiques, avant et après les pluies, c'est-à-dire pour les différentes valeurs de la succion matricielle dans le terrain. Les analyses de stabilité sont effectuées également pour le même niveau de l'eau souterraine. Il a été confirmé que l'angle φ^b et la stabilité des pentes dans le sol non saturé diminuaient sous l'effet des pluies. Avec la diminution de l'angle de la résistance au cisaillement du sol non saturé, φ^b, suite aux pluies, le facteur de sécurité des pentes diminue plus rapidement au niveau des pentes constituées de sols à grain grossier (qu'à grain fin).

1 INTRODUCTION

In the situation where the groundwater table is deep or when there are shallow slip surfaces, the soil above the slip surface is typically in an unsaturated condition. The unsaturated soil has an absorption possibility (matric suction or negative pore pressure) that increases the shear strength of unsaturated soil (Fredlund & Rahardjo 1993). It has a cohesion which consists of two components: one is effective cohesion, and the other is matric suction. For the latter it is necessary to define the angle of friction with respect to changes in matric suction φ^b and the matric suction value (u_a-u_w) in the field.

To do this we have to incorporate the effect of negative pore water pressures in the stability analysis of unsaturated soil (Hadzi-Nikovic 2002a,b). Such analyses require specific site and laboratory investigations and present an extension of conventional limit equilibrium equations.

For unsaturated soils in Belgrade's terrain, built by Quaternary silty sediments, which is well above the groundwater table, unsaturated shear strengths were determined by Hadzi-Niković (2005, 2009), using the approach proposed by Vanapalli et al. (1996.a). The angle φ^b was determined on the basis of soil-water characteristic curves (SWCC), experimentally examined in the pressure plate extractor, in accordance with method recommended by the American Society for Testing and Materials (ASTM 1993). For various matric suction values, the slope stability in unsaturated soil was estimated using the saturated shear strength parameters c' and φ' and the soil-water characteristic curve (Vanapalli & Fredlund 2000). In accordance with this approach, stability analyses of the slope were performed using the General Limit Equilibrium (GLE) method (Fredlund & Krahn 1977).

At the same time, stabililty analyses of the slope were performed for three different groundwater tables, which were recorded during three years of investigation, but ignoring effect of matric suction.

The results in this paper confirm that matric suction increases the factor of stability for slopes in a long-term unsaturated condition. Notwithstanding this fact, the slope stability is usually determined by assuming fully saturated conditions and ignoring the influence of negative pore pressure or matric suction on the unsaturated shear strength. Conventional slope stability analyses, which neglect matric suction in soil, give conservative solutions, leading to the uneconomic design of remedial measures (Fredlund 2006).

For all the other same conditions, the importance of negative pore pressure on stability increases with a lowering water level, and stability increases with increasing matric suction in unsaturated soil. This should be kept in mind for all short-term and back-calculated stability analyses for temporary slopes.

2 THEORY

The slope stability theory for unsaturated soils can be regarded as an extension of slope stability theory for saturated soil. The most important aspect of using the theory for unsaturated soils is the assessment of appropriate shear strength parameters and a matric suction value.

The shear strength parameters for a soil with matric suction are: effective angle of internal friction φ', effective cohesion c' and angle of unsaturated shear resistance with respect to matric suction φ^b.

Following these facts, the conventional limit equilibrium theory can be used for estimation of the stability of unsaturated soil. Fredlund and Krahn, 1977., proposed the General Limit Equilibrium (GLE) method (Figure 1) with equations for computing the safety factor with respect to moment equilibrium, F_m (Eq. 1) and force equilibrium F_f (Eq. 2), extended for unsaturated soil.

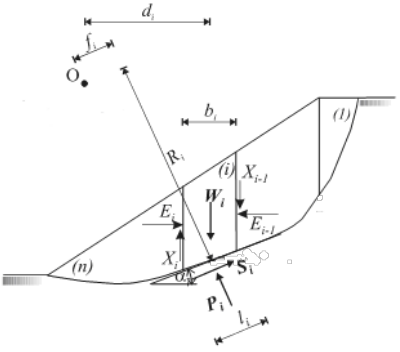

Figure 1. Slide mass and forces acting on a slice in unsaturated soil.

$$F_m = \frac{\Sigma \left\{ c_i' \cdot l_i + \left[P_i - u_{wi} \cdot l_i \frac{\operatorname{tg} \varphi_i^{\,b}}{\operatorname{tg} \varphi_i'} \right] \operatorname{tg} \varphi_i' \right\} \cdot R_i}{\Sigma \left(W_i \cdot d_i - P_i \cdot f_i \right)} \quad (1)$$

$$F_f = \frac{\Sigma \left\{ c_i' \cdot l_i + \left[P_i - u_{w_i} l_i \frac{\operatorname{tg} \varphi_i^{\,b}}{\operatorname{tg} \varphi_i'} \right] \operatorname{tg} \varphi_i' \right\} \cdot \cos \alpha_i}{\Sigma P_i \cdot \sin \alpha_i} \quad (2)$$

