Field and laboratory experience with the soft subsoil deformation

Les recherches de terrain et de laboratoire sur les déformations des sols faibles

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ABSTRACT
The paper presents the results of field and laboratory investigations carried out on two test embankments located on soft soils in north-western Poland. Comprehensive investigations including observations of test embankments and laboratory testing have been conducted in order to study the behaviour of the consolidation process in soft subsoil. This paper presents the analysis of factors determining the assessment of the deformation process of soft subsoil. The analysis was focused on determining non-linear deformation-stress characteristics used for modelling the deformation of soft subsoil under the earth structure. Deformation characteristics obtained in laboratory tests were compared with field measurements, which included vertical and horizontal displacements, as well as pore pressure dissipation. Based on analysis of field observations and laboratory tests results, the characteristics determining the consolidation process were elaborated.

RÉSUMÉ
L' article présente les résultats des essais in situ et au laboratoire réalisés sur les périmètres expérimentaux situés dans la région nord - ouest de Pologne. Les essais concernaient les mesures des variations des déplacements de la fondation, chargée par des remblais experimentaux. Des essais au laboratoire de tourbe et de gyttja ont également été réalisés afin de déterminer le procès de consolidation des sols faibles. Les résultats obtenus lors des essais au laboratoire ont été comparés aux essais in situ. Les relations empiriques décrivant les procès de deformation des fondations chargées ont été définies.

Keywords : soft soils, deformation characteristics, field investigation, laboratory tests

1 INTRODUCTION

Earth structures are nowadays localized in barren (swampy) areas in order to save fertile lands and to protect environment. In such kind of terrain organic soils e.g. peat, are often encountered. Very special properties of organic soils make the improvement of soil foundation particularly important. One of the improvement methods is a consolidation by preloading or construction by stages. In order to accelerate the consolidation process vertical drains may be installed (Lechowicz et al., 1987). Comprehensive investigations comprising observations at test embankments as well as laboratory investigation were carried out to study the influence of stress path on the deformation characteristics (Hartlen and Wolski, 1996).

The paper presents the results of laboratory and field investigations carried out on two kinds of soft soils in north-western Poland. Comprehensive investigations which included the routine and oedometer tests as well as triaxial tests have been conducted in order to study the behaviour of consolidation process in soft subsoils. Analyses of factors which determine the assessment of the deformation process of soft subsoils are presented. The main emphasis has been placed on obtaining the non-linear deformation – stress characteristics, which are being used for modelling of the deformation of soft subsoils under the earth structure (Lechowicz, 1994).

The observation of deformation performance in field investigations indicated that the consolidation process consist of two stages.

- Primary settlement (immediate and consolidation)
- Secondary and tertiary settlement (creep)

Secondary and tertiary settlement is the result of creep of soil skeleton under the effective stress. It depends on rheological properties of soil and it signifficantly depends on time (Szymanski et al. 2004).

It is important that the rate of strain can increase or decrease during the creep phase and depends on the level of deviatoric stress. The rate of strain decreases when the applied deviatoric stress is lower than deviatoric stress at failure. On the other hand when deviatoric stress is higher the rate of strain initially decreases and than continuously increases until creep failure. Consolidation of subsoil significantly caused a decrease of the strain rate (Szymanski and Sas, 2001).

2 DESCRIPTION OF THE TEST AREA

The laboratory investigations were performed on soft soils taken from test sites located on organic soils.

The two test sites were located in north-western Poland in the Notec River valley with the first near the village of Antoniny (test site No. 1) and the second near the village of Mielimaka (test site No. 2). The distance between the two sites is approximately 20 km. The river valley is about 10 km wide and the area is relatively flat, seasonally flooded, and covered with grass vegetation. The upper soft soils in the area consist of a layer of amorphous peat on top of a layer of fine-grained calcareous soil, namely gyttja. Gyttja is organic soil that originates from the remains of plants and animals rich in fats and proteins in contrast with peat which is formed from the remains of plants rich in carbohydrates. These soft organic soils were underlain by a dense sand (Wolski et al., 1988).

The geotechnical conditions before the test embankments that were constructed are summarized below.

