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Undrained strength of unsaturated fill for stability analysis

Résistance non drainée du remplissage non saturé pour analyse de stabilité

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ABSTRACT: The undrained strength s_u of saturated soil is related to the void ratio or equivalently to Hvorslev's equivalent pressure. In the transition zone of unsaturation the pore air pressure may be assumed atmospheric, air-phase being continuous. The effective stress parameter χ can be adopted, and if the critical state strength is relevant a simple linear strength envelope is applicable. From known water content and void ratio the horizontal shift of the failure envelope by the suction stress may be computed, and the resulting capillary cohesion can be used in stability analyses using the conventional solutions for saturated soils. Laboratory tests confirmed the applicability of the simple concept for compacted silty clay for water contents at or above optimum. The texture of the soil compacted dry of optimum seemed to influence the properties strongly, and the simple concept was not found applicable.

RÉSUMÉ: La force non drainée su du sol saturé est liée au taux de vide ou équivalente à la pression équivalente de Hvorslev. En régime pendulaire, on peut supposer que la pression atmosphérique dans les pores est atmosphérique, la phase atmosphérique étant continue. Le paramètre de contrainte effective χ peut être adopté et, si la résistance de l'état critique est pertinente, une simple enveloppe de résistance linéaire est applicable. À partir de la teneur en eau et du taux de vide connus, le décalage horizontal de l'enveloppe de rupture sous la contrainte d'aspiration peut être calculé, et la cohésion capillaire résultante peut être utilisée dans des analyses de stabilité utilisant les solutions classiques pour sols saturés. Les tests de laboratoire ont confirmé l'applicabilité du concept simple d'argile limoneuse compactée pour des teneurs en eau égales ou supérieures à l'optimum. La texture du sol compacté à sec d'optimum semblait influencer fortement les propriétés, et le concept simple n'a pas été jugé applicable.

Keywords: Unsaturated soil; undrained strength; short term loading; stability analysis; capillary cohesion

1 INTRODUCTION

Bringing numerical methods into geotechnical practice has not resulted in abandoning the simple stability solutions. First, when using numerical methods for analyses of boundary value problems checks by the analytical solutions are required. Secondly, the simple stability calculations are applied by geotechnical engineers in everyday practice. The analytic solutions are based on the principle of effective stress, and the strength is expressed by the Mohr-Coulomb (M-C) law.

Similarly to saturated soils, most formulations of strength for unsaturated soils are based on the M-C strength envelope. However, two fundamentally different approaches exist. The first one can use the M-C strength under the assumption that the effective stress concept remains valid at partial saturation (Bishop, 1959). The second one by Fredlund et al. (1978) was based on the concept of 'independent stress state variables' by Fredlund and Morgenstern (1977), and within the framework all constitutive laws had to be reformulated: For the strength an additional friction angle φ^b had to be introduced to express the dependence of strength on suction $u_a - u_w$. Therefore, the latter concept can hardly be reconciled with the classical analytical equations developed for saturated soils. On the other hand, if the effective stress concept is retained, the simple analytical equations for stability analyses (slopes, foundations) could be directly applied to unsaturated soils.

In this paper a simplified nomenclature is adopted and 'Bishop's stress', stemming from the original formulation by Bishop (1959), is called effective stress. Further, the empirical relationship for Bishop's factor χ by Khalili and Khabbaz (1998), and the critical state (state boundary surface - SBS) concept are followed.

2 SHORT-TERM STRENGTH FOR VARIABLE SATURATION

2.1 The saturated state

Under saturated conditions, the strength relevant for the short-term stability is the undrained strength s_u. It is directly related to the current void ratio, and can be easily quantified within SBS concept:

$$s_u = \frac{1}{2} q_u = \frac{1}{2} M e^{((\Gamma - v_0)/\lambda)} \tag{1}$$

Where q_u is the deviatoric stress at undrained failure and M, Γ and λ are parameters of the critical state line (CSL), which can be determined by laboratory tests. Alternatively, s_u can be expressed using Hvorslev's equivalent pressure, i.e. the parameters of the normal compression line (NCL). Some of the parameters can be estimated by theoretically well justified correlations, bypassing laboratory 'element' testing.