Unsaturated shear strength is a function of two stress variables: net normal stress and matric suction (Fredlund et al., 1976). The relationship of unsaturated soil shear strength function to the matric suction can be established on the basis of the primary constitutive relationships for unsaturated soil by the soil-water characteristic curves. The shear strength of unsaturated soil (Fredlund et al. 1996) can be estimated using the soil-water characteristic curve (Barbour 1998) and the saturated shear strength parameters. In this paper, the soil-water characteristic curves are defined as matric suction versus the effective degree of saturation (Brooks & Corey 1964) function, which is one of the most used methods in practice.

There are several approaches and equations for determining unsaturated shear strength (Guan et al. 2010, Sheng et al. 2011). In this study, the approach used was that proposed by Vanapalli et al. (1996.a):

$$\tau_f = c' + (\sigma - u_a)\tan\varphi' + (u_a - u_w)\tan\varphi' S_e \qquad (3)$$

where τ_f is unsaturated shear strength, c' is effective cohesion of saturated soil, φ' is effective angle of shear resistance of saturated soil, $(\sigma - u_a)$ is net normal stress, $(u_a - u_w)$ is matric suction and S_e is effective degree of saturation

The unsaturated shear strength parameter, φ^b, which is an angle of shearing resistance with respect to changes in matric suction, can also be expressed by the effective degree of saturation (Vanapalli et al. 1996.b, Vanapalli & Fredlund 1999):

$$\tan\varphi^b fn(u_a - u_w) = S_e \tan\varphi' \qquad (4)$$

It should be emphasized that it is difficult to assess an appropriate design matric suction value. If the matric suction of the soil is measured, it is recommended that this value is used only if it is highly reliable; in other cases, a factor of safety should be applied to the measured matric suction in order to obtain a design matric suction value. Another option is to accept and adopt the hydrostatic condition with respect to the groundwater table.

Soil suction can also be calculated by means of the soil-water characteristic curve in the unsaturated zone. In this study, the soil suction is calculated according to Brooks & Corey's function. Assuming that the pore air pressure is atmospheric, $u_a = 0$, soil suction is:

$$-u_w = (u_a - u_w)_b \left(\frac{1 - S_{res}}{S_r - S_{res}}\right)^{\frac{1}{\lambda}} \qquad (5)$$

where $(u_a - u_w)_b$ is the air-entry value, S_r is the degree of saturation, S_{res} is the residual degree of saturation and λ is the pore-size distribution index.

3 PROPERTIES OF SOIL AND TEST PROGRAM

This area of this study is a typical example of a loess complex covering the hilly terrain of Belgrade's territory, located near the Boulevard of King Aleksandar. The terrain is mildly sloping towards the south-west with an average gradient of 5°, and in places up to 15°. The primary morphological characteristics of the terrain have been significantly changed due to the activity of contemporary geological processes, and especially due to human activities and urbanization, which include excavations, slope cuts and fillings.

The terrain surface is made of a complex of loess deposits up to 15 m deep. Two loess horizons with a partly destroyed structure can be distinguished in the loess complex – layered with paleoelluvial soil and with clayey loess soil. Under them, delluvial clays are found. The marls and clays are at a depth of 15–18 m. Two standpipe piezometers (B-5 and B-6) were installed to monitor the fluctuation of the groundwater table. The intensity of rainfall was also recorded. Figure 2 shows the groundwater table fluctuation and variations in rainfall intensity for the period 1 October 2010 to 1 October 2013. The average groundwater table was at a depth of about 10 m below the ground surface with a maximum variation of 3.85 m in B-5 and 2.40 m in B-6.

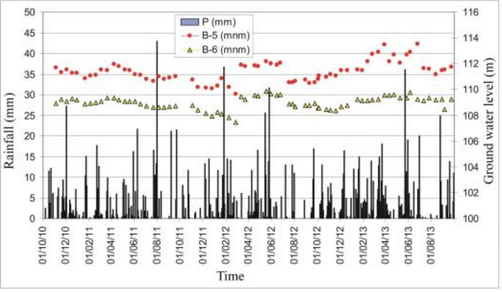

Figure 2. Groundwater table measurements from piezometers and rainfall records for three years.

The absolute water content was 18–20%, and the degree of saturation varied from 75 to 80%. Dry unit weight was 15.0–16.0 kN/m^3, and the unit weight with natural water content was $\gamma = 18.5$–19.5 kN/m^3.

