UNDRAINED SHEAR STRENGTH IN DEPENDANCE ON THE QUANTITY OF FREE WATER AND FIRMLY ADSORBED WATER IN FULLY SATURATED CLAYS

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Abstract

The article describes dependence between the undrained shear strength of fully saturated cohesive soils, the quantity of intergrain water and mineralogical properties of soils. On the basis of theoretical analysis and practical test on monomineral clay samples, it was determined that the total quantity of intergrain water is composed of free pore water and the firmly adsorbed water on the external surface of clay grains. The undrained shear strength of saturated soils is precisely dependent on the quantity of free water. The amount of free water and likewise the thickness of the water film around the clay grains are the same for different soils at the same undrained shear strength. The total quantity of firmly adsorbed water and so the total quantity of intergrain water depends on the specific surface of soils.

Keywords: undrained shear strength, clays, specific surface

1. INTRODUCTION

Mechanical properties of cohesive soils depend on the quantity of the contained water which, in turn, depends on the mineral composition and conditions in the environment. Few investigations have been performed about the above dependencies. Individual results are only known.

Koumoto [1,2] and Koumoto and Houlsby [3] found out that the relationship between the undrained shear strength c_u and the quantity of water w contained in soils could be expressed by the nonlinear function:

$$w = a\ c_u^{-b} \tag{1}$$

where a and b are soil-dependent parameters. The relationship between the water content w and undrained shear strength c_u is the straight line in logarithmic scale, where a is the content of water in soils at the undrained shear strength c_u = 1 kPa and b is slope of the line. The soil dependent parameters can be determined for specific soils by experimental analyses.

Dolinar and Trauner [4] found out that soil-dependent parameters in equation (1) could be calculated from the quantity of clay minerals p in soils and their external specific surface A_{SeC} using the expressions:

$$a_e = p\ (\chi + \delta\ A_{SeC}) \tag{2}$$

$$b_e = \gamma \cdot A_{SeC}{}^{\lambda} \tag{3}$$

where χ = 33.70, δ = 0.99, γ = 0.05 and λ = 0.27. In this case, the material parameters are determined from the quantity of intergrain water, which is expressed with the suffix e. Such an approach has been selected because the undrained shear strength only depends on the quantity of intergrain water, while interlayer water, which is strongly bound between the layers of clay particles, cannot influence it. Thus a = a_e and b = b_e for nonexpanding soils, whilst both parameters change for expanding soils. Authors in [4] have therefore proposed to rewrite the expression (1) in the form:

$$w_e = a_e\ c_u{}^{-b_e} \tag{4}$$

where w_e represents the quantity of intergrain water in soils.

Dolinar [5] also determined the relationship between the quantity of intergrain water w_e and specific surface of clay minerals in soils A_{SeC} at both the liquid and plastic limits:

$$w_{eL} = p\,(\alpha_L + \beta_L\ A_{SeC})\,; \qquad \alpha_L = 31.90 \quad \beta_L = 0.81 \tag{5}$$

$$w_{eP} = p\,(\alpha_P + \beta_P\ A_{SeC}) \qquad \alpha_P = 23.16 \quad \beta_P = 0.27 \tag{6}$$

where w_{eL} is the relative water quantity between grains at the liquid limit, w_{eP} is the relative quantity of intergrain water at the plastic limit and p is the weight portion of clay minerals in the soil.

The research results shown in this article are based upon the above stated findings. It was found out that the quantity of intergrain water, which determines the undrained shear strength of soils, consists of free pore water and the firmly adsorbed water on the external surface of clay grains. The amount of free water is the same for different soils at the same undrained shear strength and likewise the thickness of the water film around the clay grains. In this case the total quantity of intergrain water depends on the specific surface of clay grains. The results of investigation completely confirmed the above statements.

2. BASIC ASSUMPTIONS

Clay minerals, as well as water, are not chemically inert; therefore they are subject to interaction. There are several possible mechanisms of binding water; yet, a decisive role is played by types of clay minerals and types and number of exchangeable ions. Water is strongly attracted to clay mineral surfaces, and results in plasticity. As a first approximation it is assumed that all water in the soil is associated with the clay phase.

