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Anisotropy of undrained shear strength in selected cohesive soil

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ABSTRACT: The paper presents the test results performed in a Torsional Shear Hollow Cylinder Apparatus on undisturbed and reconstituted sandy silty clays (sasiCl). The material studied includes cohesive soil from the Warsaw region, namely *Warsaw Slope*. The soil samples had an overconsolidation ratio $OCR \approx 3$ and a plasticity index I_p = 34.7%. Based on the results of laboratory tests empirical correlation coefficients are proposed. Proposed empirical correlation coefficients allow to determine undrained shear strength at a selected angle of rotation of the principal stress directions for slightly overconsolidated clays.

KEYWORDS: undrained shear strength anisotropy, cohesive soil, soil structure, principal stress directions, hollow cylinder test.

1 INTRODUCTION

Investigation of anisotropy of undrained shear strength in cohesive subsoils due to rotation of the principal stress directions has a long history in soil mechanics. The standard method to study anisotropy in laboratory tests is to cut soil samples with a different orientation to the vertical direction and conduct tests in a Triaxial Apparatus and a Plane Strain Apparatus. On the basis of such research, several equations were proposed that allow to determine the undrained shear strength at a selected angle of rotation of the principal stress directions (Bishop 1966). A more advanced method is research in a Torsional Shear Hollow Cylinder Apparatus (Hight et al. 1983), in which the tested soil samples are in the shape of a hollow cylinder. Due to the problem with sample preparation, most research is still carried out on reconstituted cohesive soils and the test results are often difficult to correlate with natural soils.

The paper deals with the test results performed in a Torsional Shear Hollow Cylinder Apparatus on undisturbed and reconstituted sandy silty clays (sasiCl). The material studied includes cohesive soils from the Warsaw region, namely *Warsaw Slope*. The main objective of the laboratory tests was to determine the undrained shear strength in a wide range of angles of rotation of the principal stress directions, and to propose correlation coefficients describing the anisotropy

of undrained shear strength due to change of the angle of rotation of the principal stress directions. Influence of rotation of the principal stress directions on the undrained shear strength, and also the influence of natural and reconstituted soil structure on the strength characteristics are discussed.

2 LABORATORY TESTS

The tests were carried out as part of a doctoral dissertation (Wrzesiński 2015) in the Water Centre Laboratory of the Warsaw University of Life Sciences – SGGW. The research was performed on undisturbed and reconstituted sandy silty clays (sasiCl) using

a Hollow Cylinder Apparatus to determine the un-

drained shear strength at angles of rotation of the principal stress directions α equal to 0º, 15º, 30º, 45º, 60º, 75º and 90º. Undisturbed soil samples were taken directly from the test site, whereas the reconstituted samples were prepared in the laboratory. Soil samples, both undisturbed and reconstituted, had an overconsolidation ratio $OCR \approx 3$ and a plasticity index
I_p = 34.7%. The test results on the undisturbed soil samples were presented in Wrzesiński & Lechowicz (2015). The index properties of the tested soils are presented in Table 1.

Table 1. Index properties of the tested soils.

w_L [%]	w_P [%]	I_P [%]	I_L [-]	I_C [-]	Fraction (ISO 14688-2:2004) [%]			
					gr	sa	si	Cl
59.0	24.3	34.7	0.13	0.87	0	21	50	29

Explanations: w_L – liquid limit, w_p – plastic limit, I_p – plasticity index, I_L – liquidity index, I_C – consistency index.

The HCA tests, both on undisturbed and reconstituted soils, began with flushing that removed air and gases with the largest dimensions from the samples and tubes. The next step was saturation of the soil samples, performed using the back pressure method. This stage continued until the value of Skempton's parameter B exceeded 0.95 (Lipiński & Wdowska 2010). This procedure was applied both for undisturbed and reconstituted soil samples. In case of undisturbed soil samples, the next step was anisotropic consolidation, in which K_0 = 0.83, effective vertical stress σ'_v = 220 kPa and horizontal effective stress σ'_h = 183 kPa. After dissipation of excess pore water pressure, the parameter of intermediate principal stress directions b changed from 0 to 0.5 in the case of angles α equal to 0˚, 15˚, 30˚, 60˚, 75˚ and 90˚ or 0.3 for angle α = 45˚ (Sayao & Vaid 1991). In the next stage, the value of angle α was changed to the determined value in a particular test. Finally, the process of sample shearing was carried out in undrained conditions using the stress path involving increase in the deviator stress q and constant value of the total mean stress p. During the entire shearing process of the soil samples, constant values of parameter b and angle α were retained. In the case of the reconstituted soil samples, after the saturation process, anisotropic consolidation was performed, in which K_0 = 0.83, effective vertical stress σ'_v = 594 kPa and horizontal effective stress σ'_h = 493 kPa. After dissipation of excess pore water pressure, the soil samples were restressed to σ'_v = 220 kPa and σ'_h = 183 kPa. After stabilizing the pressure in the soil samples, the next stages such as the change of parameter b, change of angle α and shearing were performed identically as in the case of undisturbed soil samples.