2.2 The unsaturated state

Quick loading of unsaturated soil is not fully undrained (constant volume) since the pore air is compressible. The water content however remains constant. It is nowadays well understood that the straight-line approximation of the strength envelope in the terms of total stress (Figure 1) has no physical meaning and can hardly be used in design. The failure stress circles nevertheless reflect the gradual increase in saturation, and decrease in porosity, on increasing the total stress. Generally, the water retention may change from 'boundary effect zone' (capillary regime) to 'transition zone' and to the 'residual' zone of the water retention curve (WRC; Figure 2). The capillary regime and transition zone are relevant for the compacted (initially unsaturated) soil in question. In the presented simplified analysis the hysteresis of WRC is neglected.

In the capillary regime the suction is lower than the air entry (or expulsion) value ($s < s_e$), the soil is near to the saturated state. The water phase is continuous and the pressure of the air phase approximately corresponds to the pressure of the water (strictly it is higher due to the surface tension of water). Nevertheless, the saturated undrained strength s_u can be adopted in simplified stability analyses, following the procedure above.

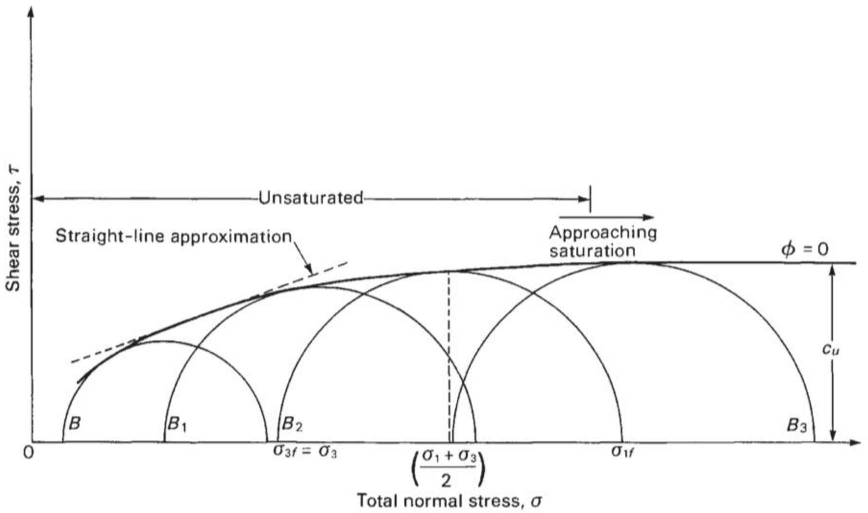

Figure 1: Total stresses at failure of unsaturated soil (Fredlund et al., 2012, p. 563).

In the transition zone the suction is higher than the air entry/expulsion value ($s > s_e$) and pore air pressure can be taken atmospheric, the air phase being continuous (three dimensional view considered). For the drained event the effective stress concept for unsaturated soil can be used, with the factor $\chi = (s_e/s)^\gamma$ where the empirical parameter γ = 0.55 (Khalili and Khabbaz, 1998).

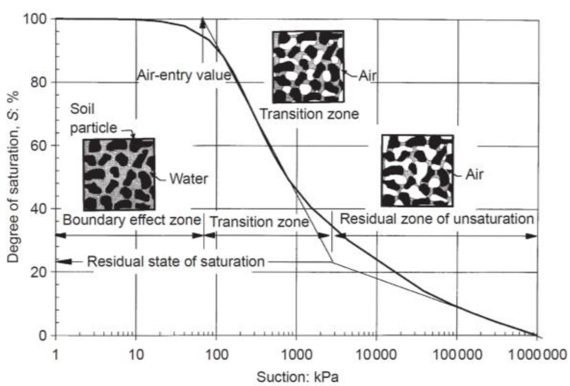

Figure 2: Schematic representation of texture of unsaturated soil (Vanapalli et al., 1999).

