Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0338

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Evaluation of creep behaviour of organic soils in a torsional shear hollow cylinder test

Evaluation du comportement au fluage de sols organiques dans l'essai au cylindre creux avec cisaillement en torsion

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ABSTRACT: The creep behaviour of Eemian gyttja was investigated by means of a triaxial creep test and a torsional shear hollow cylinder creep test. A low calcareous, mineral-organic gyttja with 12.0% of organic content I_{OM} and 31.0% of calcium carbonate $CaCO_3$ content, as well as a high calcareous, mineral-organic gyttja with 18.5% of organic content I_{OM} and 66.5% of $CaCO_3$ content were tested. Laboratory tests have shown an essential influence of time, and volumetric and deviatoric stress components on the performance of strain rate in the creep process. The empirical equation describing the relationship between the strain rate and time at shear stress levels smaller than the shear strength was verified at complex stress conditions created in the TSHC creep test. The average values of empirical parameters were evaluated from the analysis of calculation results.

RÉSUMÉ: Le comportement en fluage d'Eemian gyttja a été étudié au moyen d'un essai de fluage triaxial et d'un essai de fluage en cylindre creux avec cisaillement en torsion. Gyttja à faible teneur en calcium et minéraux organiques avec 12.0% de teneur organique en I_{OM} et 31.0% de teneur en $CaCO_3$ de carbonate de calcium, ainsi qu'un taux élevé de gyttja calcaire, minéral et organique à 18.5% de teneur organique et 66.5% de $CaCO_3$ ont été examiné. Des essais de laboratoire ont montré une influence essentielle des composantes de temps et de volumétrique et des contraintes déviatoriques sur la performance de la vitesse de déformation dans le processus de fluage. L'équation empirique décrivant la relation entre la vitesse de déformation et le temps à des niveaux de contrainte de cisaillement inférieurs à la résistance au cisaillement a été vérifiée dans des conditions de contrainte complexes créées par l'essai de fluage TSHC. À partir de l'analyse des résultats du calcul, les valeurs moyennes des paramètres empirique ont été évaluées.

Keywords: creep test; organic soil; torsional shear hollow cylinder test; triaxial test

1 INTRODUCTION

Organic soils are often considered as difficult subsoils due to their low undrained shear strength and high compressibility with a long-term time-dependent response to loading (Larsson 1986, Wolski and Hartlen 1996). In case of organic soils, in addition to the deformation due to consolidation, it is important to determine the long-term deformation caused by the creep process (Barden 1968, Wolski et al. 1988). Creep is a time-dependent process, in which soils accumulate deformations under the influence of constant effective stress (Grimstad et al. 2008, 2010, www.ntnu.edu/creep). Past research in the field of creep behaviour of soils concentrated on soft soils such as soft silts and clays (Mesri et al. 1981), as well as on soft organic soils (Den Haan 1996). Creep tests were performed as long-term oedometer tests (Tavenas et al. 1978, Den Haan 1996, Yin 1999), and undrained or drained triaxial tests on undisturbed or remoulded samples (Singh and Mitchel 1968, Lechowicz and Szymański 1988, Acharya et al. 2018). In comparison to Holocene organic soils, the organic soils of the Eemian Interglacial are stiffer, however, due to the composition of the soil skeleton with a significant organic content I_{OM} and calcium carbonate $CaCO_3$ content, they show a time-dependent response to loading.

Results of many investigations have proved that the general equation describing the strain rate $\dot{\varepsilon}$ during the creep process has the following form:

$$\dot{\varepsilon} = C(t) \cdot F(\sigma) \tag{1}$$

Where $C(t)$ is the time function and $F(\sigma)$ is the stress function.

In the case of the time function $C(t)$, several empirical relationships based on the results of oedometer tests and undrained or drained triaxial creep tests have been proposed. In the case of the stress function $F(\sigma)$, following the assumption that the stress can be split into volumetric and deviatoric components, the corresponding time-dependent strain components are the volumetric and the deviatoric creep, respectively. In advanced constitutive models used in numerical analysis, both functions are taken into consideration in the theoretical equations describing nonlinear creep mechanism.

