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Predicting the normalized, undrained shear strength of saturated fine-grained soils using plasticity-value correlations

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ABSTRACT

In soil mechanics, the plasticity of fine-grained soils is expressed using the plasticity index. This represents the difference between the water content at the liquid and plastic limits, which are often collectively referred to as the Atterberg (or consistency) limits. They are of key importance in soil mechanics because they determine, in a simple way, the interaction between the solid and liquid phases in soils, and thus provide the possibility to classify soils into groups with similar mechanical properties. As the Atterberg limits are the most distinctive and the easiest property of fine-grained soils to measure, several researchers have tried to use them to predict various mechanical properties, such as the normalized, undrained shear strength of fine-grained soils. The most widely used expression for predicting this value from the plasticity index was suggested by Skempton. Since then, there have been several studies to examine the validity of his relation. A lot of the data agree with this relation; however, there is an equally large volume of data that contradicts it. The present study shows that the correlation between the normalized undrained shear strength of cohesive soils and the plasticity index really exists, but it is not as simple as was suggested by previous studies. By considering the mineralogical properties of clay minerals and their impact on the quantity and state of water in soils, it was found that there is no uniform criterion to determine the normalized undrained shear strength from the plasticity index for all fine-grained soils.

1. Introduction

As the water content increases, the consistency of a fine-grained soil changes from a semi-solid state to a plastic state, and eventually to a liquid state. The plastic limit *PL* is the soil–water-content boundary between a semi-solid and a plastic consistency. The liquid limit *LL* is the soil–water content where further increases in water change the consistency from a plastic to a liquid state. The *PL* and *LL* are often collectively referred to as the Atterberg limits. They are of key importance in soil mechanics because they determine, in a simple way, the interaction between the solid and liquid phases in soils, and thus provide the possibility to classify soils into groups with similar mechanical properties. The results of these investigations in most cases provide a good basis for predicting other soil properties, such as deformability, expansion, hydraulic conductivity and strength.

As the Atterberg limits and the plasticity index $PI (PI = LL - PL)$, which indicates the range of the water content in which the soil has plastic properties, are the most distinctive and the easiest properties of fine-grained soils to measure, several researchers have also tried to use them for predicting the normalized undrained shear strength s_u/σ'_v. It is well known that the undrained shear strength s_u of normally consolidated fine-grained soil, normalized with respect to the current effective stress σ'_v, is unique. It can, therefore, be expected that it depends exactly on the same properties of the soil as its plasticity index. The s_u/σ'_v value is a valuable parameter in soil mechanics for an analysis of the undrained shear strength of saturated clay deposits and also for estimating the pre-consolidation pressure and over-consolidation ratio.

The most widely used expression for predicting the s_u/σ'_v value from the plasticity index was suggested by Skempton (1957). He found that the undrained shear-strength ratio of normally consolidated clays is a linear function of the plasticity index *PI*(%) for the vane shear test (Eq. (1)).

$$\frac{s_u}{\sigma'_v} = 0.11 + 0.0037PI \qquad (1)$$

There have been several studies in the past to examine the validity of Skempton's relation. A lot of the data agree with this relation; however, there is an equally large volume of data that contradicts it. The main reason why the various authors reached their different conclusions in these studies is the fact that they did not consider the influence of the soil composition on the water content at the Atterberg limits, the strength and the compressibility of soils.

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The present study shows the s_u/σ_v'–PI relationship, which was determined by considering the mineralogical properties of clays and their impact on the quantity and state of the water in the soils. It was found that there is a correlation between the normalized, undrained shear strength of cohesive soils and the plasticity index, but this relationship is not as simple as was suggested by previous studies. The applicability of the proposed method for determining the s_u/σ_v' value based on the plasticity index was tested on five samples of fine-grained soils.

2. Basic assumptions

Clay and non-clay minerals are present in fine-grained soils. To understand the influence of the soils' composition on the water content, it is necessary to know that clay minerals, as well as water, are not chemically inert; therefore, they are subject to alterations. In non-expanding clay minerals, water is strongly adsorbed on the external surfaces of the grains w_{ea}, while in expanding clay minerals it is bonded to both the external surface w_{ea} and the internal surface w_i of the grains. In addition to strongly adsorbed water, the free pore water w_{ef} occurs in saturated clays. Using a standard method for measuring the water content w, the total quantity of intergrain water w_e ($w_e = w_{ef} + w_{ea}$) and the interlayer water w_i can always be determined by drying at a temperature of 100–110 °C .

The total quantity of water w is equal to the intergrain water content in non-swelling clays (Eq. (2)), while it is higher for the portion of the interlayer water in swelling clays (Eq. (3)).

$$w = w_e = w_{ef} + w_{ea} \tag{2}$$

$$w = w_e + w_i = w_{ef} + w_{ea} + w_i \tag{3}$$

The interlayer water quantity w_i depends on the type and quantity of the interlayer cations, and the chemical composition of the pore water (Grim, 1962). It is strongly adsorbed between the layers, and therefore it cannot influence the strength and the compressibility of the clays. Any dependence between the water quantity, the effective stress and the strength can be determined on the basis of the intergrain water content w_e only.

