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TESTING OF UNDRAINED SHEAR STRENGTH IN A HOLLOW CYLINDER APPARATUS

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Abstract: The paper presents the results of tests performed in a Torsional Shear Hollow Cylinder Apparatus on undisturbed cohesive soils. The tests were performed on lightly overconsolidated clay (Cl) and sandy silty clay (sasiCl). The main objective of the tests was to determine the undrained shear strength at different angles of rotation of the principal stress directions. The results of laboratory tests allow assessing the influence of rotation of the principal stress directions on the value of undrained shear strength that should be used during designing structure foundations.

Key words: *undrained shear strength, cohesive soils, principal stress directions, hollow cylinder tests*

1. INTRODUCTION

The construction of geotechnical structures, e.g. diaphragm walls, tunnels, pad foundations or embankments, on cohesive soils, requires assessing the bearing capacity in undrained conditions. For this purpose it is necessary to determine the value of undrained shear strength that is used in calculations. In practice, it is assumed that the undrained shear strength of cohesive soil has the same value in the entire geotechnical layer [8]. However, the construction of any structure changes the stress state in the subsoil and thereby causes the rotation of principal stress directions in comparison with the initial state formed during the consolidation process [4]. This phenomenon can be presented based on calculations using the finite element method.

The effect of change in stress directions is the formation of zones in the cohesive subsoil which have different values of the undrained shear strength assigned to particular angles of rotation of the principal stress directions α and thus a different failure mechanism during the soil structure failure. Research conducted in laboratories both on undisturbed and reconstituted cohesive soils shows that the principal stress directions have significant impact on the obtained values of undrained shear strength [5]–[7], [9]. A device that allows this parameter to be determined at a specific value of angle α is the Torsional Shear Hollow Cylinder Apparatus [12]. With this device it is possible to determine the undrained shear strength of cohesive soils at the angle of rotation of the principal stress directions α between 0° and 90°. Conducting research at a specific value of angle α requires the selection of an appropriate value of the parameter of intermediate principal stress b, which is defined as

$$b = \frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3} \tag{1}$$

where σ_1 – major principal stress, σ_2 – intermediate principal stress, σ_3 – minor principal stress.

An appropriately selected value of parameter b corresponding to angle α minimizes the non-uniformity of stress distribution across the soil samples caused by both end effects and sample geometry. Values of parameter b that allow the *no-go* regions where the non-uniformity is the greatest to be avoided were proposed, e.g., by Hight et al. [4]. Particular attention during the research should be paid to the angle α of about 45° where additional *no-go* regions were established [10], [11]. In this case, lower or higher values of parameter b should be used in comparison with other tests.

This paper presents the results of research carried out in a Torsional Shear Hollow Cylinder Apparatus on selected undisturbed cohesive soils collected from the depth of 22 m and 13 m during the excavation of the Copernicus Science Centre Station of the II underground line in Warsaw [1]. Laboratory tests allowed us to determine the influence of rotation of the principal stress directions caused by the construction of diaphragm walls on the values of undrained shear strength in cohesive subsoils.

2. LABORATORY TESTS

The laboratory tests were carried out as part of a doctoral dissertation [13] in the Water Centre Laboratory of the Warsaw University of Life Sciences – SGGW using a Hollow Cylinder Apparatus. The research was performed with anisotropic consolidation and shearing in undrained conditions (CAU) on two types of undisturbed cohesive soil – clay (Cl) and sandy silty clay (sasiCl). The clay samples had an overconsolidation ratio $OCR \approx 4$ and plasticity index $I_p = 77.6\%$, whereas the samples of sandy silty clay had $OCR \approx 3$ and $I_p = 34.7\%$. The index properties of the test soils are presented in Table 1. The undrained shear strength was determined at angles of rotation of the principal stress directions α equal to 0°, 30°, 45°, 60° and 90° for clay, and equal to 0°, 15°, 30°, 45°, 60°, 75° and 90° for sandy silty clay.