Following Mašín (2010) in combining χ by Khalili and Khabbaz (1998) with the concept of WRC by Brooks and Corey (1964), the factor χ can be expressed using saturation ratio: $\chi = {S_r}^{(\gamma/\lambda_p)}$, λ_p describing the slope of WRC at the transition zone. Considering that the strength of compacted (re-worked) soil is controlled by the (effective/drained) critical state friction angle φ_c, the strength envelope for varying saturation is proposed in Figure 3. Using this concept, the suction induced 'capillary cohesion' c, relevant for the total stress analysis of the short term (constant water content) stability of compacted soil is:

$$c = p_t \tan\varphi_c = s\,\chi \tan\varphi_c = s\left(\frac{s_{e0} e_0}{es}\right)^\gamma \tan\varphi_c \qquad (2)$$

Where s_{e0} is the value of suction for reference void ratio e_0, determined from WRC (Mašín, 2010).

The capillary cohesion c and (drained) φ_c can be used in conventional stability solutions, using total stress in the case of variable saturation. In the following, the ongoing laboratory research looking at the use of the proposed concept is described, with a further simplifying assumption of $\chi = S_r$.

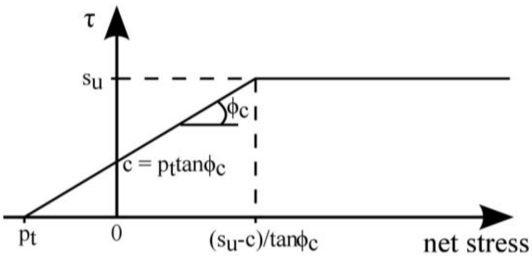

Figure 3: The strength of unsaturated soil for short term analysis

3 TESTED SOIL AND PREPARATION OF SPECIMENS

The tested soil was a loess from a pit at Horky nad Jizerou, Central Bohemia. According to USCS the soil is a low plasticity clay (CL), plotting just above the A line. The soil description and the basic properties are summarised in Table 1.

Table 1. The properties of the tested soil.

Standard compaction (Standard Proctor test)	
Maximum dry density (kg/m^3)	1810
Optimum water content (%)	15
Grain size distribution	
Sand (%)	22
Silt (%)	68
Clay (%)	10
Consistency limits	
Plastic limit (%)	18
Liquid limit (%)	30

Compacted samples were prepared to Standard Proctor specification, at water contents of 9, 14, 17 and 19%. The triaxial specimens of 38 mm diameter and twice the height were prepared from the compacted samples using a hand operated lathe. The reconstituted triaxial specimens (of the same dimensions) were prepared from a slurry of the water content above liquid limit, in a high press (38 mm diameter) under the vertical stress of 100 kPa.

4 LABORATORY TESTS

NCL was determined by conventional incremental oedometer tests on reconstituted specimens. Vertical stress up to 14 MPa was applied, i.e. the maximum mean effective stress was about 10 MPa. The uniaxial strength of the compacted soil was determined by conventional unconfined compression tests. The critical state strength of the tested soil was determined by CID triaxial tests on reconstituted specimens.

CIUP triaxial tests were carried out on compacted specimens, which were saturated prior to triaxial testing. During saturating the cell pressure corresponding to the estimated effective stress in the compacted soil was applied (in estimating effective stress $\chi = S_r$ and the concept of Figure 3 were used). After saturating, it was checked whether the dimensions had not changed, i.e., whether the effective stress value was appropriate, and the principle of effective stress was observed. After the check the specimens were subjected to conventional CIUP test.

5 TEST RESULTS AND DISCUSSION

The data from the tests on saturated specimens in the oedometer and triaxial are summarised in Figure 4. The two oedometer tests defined the 1D NCL with $N_{(e)1-D}$ = 1.37 and λ = 0.113. The initial states of the saturated reconstituted specimens prior to drained shearing show that the soil was overconsolidated. Despite the overconsolidation the reconstituted and compacted specimens defined reasonably well a common CSL with $\Gamma_{(e)}$= 1.25. The CSL in the plane s' vs. t is in Figure 5: The overconsolidated reconstituted specimens diverted more from the CSL than the compacted specimens. The critical state friction angle (φ_c = 30.3º; M = 1.2) however was found acceptable to represent the strength of the compacted soil.