3 TEST RESULTS

Laboratory tests allowed to obtain the values of the undrained shear strength at a selected angle of the principal stress directions for undisturbed and reconstituted sandy silty clays (Tables 2 and 3, Figure 1). To determine these parameters, the maximum deviator stress was used as the failure criteria. Each value of undrained shear strength was obtained at an adequate value of axial strain. All the obtained values of the undrained shear strength were normalized based on the *in situ* vertical effective stress component σ'_{vo} to obtain comparable values of the normalized undrained shear strength independent of the value of the *in situ* effective stress.

Table 2. Results of the HCA test for undisturbed sandy silty clay (Wrzesiński & Lechowicz 2015).

Angle of rotation of the principal stress directions α [º]	Undrained shear strength τ_{fu} [kPa]	Normalized undrained shear strength τ_{fu}/σ'_{vo} [-] σ'_{vo} = 220 kPa
0	129.3	0.588
15	125.8	0.572
30	117.7	0.535
45	106.6	0.485
60	101.4	0.461
75	99.8	0.454
90	98.4	0.447

Table 3. Results of the HCA test for reconstituted sandy silty clay.

Angle of rotation of the principal stress directions α [º]	Undrained shear strength τ_{fu} [kPa]	Normalized undrained shear strength τ_{fu}/σ'_{vo} [-] σ'_{vo} = 220 kPa
0	118.7	0.540
15	116.8	0.531
30	114.6	0.521
45	109,2	0.496
60	105.4	0.479
75	103.6	0.471
90	102.1	0.464

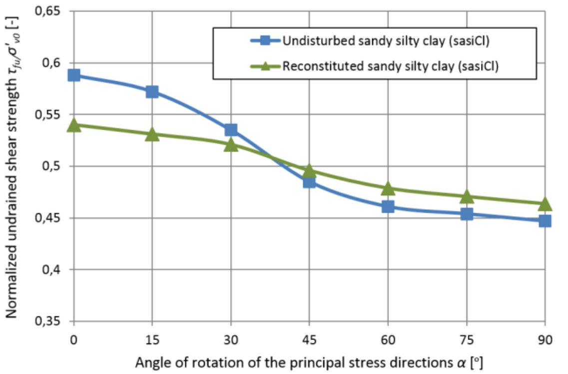

Figure 1. Change of normalized undrained shear strength for undisturbed and reconstituted sandy silty clays.

Axial strains corresponding to the obtained values of the undrained shear strength were in the range of 8.4–13.8% for undisturbed sandy silty clay and in the range of 9.4–11.8% for reconstituted clay.

Different values of the undrained shear strength for the same angle α were obtained for undisturbed and reconstituted soil samples. Values of the normalized undrained shear strength, both in the case of undisturbed sandy silty clay and the reconstituted clay, decrease with the increasing angle of rotation of the principal stress directions. However, the course of the decrease is different in the undisturbed and the reconstituted soils.

4 ANALYSIS OF THE TEST RESULTS

Analysis of the test results shows that in the case of undisturbed sandy silty clay, a higher decrease in the undrained shear strength is for angles α between 0º and 45º, whereas a decrease in the undrained shear strength is much smaller for angles above 45º. In the case of reconstituted sandy silty clay the decrease is nearly equally distributed at angles between 0º and 90º. The obtained changes in the normalized undrained shear strength for overconsolidated cohesive soils is similar to that presented in the literature for cohesive soils (Jardine & Menkiti 1999, Lin & Penumadu 2005, Nishimura et al. 2007). A change in the undrained shear strength both for undisturbed and reconstituted sandy silty clays may be described using a relationship between the obtained values of the undrained shear strength and angles of rotation of the principal stress directions.

The undrained shear strength at a wide range of angles of rotation of the principal stress directions $\tau_{fu}{}^{\alpha}$ can be evaluated as:

$$\tau_{fu}^{\alpha} = \tau_{fu}^{90^\circ} + \eta_{\tau_{fu}}\left(\tau_{fu}^{0^\circ} - \tau_{fu}^{90^\circ}\right) \qquad (1)$$

where: $\eta_{\tau_{fu}}$ - index of change in undrained shear strength, $\tau_{fu}{}^{90^o}$ - undrained shear strength at $\alpha = 90^\circ$, $\tau_{fu}{}^{0^o}$ - undrained shear strength at $\alpha = 0^\circ$.