On the basis of analysis of single-step constant load, drained and undrained triaxial compression tests, Singh and Mitchell (1968) proposed an empirical equation for the prediction of the axial strain rate $\dot{\varepsilon_a}$ performance in time.

The analyses carried out by Yaid and Campanella (1977), as well as Mesri et al. (1981) indicate that Singh and Mitchell's equation describes adequately the creep characteristics of a variety of soils for values of the shear stress in the range of 30-90% of shear strength.

The test results (Lechowicz and Szymański 1988) indicate that for organic soils, the development of the axial strain rate $\dot{\varepsilon_a}$ with time for shear stress levels lower than the shear strength can be predicted using the equation:

$$\dot{\varepsilon}_a = \beta_a \cdot sinh(\alpha_a \cdot q) \cdot \left(\frac{t_o}{t}\right)^m \tag{2}$$

Where α_a (m^2/kN) and β_a (%/min) are viscosity parameters, q (kPa) is deviator stress, t_o (min) is the unit of time, usually taken as one minute, m(-) is the slope of the log ($\dot{\varepsilon}_a$) – log (t) line, t (min) is the elapsed time.

For organic soils the development of the axial strain rate with time for shear stress levels equal or higher than the shear strength can be predicted using the equation (Lechowicz and Szymański 1988):

$$\dot{\varepsilon_a} = \beta_a \cdot sinh(\alpha_a \cdot q) \cdot \left(\frac{t_o}{t}\right)^m \cdot exp\left[\lambda_o \cdot \left(\frac{q}{q_f}\right)^n \cdot t\right] \tag{3}$$

Where λ_o (-) is the λ (-) parameter at $q/q_f = 1$, q_f (kPa) is the deviator stress at failure, n (-) is the slope of log λ – log (q/q_f) line.

The construction of geotechnical structures, e.g. diaphragm walls, tunnels, buildings with basements or embankments, causes changes in the stress state and deformations in the subsoil. In comparison with the initial stress state formed throughout the sedimentation process, during loading the deformation process occurs in complex stress states with the rotation of the principal stress directions in the subsoil (Zdravković and Jardine 2001). In order to perform such complex stress states, the creep test should be carried out in the Torsional Shear Hollow Cylinder (TSHC) apparatus.

The paper presents laboratory test results performed on high and low calcareous, mineral-organic gyttja in a triaxial apparatus and TSHC apparatus. Creep tests were carried out in drained and undrained conditions at different levels of the mobilized deviator stress. The test results enabled the determination of the creep characteristics of the gyttja at anisotropic stress states.

2 CHARACTERISTICS OF THE TESTED ORGANIC SOILS

One of the most difficult sites due to geotechnical conditions in Warsaw (capital of Poland) is the area of the "Żoliborz channel". In this site, organic soils i.e. organic mud and gyttja reach a thickness of up to 10 m. Organic soils of the geomorphologic structure from the Eemian Interglacial are overconsolidated with an overconsolidation ratio *OCR* varying within 2 and 4. The "Żoliborz channel" is located in the western part of Warsaw, nowadays being intensely developed (underground station and tunnel, residential and office buildings with two or three underground levels). For this reason, organic soils require advanced research methods in order to predict their long-term behaviour under load during construction and long-term maintenance.

The laboratory tests were carried out for low calcareous, mineral-organic gyttja with 12.0% of organic content I_{OM} and 31.0% of calcium carbonate $CaCO_3$ content, and for high calcareous, mineral-organic gyttja with 18.5% of organic content I_{OM} and 66.5% of $CaCO_3$ content.

The index properties of the gyttja studied are given in Table 1.