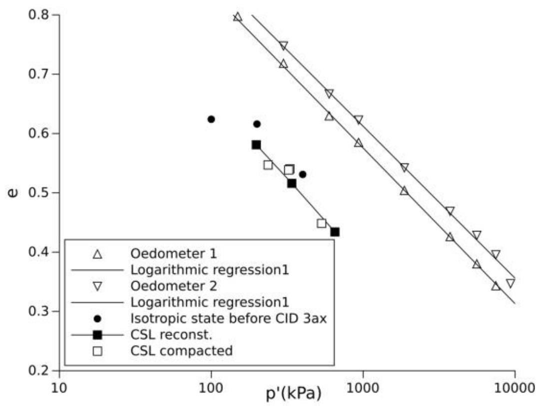

Figure 4: 1-D NCL and CSL of saturated specimens.

In Figure 6, the triaxial (CID and CIUP) stress paths normalized with respect to CSL show mild strength peaks of the compacted specimens. However the critical states were approached reasonably well. It demonstrates that the strength of the compacted soil can be represented by the friction angle at the critical state φ_c, and the strength envelope of Figure 3 is applicable.

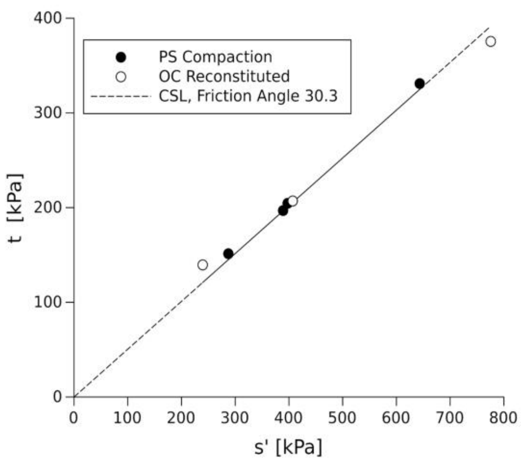

Figure 5: The critical state line (s' = 1/2(σ_a' + σ_r'), t = 1/2(σ_a - σ_r).

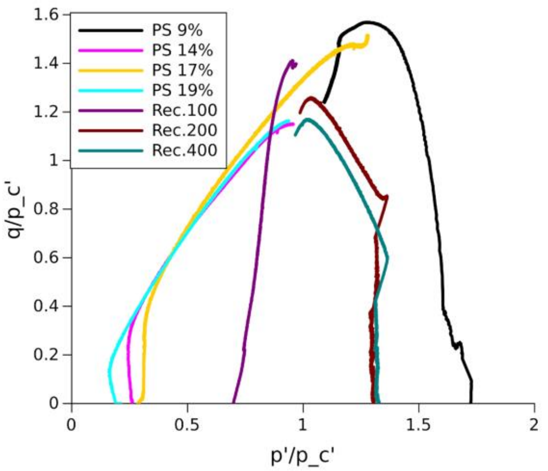

Figure 6: The stress paths of triaxial tests on over-consolidated reconstituted, and on compacted specimens, normalized with respect to CSL.

Table 2 summarizes the data obtained from four pairs of strength tests on compacted specimens at the arbitrary water contents of 19%, 17%, 14% (= w_{opt}) and 9%. At each water content the unconfined compression test (UC in Table 2) was carried out and the negative pore pressure and suction (taking $\chi = S_r$) were evaluated using the concept of Figure 3. The second specimen of the same nominal water content was subjected to CIUP test after saturation (see Chapter 4). It can be seen that at $w \geq w_{opt}$ the concept of Chapter 2 works well (Figure 7). For the pair compacted dry side of optimum ($w \approx$ 9%) the unconfined compression $q_c/2 > s_u$. It is hypothesised, following Wheeler and Sivakumar (2000), that compacting at low water content produced a different soil texture, with substantially different hydraulic and strength properties, for which the simple assumptions of the concept/parameters of Chapter 2 did not work.