The physical properties of organic soils at the test sites are presented in Table 1 and Table 2.

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Table 1. Physical properties of organic soils at test site No. 1

Properties	Peat	Calcareous soil
Water content w [%]	310	110
Plastic limit w_p [%]	190	55
Liquid limit w_l [%]	315	110
Density of solid particles ρ_s [tm^{-3}]	> 1.6	>2.55
Bulk density ρ [tm^{-3}]	1.15	1.42
Dry density ρ_d [tm^{-3}]	0.28	0.68
Organic matter content I_{OM} [%]	~ 80	~ 35
Degree of humification R [%]	~ 60	-

Table 2. Physical properties of organic soils at test site No. 2

Properties	Peat	Calcareous soil
Water content w [%]	380	115
Plastic limit w_p [%]	140	50
Liquid limit w_l [%]	340	120
Density of solid particles ρ_s [tm^{-3}]	> 1.6	>2.58
Bulk density ρ [tm^{-3}]	1.05	1.42
Dry density ρ_d [tm^{-3}]	0.26	0.67
Organic matter content I_{OM} [%]	~ 80	~ 27
Degree of humification R [%]	~ 60	-

At the test site No. 1 the organic subsoil consists of a 3.1-m-thick peat layer and a 4.7-m-thick gyttja layer. At the test site No. 2 the 7.5-m-thick organic subsoil consists of a 6.7-m-thick peat layer and 0.8-m-thick gyttja layer. The groundwater table is present in the peat layer at a depth of 0.5-0.8 m below the surface. The GWT in the gyttja and sand layers is 0.6-1.6 m higher than that of the upper peat stratum because of artesian pressure in the sand layer.

3 FIELD INVESTIGATIONS

At the test sites two embankments were built in stages to reach the final height of 4.0 m. The embankment construction had to be divided into three stages (Szymanski et al., 2005).

The subsoil behaviour was monitored by means of piezometers, various types of settlement gauges, and inclinometers that allowed measurements of vertical and horizontal displacements and pore pressures.

Observation of vertical displacements in the subsoil was performed by means of settlement gauges of 4 types: hose, plate, screw and magnetic.

Flexible tube of hose settlement gauge used to obtain continuous settlement distributions across the embankment was installed in subsoil before the construction started. The pore pressures in the compressible layers were measured at different levels and locations using the BAT system. The vertical gauges and piezometers were installed at the centre of the embankment, at the middle of the slopes, at the toes of the slopes and outside the embankments.

The magnitude of subsoil deformation during each construction stage is presented in Figure 1.

The observation of deformation values indicated that the consolidation process consist of two stages (Fig. 2 and Fig. 3).

- Primary settlement (immediate and consolidation)
- Secondary and tertiary settlement (creep)

Primary settlement is the result of:

- Immediate (initial) undrained elastic deformation of the subsoil under a aplied load.
- Consolidation of the soil connected with dissipation of excess of pore in the soil.

The calculation of initial settlement are performed on the base of elastic theory using undrained Young's modulus E_u and Poisson's Ratio υ = 0.5. To evaluate the deformation characteristics triaxial undrained tests are performed.

Parameters for calculation the settlements of the consolidation stage are delivered from compression tests, mainly from oedometer IL (incremental loading) test or oedometer test with continous loading CL as well as triaxial tests.