Table 1. Index properties of the gyttja studied

Index properties	Low calcareous mineral-organic	High calcareous mineral-organic
w_n (%)	74.5	115.5
w_P (%)	68.0	117.0
w_L (%)	104.5	156.0
I_P (%)	36.5	39.0
I_C (-)	0.82	1.04
I_{OM} (%)	12.0	18.5
$CaCO_3$ (%)	31.0	66.5
ρ (t/m^3)	1.51	1.34
ρ_d (t/m^3)	0.865	0.622
ρ_s (t/m^3)	2.50	2.40
e_o (-)	1.889	2.860

Notes: w_n – water content, w_P – plastic limit, w_L – liquid limit, I_P – plasticity index, I_C – consistency index, I_{OM} – organic content, $CaCO_3$ – calcium carbonate content, ρ – unit bulk density, ρ_d – dry density, ρ_s – specific density, e_o – void ratio.

3 CREEP TESTS IN A TRIAXIAL APPARATUS

3.1 Testing procedure

Creep behaviour of gyttja in a triaxial apparatus was tested on undisturbed (U) samples taken as block samples for low and high calcareous, mineral-organic gyttja during the excavations for residential buildings with two-floor basements near Skierniewicka Str. in Warsaw. The tested samples have a diameter of 50 mm and a height of 100 mm. The testing program included single-step and multi-step undrained creep triaxial tests (UCTT) and drained creep triaxial tests (DCTT).

In a triaxial apparatus the creep tests were carried out in an axi-symmetrical stress state where the intermediate principal stress σ_2 is equal to the minor principle stress σ_3. Creep triaxial tests were performed in four consecutive stages: flushing, saturation, reconsolidation and finally, single-step or multi-stage creep in undrained (UC) or drained (DC) conditions. During flushing, air and gases bubbles with the largest dimensions were removed from the samples and tubes. Saturation of soil samples was performed using the back pressure method with a back pressure of 200 kPa. This stage lasted until the value of Skempton's parameter B exceeded 0.95. After that, anisotropic reconsolidation was performed to reach in situ effective stress conditions using vertical effective stress σ'_v = 100 kPa and horizontal effective stress σ'_h = 75 kPa. The value of K_o during the reconsolidation process was equal to 0.75.

After reconsolidation, single-step or multi-step creep began, and deviator stress q and effective confining stresses σ'_3 were applied in Δq and $\Delta\sigma'_3$ increments. The Δq increments were applied with weights placed on the loading piston. The $\Delta\sigma'_3$ increments were applied by increasing the cell pressure with constant back pressure. Axial displacements and pore water pressures or volume changes were measured. The total duration of the creep tests ranged from two to four weeks (Goławska 2019).

Values of effective stress components, the effective mean stress p' versus deviator stress q used in the single-step creep triaxial test are shown in Figure 1. The initial level of the mobilized deviator stress q_o/q_f representing in situ stress conditions was 0.171 but level of the mobilized deviator stress q/q_f during single-step creep test was 0.514.

In order to determine the undrained shear strength τ_{fu} and deviator stress at failure $q_f = 2{\cdot}\tau_{fu}$, a consolidated undrained triaxial test was additionally carried out. The soil sample was subjected to the same three stages (flushing, saturation, reconsolidation). Finally, the process of sample shearing was carried out in the stress path, involving an increase in the major principal stress σ_1 and a constant value of minor principal stress σ_3. For low calcareous, mineral-organic gyttja, the undrained shear strength τ_{fu} = 73 kPa.

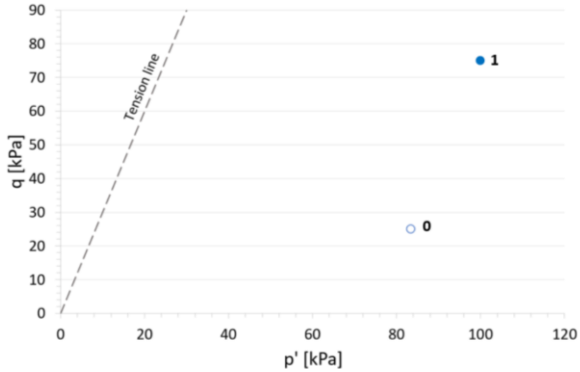

Figure 1. Values of effective stress components p' and q used in a single-step drained creep triaxial test: point 0 – q_o = 25 kPa, 1 – q = 75 kPa

3.2 Results of creep triaxial tests

The development of axial strain ε_a with log t and axial strain rate $\dot{\varepsilon}_a$ with log t for the single-step drained creep triaxial tests (DCTT) for low calcareous, mineral-organic gyttja is shown in Figures 2 and 3.