Table 2. Comparison of UC and CIUP test results

w/Type of test (%)	*e*	S_r	s_u test *(kPa)*	s_u SBS *(kPa)*	$q_c/2$ test *(kPa)*
19/CIUP	*.547*	*.835*	*155*	*157*	-

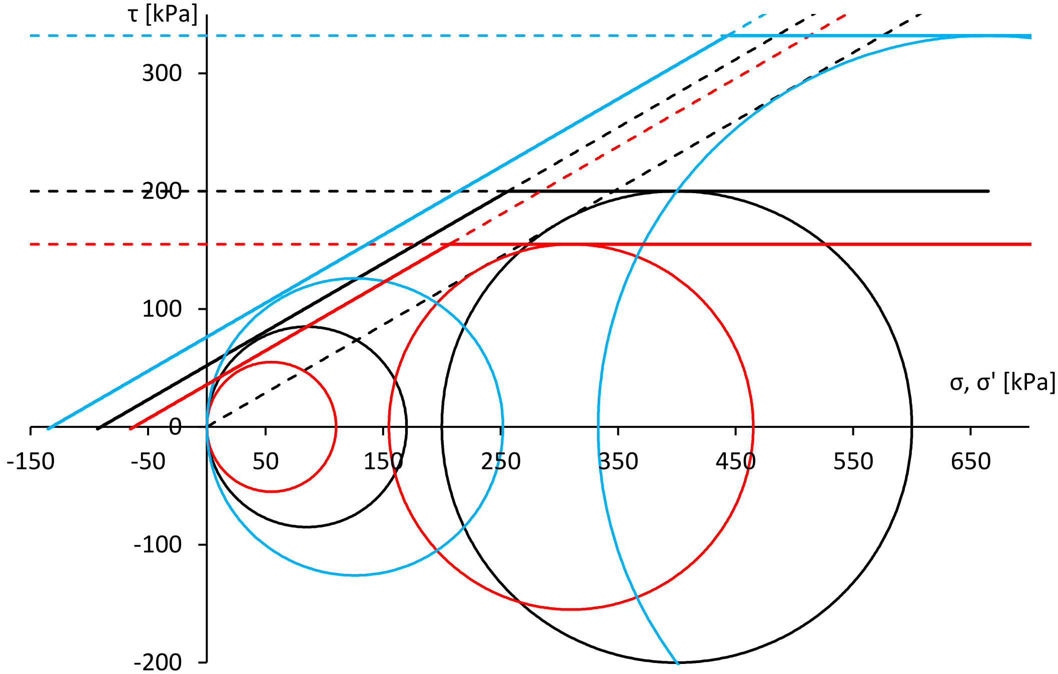

Figure 7: Failure stresses of unsaturated specimens in unconfined compression, and after saturating at the given void ratio → the corresponding undrained strengths s_u.

19/UC	*.558*	*.88*	-	*143*	*56*
17/CIUP	*.540*	*.835*	*201*	*166*	-
17/UC	*.512*	*.875*	-	*208*	*85*
14/CIUP	*.448*	*.847*	*333*	*350*	-
14/UC	*.451*	*.837*	-	*342*	*119*
9/CIUP	*.539*	*.353*	*197*	*167*	-
9/UC	*.550*	*.449*	-	*152*	*214*

6 CONCLUSIONS

A simple concept of strength for short-term stability analyses of unsaturated soil based on effective stress was presented. The proposed concept makes it possible to use conventional stability solutions in simple analyses of short-term stability problems involving unsaturated soils.

At the saturated state, the critical state friction angle proved the relevant parameter for the strength of compacted silty soil.

For unsaturated states the critical state friction angle was acceptable for compaction at higher water contents (at or above optimum). Further, at the high water contents saturation ratio could be taken the effective stress parameter ($\chi = S_r$) for describing strength.

7 ACKNOWLEDGEMENT

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