According to the Casagrande classification, the loess sediments of the zone of aeration are medium-plasticity clays, CI, with liquid limit LL = 41%, a plastic limit *PL* = 23%, a plasticity index *PI* = 18% and colloidal activity $K_p > 1.25$.

In accordance with these geological and hydrogeological characteristics of the terrain and the physical properties of soil (phase content, pore size, absolute water content, degree of saturation), it is clear that the soil is well above the groundwater table and it is unsaturated.

The laboratory testing was performed on undisturbed samples of several loess soils above the groundwater level for typically unsaturated silty soils in order to determine:

- Soil-water characteristic curves, i.e. effective degree of saturation, S_e versus matric suction (u_a-u_w) relationships.
- Unsaturated shear strength, τ_f, versus matric suction (u_a-u_w) relationships.
- Variation of the unsaturated shear resistance φ^b with matric suction (u_a-u_w).

Soil-water characteristic curves were obtained from results of experimental testing by draining saturated soil samples under different pressures performed in a 15 bar pressure plate extractor, according to the ASTM: D2325-68 and D3152-72. All testing and their results have been presented in studies by Hadži-Niković (2005, 2014).

Direct shear tests for determining effective cohesion, *c'*, and effective angle of shear resistance, *φ'*, of saturated soil, were also performed.

4 RESULTS AND ANALYSES

The results obtained from the testing performed were used for the stability analyses of the slope in real engineering-geological conditions in the unsaturated Quaternary silty sediments. The results for the sample B-1(3.30–3.60) are presented here. The soil-water characteristic curve and variation of the friction angle, φ^b with matric suction, (u_a-u_w), using Equation (5), are presented in Figures 3 and 4, respectively.

Stability analyses were performed to assess the effect of matric suction changes on the factor of safety of the slope. For simplicity, it was assumed that soil is homogenous and isotropic. The water table was located at the depth of 8.15 to 12.00 m and 9.40 to 11.8 m below the ground surface at B-5 and B-6, respectively.

Shear strength parameters c' = 15 kPa and φ' = 24^0 from saturated CD triaxial tests, and $\varphi^b = 18^0$ from SWCC and Eq. (4) for matric suction of 60 kPa in the terrain (Eq.5), were used in the slope stability analyses.

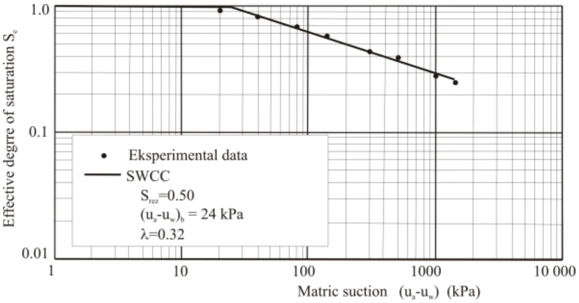

Figure 3. Soil water characteristic curve for sample B-1 (3.30–3.60).

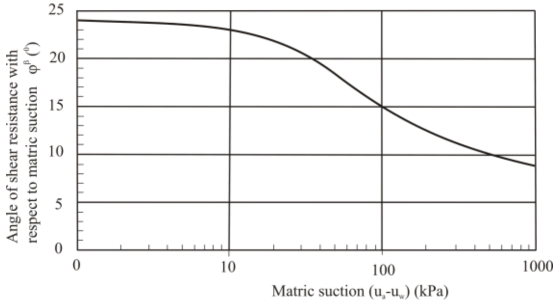

Figure 4. Unsaturated shear resistance φ^b versus matric suction.

The GLE method was used for slope stability analyses using SLOPE/W software, taking into account the circular slip surface.

For the first analyses, the effect of matric suction was ignored (Figure 5), but analyses were performed for different groundwater tables. Over three years of monitoring, the maximum groundwater table fluctuation was ± 2.0 m. The greatest rainfalls were not always followed by an increase in the groundwater table; that is, there was not a strong relationship between rainfall and the groundwater table (Figure 2).

Stability analyses were performed for the average (at the depth of 10 m), highest (8.0 m) and lowest (12.0 m) groundwater tables (GWT). The results obtained (i.e. factors of safety – Fs) were: for average

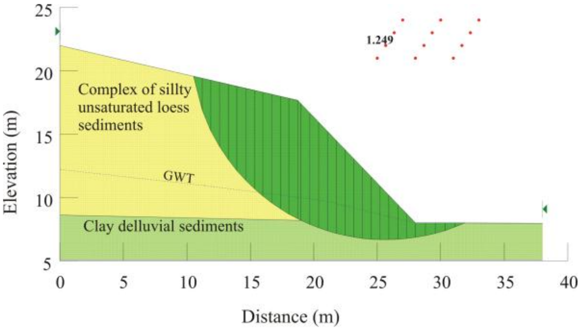

Figure 5. Potential circular slip surface for zero matric suction.