For the level of mobilized deviator stress q/q_f = 0.514 no sign of failure was detected even after $4{\cdot}10^4$ minutes. The analysis of creep test results shows that the values of empirical parameters to Equation (2) for low calcareous, mineral-organic gyttja are: α_a = 0.0373 m^2/kN, β_a = 0.0095 %/min, m = 0.782.

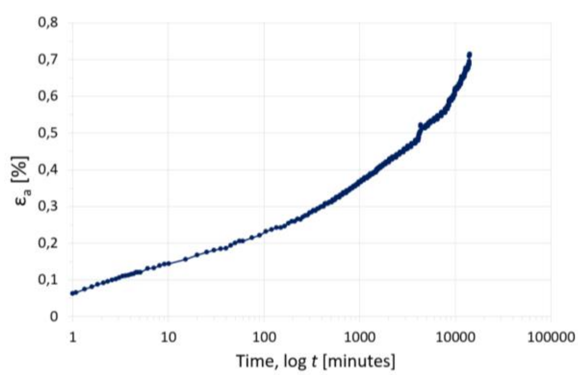

Figure 2. Development of axial strain ε_a with log t for low calcareous, mineral-organic gyttja subjected to single-step drained creep triaxial test (DCTT)

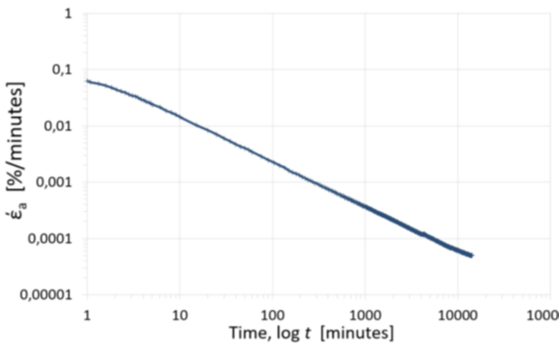

Figure 3. Development of axial strain rate $\dot{\varepsilon}_a$ with log t for low calcareous, mineral-organic gyttja subjected to single-step drained creep triaxial test (DCTT)

4 CREEP TESTS IN A TORSIONAL SHEAR HOLLOW CYLINDER APPARATUS

4.1 Testing procedure

Creep behaviour of gyttja in a Torsional Shear Hollow Cylinder apparatus was tested in the Water Centre Laboratory of the Warsaw University of Life Sciences – SGGW. The creep tests were carried out on reconstituted (R) cylindrical specimens with an internal diameter of 60 mm, external diameter of 100 mm and height of 200 mm. The tests were performed with anisotropic reconsolidation and multi-step creep in undrained or drained conditions.

Material for reconstituted samples was from block samples taken from the depth of 9.5 m below ground level during the excavation for residential buildings with two-floor basements near Skierniewicka Str. in Warsaw. The samples were reconsolidated to obtain an overconsolidation ratio *OCR* equal to 2, in situ effective vertical stress σ'_v = 100 kPa and horizontal effective stress σ'_h = 75 kPa.

In a torsional shear hollow cylinder apparatus, the creep tests were carried out at given values of the intermediate principal stress parameter *b* and angle of the principal stress rotation *α*. Parameter *b* is defined as:

$$b = \frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3} \tag{4}$$

Where σ_1 (kPa) is the major principal stress, σ_2 (kPa) is the intermediate principal stress, σ_3 (kPa) is the minor principal stress.