It is known that soils have equal undrained shear strength at the liquid limit, almost identical hydraulic permeability and the same pore water suction. This means that the average effective pore size and the quantity of adsorbed water per a clay grain surface unit are the same. Presupposing that these facts hold true for the total plastic state of soils, the quantity of water between grains, at equal undrained shear strength is linearly dependent on specific surface of clay grains in the soil [5]. It was also discovered that some layers of water molecules are firmly bound to the grain surface, whilst the water at a greater distance is free [6]. From these facts it can be expected that the undrained shear strength of saturated soils is precisely dependent on the quantity of free pore water. Presupposing that the quantity of free water in different clays is the same at the same undrained shear strength, the total quantity of intergrain water must depend on the quantity of firmly adsorbed water. Due to the structural similarity of different clay grains it is to be expected that the interaction forces between grain surfaces and the adsorbed water are the same. This means that also the thickness of the firmly adsorbed water around the clay grains is the same at the same undrained shear strength. In this case the total quantity of adsorbed water depends on the specific surface of clay particles in soils.

3. DATA ABOUT TESTED SAMPLES

Three monomineral samples (Table 1) were used in tests: a well crystallized kaolinite (sample 1), a poorly crystallized kaolinite (sample 2) and Ca-montmorillonite (sample 3). The samples originate from regions in the United States and are intended for different studies. Data applying to chemical and mineralogical properties of tested samples are taken from Data Handbook for clay minerals and other non-metallic minerals [7].

4. RESULTS

The quantity of intergrain water w_e in saturated samples was determined by equations (2), (3) and (4) on the base of known specific surface A_{SeC} of clay samples at undrained shear strengths c_u = 2.66 kPa, c_u = 10.60 kPa, c_u = 42.50 kPa and c_u = 266 kPa. The first and the last value correspond to undreined shear strength at the liquid limit and plastic limit. Supposing that for different soils the part of free water w_{ef} is the same at the same undrained shear strength c_u and likewise the thickness of the firmly adsorbed water around the clay grains d_a. In this case the quantity of the total intergrain water w_e can be expressed for different soils by the equation:

$$w_e = d_a \ A_{SeC} + w_{ef} \tag{7}$$

In accordance with the equation (7) the total quantity of intergrain water w_e in samples was divided into free water w_{ef} and adsorbed water $w_{ea} = d_a \ A_{SeC}$ (Table 1).

It is evident from Table 1 that the quantity of free water w_{ef} at the liquid limit (c_u = 2.66 kPa = w_{eL}) and plastic limit (c_u = 266 kPa = w_{eP}) is equal to the parameters α_L = 31.90 [%] and α_P = 23.16 [%] from equations (5) and (6). In given expressions these values represent the quantity of intergrain water at the liquid limit and plastic limit at A_{SeC} = 0 m^2/g. The thickness of firmly adsorbed water d_a is equal to the parameters β_L = 0.81 and β_P = 0.27 in the same equations. The total quantity of firmly adsorbed water w_{ea} in this case depends on the specific surface of clay minerals A_{SeC}. In this way the correctness of stated presumptions expressed in equation (7) are confirmed.

It is also evident from Table 1 and Figure 1 that the quantity of free water w_{ef} and the thickness of the firmly adsorbed water d_a around the clay grains depend on undrained shear strength c_u. These relationships are linear when the logarithmic scale is used. They are given by equations:

$$d_a = f_a \ c_u^{-g_a} ; \qquad f_a = 10.20 \quad \text{and} \quad g_a = 0.23 \tag{8}$$

$$w_{ef} = f_f \ c_u^{-g_f} ; \qquad f_f = 34.34 \quad \text{and} \quad g_f = 0.07 \tag{9}$$

Table 1: *The specific surface of clays* A_{SeC}*, calculated quantity of intergrain water* w_e*, quantity of free water* w_{ef}*, thickness of the water film around the clay grains and quantity of firmly adsorbed water* w_{ea} *at the chosen undrained shear strengths* c_u.