Each HCA test was performed in six consecutive stages: flushing, saturation, consolidation, change of intermediate principal stress parameter b, change of angle of rotation of the principal stress directions α, and finally shearing in undrained conditions. Flushing was carried out to remove air and gases having the largest dimensions from the sample and tubes. Saturation of soil samples was performed using the back pressure method. This stage lasted until the value of Skempton's parameter B exceeded 0.94 [3]. Next, anisotropic consolidation was performed. In the case of clay, the value of K_0 during the consolidation process was equal to 0.97, whereas for sandy silty clay, the K_0 was equal to 0.83. After dissipation of excess pore water pressure, parameter b started to change to a value of 0.5 in the case of angles α at 0°, 15°, 30°, 60°, 75° and 90° or 0.3 for angle $\alpha = 45°$ [11], [14]. In the next step, the value of angle α changed to the determined value in a particular test. Finally, the process of sample shearing was carried out in the stress path involving the 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 kept.

3. TEST RESULTS

The laboratory tests allowed the values of the undrained shear strength to be obtained at a selected angle of rotation of the principal stress directions for particular soil types (Figs. 1 and 2, Tables 2 and 3). To determine these parameters, both the maximum deviator stress and the maximum effective principal stress ratio were used as the failure criteria. Each value of the undrained shear strength obtained for a particular failure criterion 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.

Axial strains corresponding to the obtained values of the undrained shear strength are in the range of 2.2–5.4% for clay and in the range of 8.4–13.8% for sandy silty clay using the maximum deviator stress as the failure criterion. Using the maximum effective principal stress ratio as the failure criterion, these values are in the range of 1.8–3.5% for clay and in the range of 7.6–9.1% for sandy silty clay. Both in the case of clay and sandy silty clay, higher values of the undrained shear strength were obtained by taking the maximum deviator stress as the failure criterion rather than the maximum effective principal stress ratio. Comparing both failure criteria, the difference in the determined values of the undrained shear strength of clay is the smallest and equal to 1.1 kPa at $\alpha = 45°$, whereas it is the largest and equal to 8.9 kPa at $\alpha = 90°$. In the case of sandy silty clay the difference is the smallest and equal to 1.2 kPa at $\alpha = 0°$, and is the highest and equal to 5.6 kPa at $\alpha = 60°$.

Table 1. Index properties of the test soils

Type of soil EN ISO 14688-1	Overconsolidation ratio OCR [–]	Effective vertical stress σ'_v [kPa]	Liquid limit w_L [%]	Plastic limit w_p [%]	Plasticity index I_p [%]	Liquidity index I_L [–]	Consistency index I_C [–]
Cl	≈4	310	112.9	35.3	77.6	–0.06	1.06
sasiCl	≈3	220	59.0	24.3	34.7	0.13	0.87

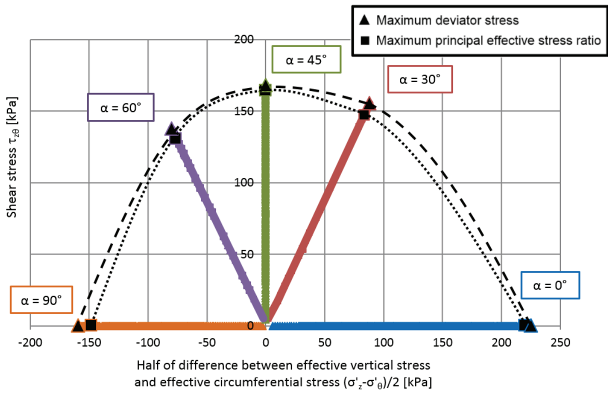

Fig. 1. Effective stress paths for clay in axes $(\sigma'_z - \sigma'_\theta)/2 - \tau_{z\theta}$

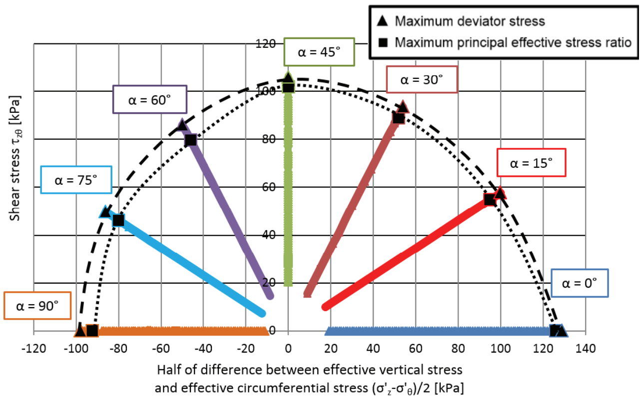

Fig. 2. Effective stress paths for sandy silty clay in axes $(\sigma'_z - \sigma'_\theta)/2 - \tau_{z\theta}$