Creep TSHC tests were performed in six consecutive stages: flushing, saturation, reconsolidation, change of intermediate principal stress parameter *b*, change of angle of principal stress rotation *α*, and finally, multi-step creep in undrained or drained conditions. Saturation of soil samples was performed using the back pressure method. This stage lasted until the value of Skempton's parameter *B* exceeded 0.95. After that, anisotropic reconsolidation was performed. The value of K_o during the reconsolidation process was equal to 0.75. The next step was to change the intermediate principal stress parameter *b* from value 0 to 0.5. After that the value of angle of principal stress rotation *α* was changed to the determined value in a particular test.

In the multi-step creep, deviator stress *q* was applied in Δq increments with a constant value of total mean stress *p*. The initial level of the mobilized deviator stress q_o/q_f representing in situ stress conditions was 0.243 but levels of the mobilized deviator stress q/q_f during multi-step creep test were ranged from 0.282 to 0.553. Axial displacements and pore water pressures or volume changes have been measured. The total duration of the creep tests ranged from two to four weeks.

Values of effective stress components, the effective mean stress *p'* versus deviator stress *q* used in creep TSHC test with *b* = 0.5 and *α* = 0º are shown in Figure 4. The values of the total mean stress *p* during tests were equal to 338 kPa. A detailed description of the laboratory tests is presented in the PhD thesis by Goławska (2019).

In order to determine the undrained shear strength τ_{fu} and deviator stress at failure q_f , a consolidated undrained TSHC test was additionally carried out. The soil sample was subjected to the

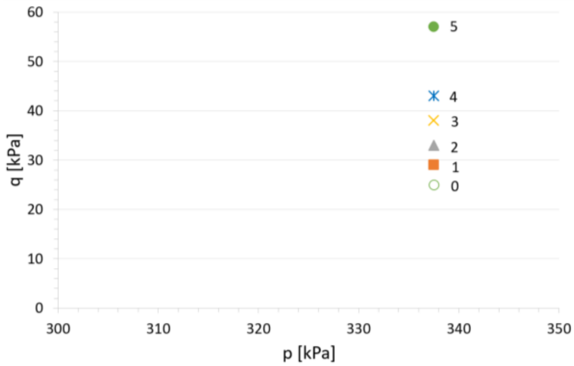

Figure 4. Values of stress components p and q used in multi-step undrained creep TSHC test: point 0 – q_o = 25 kPa, 1 – q = 29 kPa, 2 – q = 33 kPa, 3 – q = 38 kPa, 4 – 43 kPa, 5 – q = 57 kPa

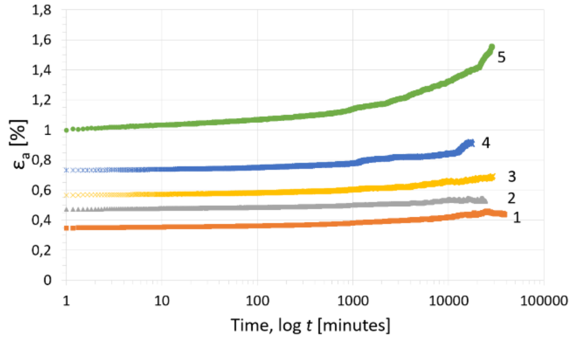

Figure 5. Development of axial strain for high calcareous mineral-organic gyttja subjected to muti-step undrained creep TSHC test: line 1 – q=29 kPa, 2 – q=33 kPa, 3 – q=38 kPa, 4 – 43 kPa, 5 – q=57 kPa

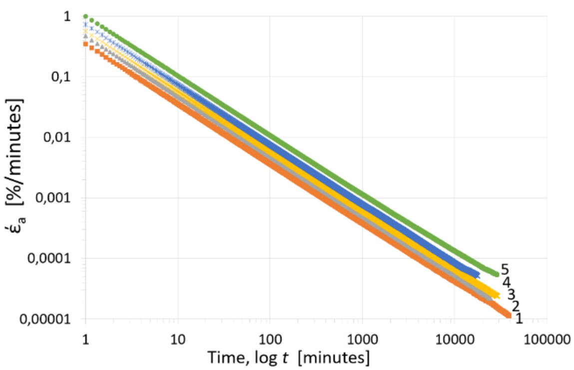

Figure 6. Development of axial strain rate for high calcareous mineral-organic gyttja subjected to multi-step undrained creep TSHC test: line 1 – q = 29 kPa, 2 – q = 33 kPa, 3 – q = 38 kPa, 4 – 43 kPa, 5 – q = 57 kPa