The interaction forces between the external surfaces of the grains and the adsorbed water are the same for all clay minerals due to the equal surface structure. This leads to the conclusion that for an equal quantity of free pore water w_{ef}, the thickness of the adsorbed water film t_a is the same for the different clay grains (Mitchell, 1993; Dolinar and Trauner, 2004). The quantity of water that is adsorbed on the external surfaces of the clay grains w_{ea}, depends, in this case, on the specific surface area of the clay grains expressed in terms of the unit mass of clay grains A_{SC}[m^2/g] — Eq. (4).

$$w_{ea} = t_a \cdot A_{SC} \tag{4}$$

Taking into consideration the above-mentioned assumptions, the intergrain water content w_e depends on the free pore water quantity w_{ef}, and on the exterior surface areas of the clay grains. It is to be expected that the quantity of free pore water only depends on the stress state (Dolinar 2006), which means that it must be the same at an equal effective stress σ', and independent of the type and the size of the clay mineral (Eq. (5)).

$$w_{e|\sigma'} = w_{ef|\sigma'} + t_{a|\sigma'} \cdot A_{SC} \tag{5}$$

Eq. (5) is valid for soils that contain clay minerals only. In cases of clay- and non-clay minerals in soils, the findings of Mitchell (1993) and Seed et al. (1964) must be considered, i.e., the water in the soils is mainly bound to clay grains. Thus, the intergrain water quantity also depends on the mass fraction p of the clay grains in the soil (p is the content of clay minerals in the soil divided by 100; $0 < p \le 1$). In this case Eq. (5) is rewritten as follows

$$w_{e|\sigma'} = p \cdot w_{ef|\sigma'} + t_{a|\sigma'} \cdot A_S \tag{6}$$

where $p \cdot A_{SC} = A_S$; A_S [m^2/g] is the grain surface per unit mass of the soil.

On the basis of the above-mentioned findings and tests on experimental soils, Dolinar and Trauner (2004), Trauner et al. (2005) and Dolinar (2006) expressed the relationships between the intergrain water quantity w_e and the undrained shear strength s_u (Eqs. (7)–(9)) or the dependence of the vertical effective stress σ_v' (Eqs. (10)–(12)) on the quantity p and the size A_S of the clay grains in the soil composition as follows:

$$w_e = a_e s_u^{-b_e} \tag{7}$$

$$a_e = 33.70p + 0.99A_S \tag{8}$$

$$b_e = 0.05(A_S/p)^{0.27} \tag{9}$$

$$w_e = i_e \sigma_v'^{-j_e} \tag{10}$$

$$i_e = 33.46p + 1.39 \cdot A_S \tag{11}$$

$$j_e = 0.05(A_S/p)^{0.27} \tag{12}$$

They also determined the quantity of intergrain water w_e at the liquid limit $w_{e|LL}$ (Eq. (13)), the plastic limit $w_{e|PL}$ (Eq. (14)) and the plasticity index $w_{e|PI}$ (Eq. (15)).

$$w_{e|LL} = 31.90p + 0.81A_S \tag{13}$$

$$w_{e|PL} = 23.16p + 0.27A_S \tag{14}$$

$$w_{e|PI} = w_{e|LL} - w_{e|PL} = 8.74p + 0.54A_S \tag{15}$$

The coefficients in Eqs. (7)–(15) were determined by testing artificial mono-mineral clay mixtures. They are valid for remoulded, saturated clays without organic and other admixtures, distilled water and a temperature of 20 °C.

The liquid limit LL, plastic limit PL and plasticity index PI always express the total water content due to the soils being dried at a temperature higher than 100 °C (BSI, 1990). Hence it follows that:

$LL = w_{e|LL}$ (non-swelling soils); $LL = w_{e|LL} + w_{i|LL}$ (swelling soils)
$PL = w_{e|PL}$ (non-swelling soils); $PL = w_{e|PL} + w_{i|PL}$ (swelling soils)
$IP = w_{e|PI}$ (non-swelling soils); $IP = w_{e|PI} + (w_{i|LL} - w_{i|PL})$ (swelling soils)

The above findings make it possible to express the dependence of the undrained shear strength s_u (Eq. (7)) on the vertical effective stress σ_v' (Eq. (10)) at which the soils were previously consolidated, the parameter being $j_e = b_e$.

$$s_u = \sqrt[be]{\frac{a_e}{i_e}\sigma_v'} \tag{16}$$

Eq. (16) shows that the value s_u/σ_v' is constant and determined for different soils with the material parameters a_e, b_e (j_e) and i_e. Because these parameters depend on the external surface of the clay grains A_S and the content of clay minerals p in the soil composition, Eq. (16) can be written as (17).

$$\frac{s_u}{\sigma_v'} = \sqrt[be]{\frac{a_e}{i_e}} = \sqrt[(0.05)A_S/p)^{0.27})]{\frac{33.70p + 0.99A_S}{33.46p + 1.39A_S}} \tag{17}$$