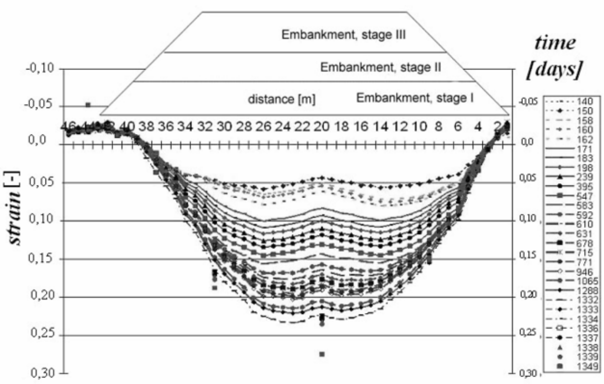

Figure 1. Vertical displacements of embankment subsoil

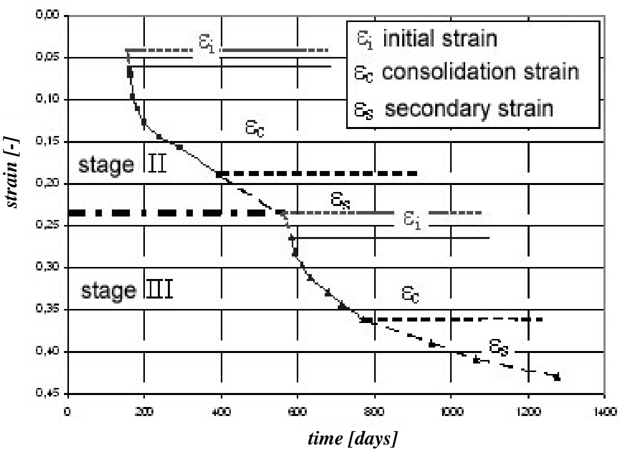

Figure 2. Course of vertical strain of peat during subsoil consolidation

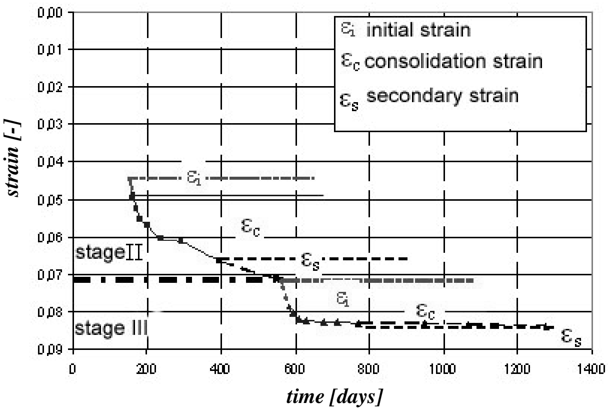

Figure 3. Course of vertical strain of calcareous soil during subsoil consolidation

For calculations the secondary compression (creep settlements) mainly coefficient of secondary consolidation c_α is applied. The coefficient is evalueted for each load of step during oedometer IL test. This parameter is a function of stress history and deformation and the variation within the particular range of stresses and deformations to be applied in the field should be determined. The coefficient of secondary compression may be expressed as C_α=de/dlog t or as $C_{\alpha\varepsilon}$=dε/dlogt, where $C_\alpha=C_{\alpha\varepsilon}(1+e_o)$.

Conventional creep settlements are regarded as being approximately linear in log time and are described as secondary settlement. In long – term tests there is sometimes a downwards curvature of the log time-settlement curve in the secondary compression phase. This phenomenon is sometimes called tertiary compression.

4 LABORATORY TEST RESULTS

Laboratory tests presented in the paper were performed on peat and calcareous undisturbed soil samples taken from organic subsoil using Shelby sampler according to international standard. These laboratory investigations consist of routine test, oedometer and triaxial tests. Triaxial tests were performed to evaluate the deformation and strength characteristics for overconsolidated and normally consolidated stress states, which are required for estimating the displacement of organics subsoil. In order to determine the deformation parameters for undrained and fully drained conditions, triaxial tests were carried out (Szymanski et al., 2006).

The results obtained in laboratory tests for undrained conditions are presented in Figure 4 and Figure 5 and for fully drained conditions are shown in Figure 6 and Figure 7.

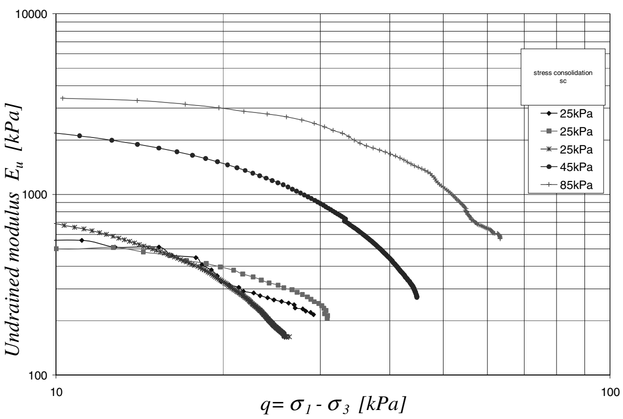

Figure 4. Variability of undrained modulus E_u obtained in triaxial tests CU for peat