Sample	1	2	3
A_{SeC} [m²/g]	10.05	23.50	97.42
	$w_e = a_e\, c_u^{-b_e} = d_a\, A_{SeC} + w_{ef}$ [%]		
c_u = 2.66 kPa = w_{eL}	40.0	50.9	110.8
c_u = 10.6 kPa	35.0	43.3	87.2
c_u = 42.5 kPa	30.8	36.8	68.7
c_u = 266 kPa = w_{eP}	25.8	29.8	50.0
	w_{ef} [%]		
c_u = 2.66 kPa = w_{eL}	31.9	31.9	31.9
c_u = 10.6 kPa	29.1	29.3	29.1
c_u = 42.5 kPa	26.5	26.7	26.9
c_u = 266 kPa = w_{eP}	23.1	23.3	23.1
	d_a [x 10 nm]		
c_u = 2.66 kPa = w_{eL}	0.81	0.81	0.81
c_u = 10.6 kPa	0.59	0.59	0.59
c_u = 42.5 kPa	0.43	0.43	0.43
c_u = 266 kPa = w_{eP}	0.27	0.27	0.27
	$w_{ea} = d_a\, A_{SeC}$ [%]		
c_u = 2.66 kPa = w_{eL}	8.1	19.0	78.9
c_u = 10.6 kPa	5.9	14.0	58.1
c_u = 42.5 kPa	4.3	10.1	41.8
c_u = 266 kPa = w_{eP}	2.7	6.5	26.9

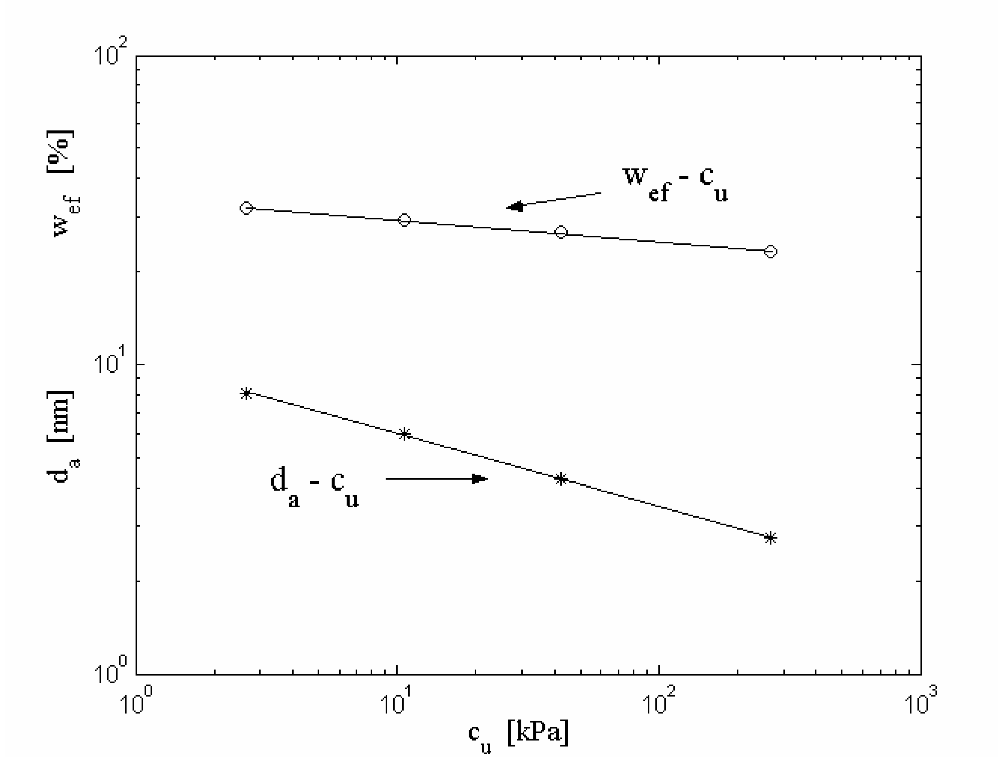

Figure 1: *The quantity of free pore water* w_{ef} *and the thickness of the firmly adsorbed water* d_a *as a function of undrained shear strength* c_u.

5. CONCLUSION

This paper presents the following findings which are based on theorethical analysis and practical test on monomineral clay samples:

- Intergrain water in soils consists of free water and firmly adsorbed water.
- The undrained shear strength of saturated soils is precisely dependent on the quantity of free water.
- The quantity of free water is the same for different soils at the same undrained shear strength.
- The thickness of the water film around the clay grains is the same for different soils at the same undrained shear strength which confirms that the total quantity of adsorbed water depends on specific surface of clay grains.

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