Table 2. Results of the HCA test for clay [12]

Angle of rotation of principal stress directions α [°]	Parameter of intermediate principal stress b [–]	Failure criterion	Undrained shear strength τ_{fu} [kPa]	Normalized undrained shear strength τ_{fu}/σ'_{vo} [–] $\sigma'_{vo} = 310$ kPa	Axial strain at failure ε_z [%]
0	0.5	Max. q	228.5	0.737	2.2
		Max. σ'_1/σ'_3	226.1	0.729	1.9
30	0.5	Max. q	201.8	0.651	3.1
		Max. σ'_1/σ'_3	195.3	0.630	1.8
45	0.3	Max. q	178.5	0.576	3.5
		Max. σ'_1/σ'_3	177.4	0.572	3.2
60	0.5	Max. q	172.4	0.556	4.3
		Max. σ'_1/σ'_3	170.2	0.549	3.5
90	0.5	Max. q	160.1	0.516	5.4
		Max. σ'_1/σ'_3	151.2	0.488	3.4

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

Angle of rotation of principal stress directions α [°]	Parameter of intermediate principal stress b [–]	Failure criterion	Undrained shear strength τ_{fu} [kPa]	Normalized undrained shear strength τ_{fu}/σ'_{vo} [–] $\sigma'_{vo} = 220$ kPa	Axial strain at failure ε_z [%]
0	0.5	Max. q	129.3	0.588	8.4
		Max. σ'_1/σ'_3	128.0	0.582	7.6
15	0.5	Max. q	125.8	0.572	9.3
		Max. σ'_1/σ'_3	123.1	0.560	7.9
30	0.5	Max. q	117.7	0.535	10.2
		Max. σ'_1/σ'_3	115.6	0.525	8.1
45	0.3	Max. q	106.6	0.485	13.4
		Max. σ'_1/σ'_3	104.3	0.474	8.6
60	0.5	Max. q	101.4	0.461	13.8
		Max. σ'_1/σ'_3	95.8	0.435	9.1
75	0.5	Max. q	99.7	0.454	12.4
		Max. σ'_1/σ'_3	95.3	0.433	8,9
90	0.5	Max. q	98.4	0.447	11.3
		Max. σ'_1/σ'_3	93.4	0.425	8.4

Values of the normalized undrained shear strength both in the case of clay with $OCR \approx 4$ and sandy silty clay with $OCR \approx 3$ decrease with the increasing angle of rotation of the principal stress directions. Taking as the failure criterion both the maximum deviator stress and the maximum principal effective stress ratio, the decrease in the normalized undrained shear strength is similar.

In the case of clay, the decrease in the undrained shear strength value is the highest for the angle α between 0° and 45°, whereas the decrease is smaller for angles above 45°. Considering changes in this parameter for sandy silty clay, the highest decrease is between 15° and 45°. Above 45° the decrease of this parameter is smaller than in the case of clay. Assuming the maximum deviator stress as the failure criterion, the normalized undrained shear strength is about 22% lower for the test at angle $\alpha = 45°$ and about 30% lower at angle $\alpha = 90°$ in comparison with the test at angle $\alpha = 0°$ in the case of clays. A smaller decrease in this parameter is observed for sandy silty clay, where the normalized undrained shear strength is about 18% lower at angle $\alpha = 45°$ and about 24% lower at angle $\alpha = 90°$ than for the shearing test at angle $\alpha = 0°$.

4. ANALYSIS OF THE TEST RESULTS

Based on the tests performed, it can be observed that both in the case of overconsolidated clay and sandy silty clay, a higher decrease in the undrained shear strength occurs for angles α between 0° and 45°, whereas the decrease in the undrained shear strength is much smaller for angles above 45°. The obtained change in the normalized undrained shear strength for overconsolidated cohesive soils is similar to that presented in the literature for this type of soil [5]–[7], [9]. The change in the undrained shear strength both for clay and sandy silty clay 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 any angle of rotation of the principal stress directions τ_{fu}^{α} can be evaluated as:

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

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

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

$$\eta_{\tau_{fu}} = \frac{\tau_{fu}^{\alpha} - \tau_{fu}^{90^\circ}}{\tau_{fu}^{0^\circ} - \tau_{fu}^{90^\circ}}. \tag{3}$$

Based on the laboratory test results the following relationship between the index of the change in the undrained shear strength at any angle α is proposed

$$\eta_{\tau_{fu}} = 1 - (\sin\alpha)^{e^{a+bx^n}} \tag{4}$$

where $x = \alpha/90°$; $a = 0.28$, $b = -0.80$, $n = 2$ for clay and $a = 0.52$, $b = -2.14$, $n = 2$ for sandy silty clay.

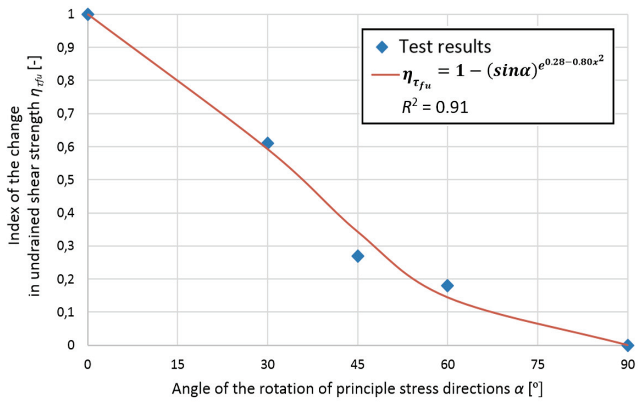

Fig. 3. Relationship describing the index of change in the undrained shear strength for clay

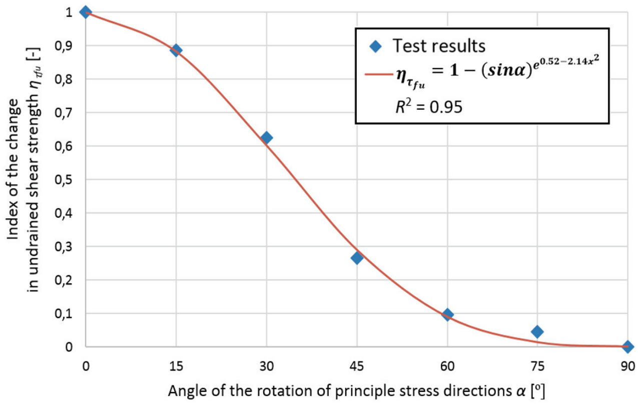

Fig. 4. Relationship describing the index of change in the undrained shear strength for sandy silty clay

The obtained forms of relationship (4) for overconsolidated clay and sandy silty clay are presented in Figs. 3 and 4.

The coefficient of determination R^2 for the relationship determining the change in the undrained shear strength for clay is equal to 0.91, whereas for sandy silty clay it is equal to 0.95. Test results show that the values of empirical parameters in equation (4) depend on the type and structure of the soil and the stress history. The proposed equation has been derived on the basis of tests performed on lightly overconsolidated clays with a low impact of the glacitectonic disturbances on the soil structure. Research was carried out in the Hollow Cylinder Apparatus and proposed correlation differs from the commonly known equation proposed by Bishop [2], that was derived based on the research in Triaxial Apparatus. The use of the correlation presented allows one determine the values of the undrained shear strength at any angle of rotation of the principal stress directions that should be used in calculations of the bearing capacity during designing of geotechnical structures.

5. CONCLUSIONS

Tests performed in the Torsional Shear Hollow Cylinder Apparatus both on clay with the overconsolidation ratio $OCR \approx 4$ and on sandy silty clay with the $OCR \approx 3$ showed that the value of the normalized undrained shear strength τ_{fu}/σ'_{vo} decreases with an increase of the angle of rotation of the principal stress directions α. The decrease in the normalized undrained shear strength is higher for the angle α between 0° and 45° in comparison with the values for the angle α between 45° and 90°.

The relation for determining the index of change in the undrained shear strength $\eta_{\tau_{fu}}$ as a function of the angle of rotation of the principal stress directions α was proposed. Based on the test results, empirical coefficients were determined for the proposed relation for lightly overconsolidated clay and sandy silty clay which are characterized by low impact of the glacitectonic disturbances on the soil structure.

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