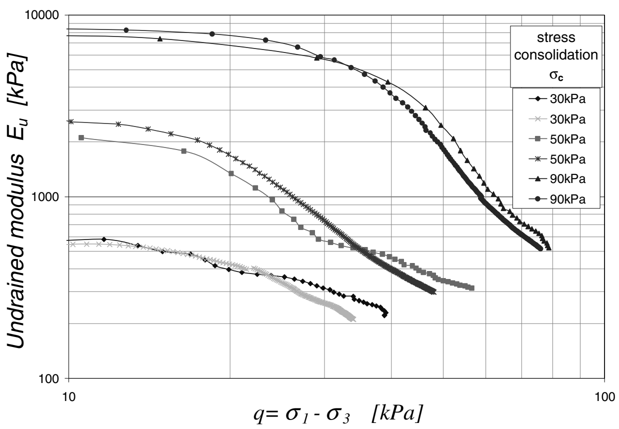

Figure 5. Variability of undrained modulus Eu obtained in triaxial tests CU for calcareous soil

The relationship between the Young modulus E_u for undrained conditions versus deviatory stress q and consolidation stress σ_c can be shown as follows:

$$E_u = \beta_0 \cdot q^{\beta_1} \cdot \sigma_c^{\beta_2}\ , \tag{1}$$

where β_0, β_1, β_2 - empirical coefficients.

The analysis of test results gives the following values of empirical coefficients to Equation (1) for peat: β_0=17.5, β_1=-0.86, β_2=1.70 and for calcareous soil β_0=3.51, β_1=-0.78, β_2=2.11.

The relationship between the Young modulus E for fully drained conditions versus effective stress components σ'_1 and σ'_3 can be shown as:

$$E = \alpha_0 \cdot \sigma_1'^{\alpha_1} \cdot \sigma_3'^{\alpha_2}\ , \tag{2}$$

where α_0, α_1, α_2 - empirical coefficients.

For organic soils from the Antoniny site the following values of empirical coefficients to Equation (2) for peat are obtained α_0=2770, α_1=-1.95, α_2=2.16 and for calcareous soil α_0 =947, α_1 =-1.12, α_2 =1.53.

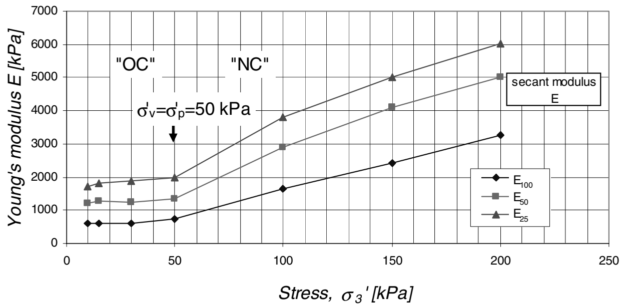

Figure 6. Relationship between Young's modulus E and effective stress component σ'_3 obtained in triaxial tests CD for peat

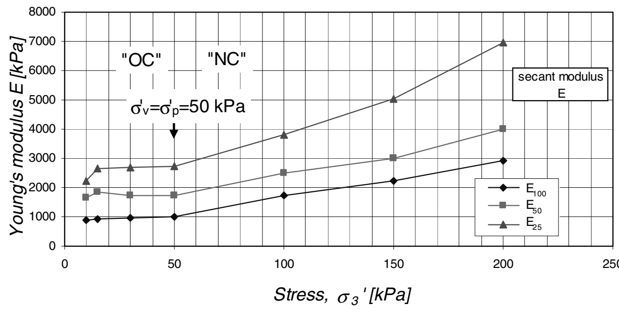

Figure 7. Relationship between Young's modulus E and effective stress component σ'_3 obtained in triaxial tests CD for calcareous soil

Considerable secondary deformations which depend on time occur in organic soils (Szymanski and Sas, 2001). Creep tests were performed in standard triaxial cells for peat and calcareous soils. For each soil two series of tests were performed: first on unconsolidated samples and second on samples consolidated under the effective stress of about 35 kPa. Test series were done under different deviatoric stresses (Fig. 8 and Fig. 9).