The index of change in undrained shear strength due to the change of the angle of rotation of the principal stress directions is defined as:

$$\eta_{\tau_{fu}} = \frac{\tau_{fu}^{\alpha} - \tau_{fu}^{90^\circ}}{\tau_{fu}^{0^\circ} - \tau_{fu}^{90^\circ}} \qquad (2)$$

Based on the laboratory test results, the following relationship between the index of change in undrained shear strength at any angle α was proposed by Wrzesiński & Lechowicz (2015):

$$\eta_{\tau_{fu}} = 1 - (sin\alpha)^{e^{a+bx^n}} \qquad (3)$$

where $x = \alpha / 90^\circ$.

In the case of undisturbed soil samples, the empirical parameters are equal to: a = 0.52, b = -2.14, n = 2 (Wrzesiński & Lechowicz 2015), whereas for reconstituted samples they are equal to: a = 0.64, b = -0.20, n = 2.

The obtained relationships (3) for undisturbed and reconstituted sandy silty clays are presented in Figures 2 and 3. The coefficient of determination R^2 for the relationship determining change in undrained shear strength for undisturbed sandy silty clay equals to 0.95, whereas for reconstituted clay it equals to 0.92.

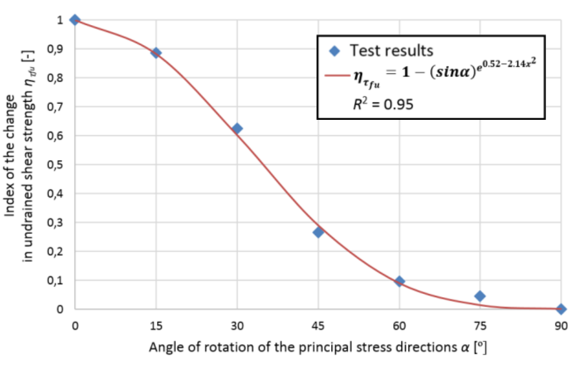

Figure 2. Relationship describing the index of change in undrained shear strength for undisturbed sandy silty clay (Wrzesiński & Lechowicz 2015).

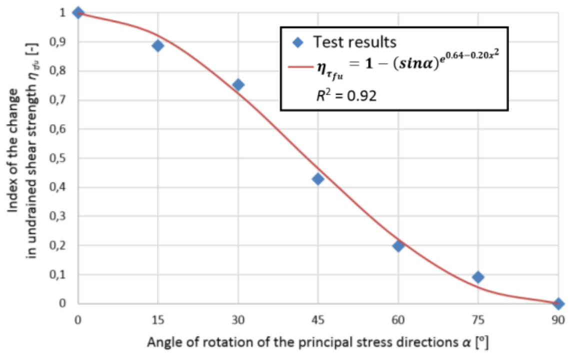

Figure 3. Relationship describing the index of change in undrained shear strength for reconstituted sandy silty clay.

Equation (3) has been derived on the basis of tests performed on slightly overconsolidated clays with low impact of glaciotectonic disturbances on the soil structure. Research on undisturbed and reconstituted soil samples shows that the values of empirical parameters in equation (3) depend on the type and structure of the soil and the stress history.

The research was carried out in the Hollow Cylinder Apparatus and the proposed correlation differs from the commonly known equation by Bishop (1966), that was based on the research performed mainly in the Triaxial Apparatus.

5 CONCLUSIONS

Tests performed in the Torsional Shear Hollow Cylinder Apparatus have shown that the values of undrained shear strength are different for undisturbed and reconstituted sandy silty clays with the overconsolidation ratio $OCR \approx 3$ and plasticity index $I_p = 34.7\%$. The courses of strength characteristics were different for particular soils, and the differences in the values of undrained shear strength reached even 10%.

The test results of undrained shear strength at a wide range of angles of rotation of the principal stress direction have shown that the value of normalized undrained shear strength τ_{fu}/σ'_{vo} decreases with increase of the angle of rotation of the principal stress directions α both for undisturbed and reconstituted sandy silty clays. In case of undisturbed sandy silty clay, the decrease in normalized undrained shear strength is higher for angle α between 0º and 45º in comparison to values for angle α between 45˚ and 90˚. In reconstituted sandy silty clay, the decrease is nearly equally distributed for angles between 0º and 90º. The empirical coefficients for the correlation proposed by Wrzesiński & Lechowicz (2015) are significantly different for undisturbed and reconstituted, slightly overconsolidated sandy silty clays.

Due to the difference in the obtained strength characteristics, the test results performed on reconstituted soils can be used as reference and provide view of anisotropy of undrained shear strength in the subsoil. Parameters obtained from the research on reconstituted soils should not be used directly in design of geotechnical structures due to the different conditions of soil structure formation and the impact of glaciotectonic disturbances in natural subsoil.

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