GWT Fs = 1.25 (Figure 5); for the lowest GWT, Fs = 1.29, representing an increase of about 3%; and for the highest GWT, Fs = 1.15, a decrease of about 8 %.

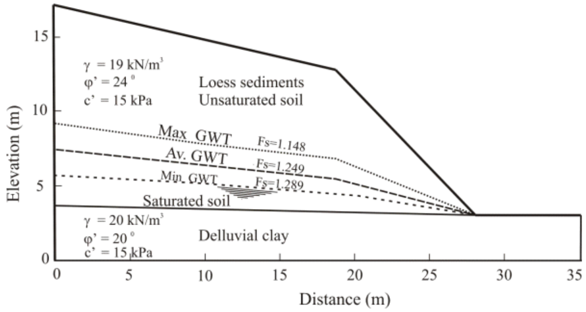

Figure 6. Factor of safety for different groundwater levels and zero matric suction.

For subsequent analyses, matric suction was taken into account as part of the cohesion. Factors of safety increased with an increase in matric suction.

The average suction of 60 kPa, i.e. degree of saturation Sr = 0.80, becomes the equivalent to cohesion of 19.5 kPa and the associated change in the factor of safety was 1.25 to 1.48 (Figure 7), an increase of about 19%. It was found that even after rainfall, i.e. for Sr = 0.85, the average matric suction in the terrain remained 35 kPa.

For dry conditions Sr = 0.75, the average matric suction can reach about 100 kPa. The factor of safety at this matric suction increases by approximately 40%. This illustrates the important influence of change in matric suction value on the stability of slope, which is more important than the groundwater table change.

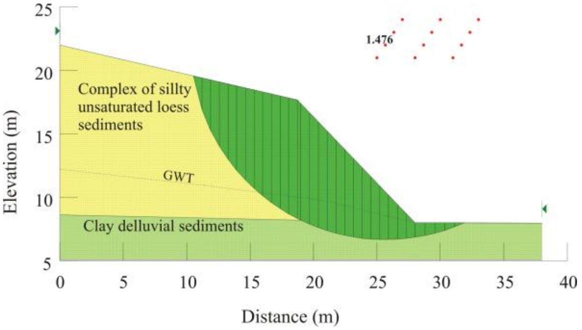

Figure 7. Potential circular slip surface for average matric suction of 60 kPa.

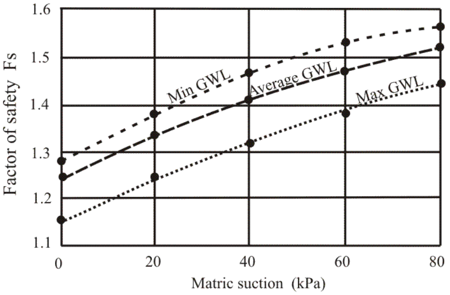

Figure 8. Effect of matric suction on factor of safety of unsaturated Quaternary silty soil slope.

The grain-size distribution is also very significant for the SWCC and for unsaturated shear strength. An increase in the grain size of soil decreases the effect of matric suction on unsaturated shear strength. Sandy loess soil with a greater grain size has a steeper SWRC and lower degree of saturation value for the same matric suction value (Hadzi-Niković 2009, 2014). Unsaturated shear resistance decreases rapidly in comparison with macro-porous loess soil, because desaturation lasts a shorter time. If the φ^b angle for unsaturated soil is decreased due to rainfall, the safety factor of the slope decreases faster for coarse-grained soil than for fine-grained soil.

5 CONCLUSION

If the groundwater table is deep, and the soil mass above the groundwater table is unsaturated, stability analyses should be performed with matric suction or negative pore water pressures. Such analyses require specific site and laboratory investigations and present an extension of conventional limit equilibrium equations.

The results obtained confirm that the inclusion of the effects of matric suction on unsaturated shear strength increases the value of the stability factor. Higher matric suction values give a higher factor of safety for the slope.

Matric suction values near the ground surface are the first to be affected by rainfall, followed by those at greater depths. But here, matric suction remained above the deep groundwater table even after rainfall. For all the other conditions, the effect of negative pore water pressure on stability is more important than the fluctuation of the groundwater table due to rainfall.

For all the other conditions, the importance of negative pore pressure on stability increases with the lowering of the water level, and stability factors increase with increasing matric suction for the unsaturated soil. That would keep in mind for all temporary slopes, short-term and back-calculated stability analyses.

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