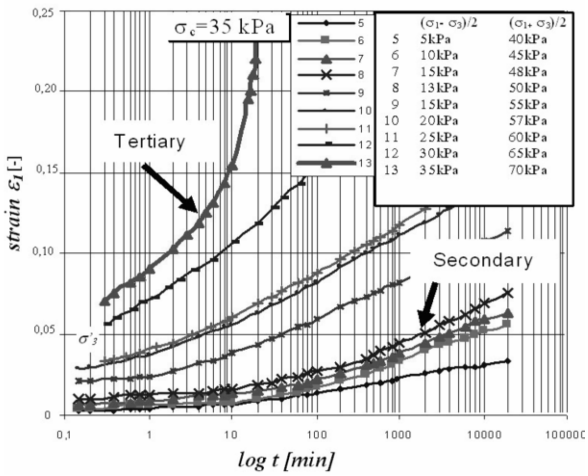

Figure 8. Strain versus log time for consolidated peat

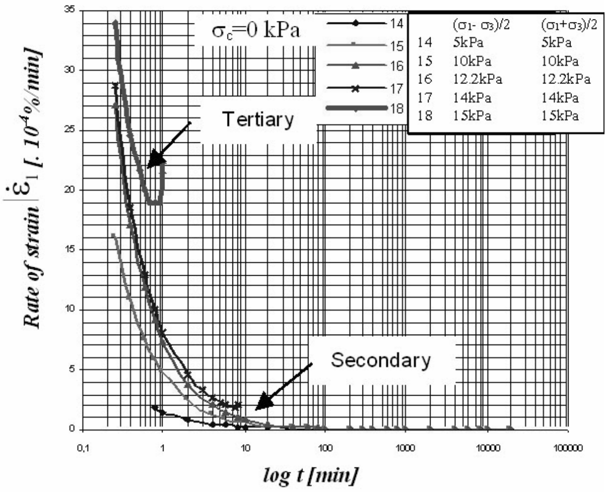

Figure 9. Rate of strain versus log time for in-situ calcareous soil

Results of laboratory tests indicated that the parameters describing secondary compression depend to considerable extent on the effective stress level. Conventional creep settlements are regarded as being approximately linear in log time and are described as secondary settlements. In the long-term tests there is sometimes an upwards curvature of the log time-settlement curve in the secondary compression phase. This phenomenon is called tertiary compression (Szymanski et al., 2005).

The analysis of the development of vertical and horizontal strains in organic soils during the deformation process indicates significant creep of the soil skeleton.

It is important that the rate of strain can increase or decrease during the creep phase and depends on the level of deviatoric stress. The rate of strain decreases when the applied deviatoric stress is lower than deviatoric stress at failure. On the other hand when deviatoric stress is higher the rate of strain initially decreases and than continuously increases until creep failure. Consolidation of subsoil significantly caused a decrease of the strain rate.

5 CONCLUSIONS

Observations of the consolidation process in organic soils demonstrate large values and a non-linear character of deformation. Therefore, the prediction of consolidation performance in organic subsoil should be carried out by methods which take into account the variation of soil parameters and large strains analysis.

Laboratory tests presented in this paper indicate that the strength parameters c' and φ' depend on the stress range, therefore the different values should be used for overconsolidated and normally consolidated stress state. It is important to note that deformation parameters E and E_u depend not only on the stress range but also on stress level and stress history.

Analysis of the development of vertical and horizontal strains in organic soils during the deformation process indicates significant creep of the soil skeleton. The part of strain can be described by ε_s for a given consolidation stress depending on time and stress level.

Observations of the consolidation process in organic soils demonstrate large values and a non-linear character of deformation. The use of consolidation theory for the prediction of soil displacements under embankments requires taking into consideration the variable soil parameters which depend on the effective stress level and preconsolidation phenomena.
This fact should be taken into consideration in the modeling process of consolidation performance.

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