same five stages (flushing, saturation, reconsolidation, change of intermediate principal stress parameter b, change of angle of principal stress rotation α). Finally, in the sixth stage the process of sample shearing was carried out in the stress path, involving an increase in the deviator stress q and a constant value of total mean stress p. For high calcareous, mineral-organic gyttja the undrained shear strength τ_{fu} = 51.5 kPa.

4.2 Results of creep TSHC tests

Development of axial strain ε_a with log t and axial strain rate $\dot{\varepsilon}_a$ with log t for undrained creep TSHC tests with b = 0.5 and α = 0º for high calcareous, mineral-organic gyttja is shown in Figures 5 and 6.

For the level of mobilized deviator stress q/q_f ranging from 0.282 to 0.553, no sign of failure was detected even after $4 \cdot 10^4$ minutes. The ε_a – log t curves are similar in shape. The highest ε_a developed under the first deviator stress increment. Strain rates $\dot{\varepsilon}$ for smaller mobilized deviator stress q/q_f were smaller. However, the $\dot{\varepsilon}$ decreased more rapidly under the smaller q/q_f and slowly under the higher q/q_f (Goławska 2019).

The analysis of parameter values obtained for Eemian gyttja from the TSHC creep test indicates that for the prediction of the axial strain rate in time, the following average parameter values can be used in Equation (2) for high calcareous, mineral-organic gyttja: α_a = 0.0373 m²/kN, β_a = 0.26 %/min, m = 0.975.

Based on the obtained empirical parameters, verification calculations have been carried out. Figure 7 presents calculated and measured strain rates at different values of deviator stress for selected times. The comparison of the measurement results with the calculated relationship of the strain rate and the deviator stress for selected times has confirmed the applicability of Equation (2) in the prediction of strain rates in the creep process.

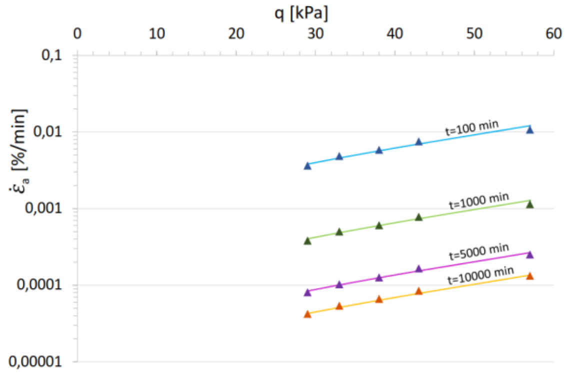

Figure 7. Relationship between axial strain rate and deviator stress for high calcareous mineral-organic gyttja subjected to multi-step undrained creep TSHC test

In order to describe the general performance of the strain rate in the creep process, TSHC undrained and drained creep tests are carried out at different angles of rotation of the principal stress directions at different levels of volumetric and deviatoric stress components.

5 CONCLUSIONS

Results of triaxial creep tests and torsional shear hollow cylinder creep tests have shown that the performance of strain rate in the creep process of Eemian gyttja is a more complex phenomenon depending not only on time but also on changes of volumetric and deviatoric stress components. The prediction of the strain rate in time during the creep process for Eemian gyttja at shear stress levels lower than the shear strength may be done based on Equation (2) with evaluated values of empirical parameters for $b = 0.5$ and $\alpha = 0^{o}$. Further TSHC creep tests are carried out at different levels of mobilized deviator stress and at different angles of rotation of the principal stress directions.

6 ACKNOWLEDGEMENTS

This work, carried out in 2015–2018 at the Warsaw University of Life Sciences–SGGW and the Białystok University of Technology, was supported by the Polish Ministry of Science and Higher Education.

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