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EVALUATION OF DEFORMATION AND STRENGTH PARAMETERS OF ORGANIC SOILS FOR THE DESIGN OF GEOTECHNICAL STRUCTURES

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Abstract. The evaluation of deformation and strength parameters of Holocene organic soils obtained from DMT dilatometer tests based on empirical relationships and ANN Artificial Neural Networks is presented. The evaluation of undrained shear strength τ_{fu}, deformation modulus $E_{0.1\%}$ and initial shear modulus G_0 of Eemian organic soils obtained from DMT dilatometer tests and SDMT seismic dilatometer tests is given, and then its comparison with the values obtained from triaxial tests for the design of underground structures supported by diaphragm walls of the stations of the underground line II in Warsaw, is shown.

Keywords: Deformation modulus, eemian organic soils, holocene organic soils, initial shear modulus, undrained shear strength.

1. Introduction

Earth structures such as dam embankments, levees, dykes, and road and railway embankments are often constructed in difficult geotechnical conditions [1–6]. In general geotechnical practice organic soils are considered as difficult subsoils due to their high compressibility with creep effects, low undrained shear strength and nonlinear variability of material characteristics [7–13]. Holocene organic soils are classified as very soft soils with the consistency index $I_C < 0.5$ and undrained shear strength τ_{fu} often not exceeding 25 kPa. Organic soils formed during the Eemian Interglacial of the Pleistocene Period reveal slightly better index properties, and higher stiffness and strength than Holocene organic soils. However, due to the composition of the soil skeleton with significant organic matter and calcium carbonate contents, they also show up non-linear mechanical characteristics and a time-dependent response to loading. For the design of embankments on organic subsoil, the crucial problems to be solved include the assessment of embankment stability, and large vertical and horizontal deformations of the subsoil during and after construction [1, 2]. Embankment construction on organic subsoil is possible using a staged construction involving ground improvement by consolidation or various ground improvement methods, e.g. inclusions of different rigidity.

Nowadays, the construction and modernization of facilities and infrastructure in urban agglomerations is often performed in complex geotechnical conditions. Subsoil studies and tests with regard to the importance of the structure and complexity of the foundation conditions are based on the combined analysis of field and laboratory test results. In recent practice, among possible *in situ* tests, the SDMT seismic dilatometer test is increasingly used also for heavily preconsolidated cohesive soils and organic soils. When modelling the behaviour of deep excavation casings by diaphragm walls using a linear elastic-perfectly plastic model, it is necessary to apply deformation parameters determined in the range of small strains. For the design of diaphragm walls in organic soils, it is advisable to use a more advanced soil model, e.g. a non-linear elastic-plastic model with creep [14–18].

Practical cases of evaluating deformation and strength parameters of organic soils loaded by embankments are shown in the paper. The evaluation of deformation and strength parameters of Holocene organic soils from the Antoniny test site located in north-western Poland in the Noteć River valley and obtained from DMT dilatometer tests is here presented. The constrained modulus M^{oc} for the preconsolidated state and the constrained modulus M^{nc} for the normally consolidated state, as well as the recompression index C_r and the compression index C_c for the normally consolidated state of Holocene peat and gyttja, are presented. The undrained shear strength τ_{fu} of Holocene organic soils evaluated from DMT dilatometer tests based on empirical relationships and Artificial Neural Networks is also shown. The evaluation of deformation and strength parameters of Eemian organic soils in the design of underground structures such as deep excavations supported by diaphragm walls for the stations of the underground line II in Warsaw is shown. The values of undrained shear strength τ_{fu}, deformation modulus $E_{0.1\%}$ at vertical strain ε_1 of 0.1 % and initial shear modulus G_0 for Eemian gyttja evaluated from DMT dilatometer tests and SDMT seismic dilatometer tests are compared with the values obtained from triaxial tests.

Soil type	**Organic content** I_{om} [%]	**$CaCO_3$ content** [%]	**Water content** w_n [%]	**Liquid limit** w_L [%]	**Density** unit ρ [$t\,m^{-3}$]	specific ρ_s [$t\,m^{-3}$]
Peat	65–75	10–15	310–340	305–450	1.05–1.10	1.45–1.50
Gyttja	5–20	65–90	105–140	80–110	1.25–1.40	2.2–2.3

TABLE 1. Physical properties of Holocene organic soils.

Soil type	**Organic content** I_{om} [%]	**$CaCO_3$ content** [%]	**Water content** w_n [%]	**Liquid limit** w_L [%]	**Density** unit ρ [$t\,m^{-3}$]	specific ρ_s [$t\,m^{-3}$]
Organic mud	8–12	–	32–34	50–55	1.60–1.65	2.4–2.5
Gyttja low-carbonate mineral	7–9	29–38	60–80	75–85	1.60–1.65	2.40–2.45
Gyttja high-carbonate mineral-organic	17–25	54–77	80–120	120–130	1.55–1.60	2.30–2.35

TABLE 2. Physical properties of Eemian organic soils.

2. CHARACTERISTICS OF THE ORGANIC SOILS

2.1. HOLOCENE ORGANIC SOILS

The physical properties of typical Holocene organic soils: organic mud, high-carbonate gyttja and amorphous peat are shown in Table 1. In order to correctly identify organic soils within the basic physical properties, in addition to natural moisture, liquidity limit, bulk density and specific density, it is necessary to determine the organic content Iom, by burning the soil at a maximum temperature of +440 °C, and to determine the calcium carbonate $CaCO_3$ content.

2.2. EEMIAN ORGANIC SOILS

Older organic soils formed during the Eemian Interglacial of the Pleistocene Period show slightly better physical and mechanical properties. Table 2 shows the physical properties of typical organic soils from the Eemian Interglacial: organic mud, low-carbonate mineral gyttja and high-carbonate mineral-organic gyttja.

3. DEFORMATION AND STRENGTH PARAMETERS

3.1. HOLOCENE ORGANIC SOILS

Experience from organic soils indicates that the value of constrained modulus M is not constant but is an effective stress dependency. For staged construction of embankments on organic soils, when effective vertical stress several times exceeds the initial preconsolidation pressure, for calculation of subsoil settlement not only the constrained modulus M^{oc} for the preconsolidated state but also the constrained modulus M^{nc} for the normally consolidated state should be evaluated. Analysis of test results for Holocene organic soils indicates that based on DMT dilatometer tests the constrained modulus for the preconsolidated state M^{oc} and for the normally consolidated state M^{nc} can be calculated using factors R_M^{oc} and R_M^{nc} from the following relations [19]:

$$M^{oc} = R_M^{oc} \cdot E_D, \tag{1}$$

$$M^{nc} = R_M^{nc} \cdot E_D, \tag{2}$$

for peat:

$$R_M^{oc} = 0.20 + 1.60 \cdot \log K_D, \tag{3}$$

$$R_M^{nc} = 0.90 + 0.60 \cdot \log I_D, \tag{4}$$

and for gyttja:

$$R_M^{oc} = 0.12 + 2.10 \cdot \log K_D, \tag{5}$$

$$R_M^{nc} = 0.95 + 0.55 \cdot \log I_D, \tag{6}$$

where: E_D – dilatometer modulus, K_D – horizontal stress index, I_D – material index.

The profiles of the constrained module for the organic subsoil at the Antoniny site evaluated from DMT dilatometer tests based on the Equations (1)-(6) are shown in Figure 1a and compared with the values obtained from the oedometer tests.

A comparison of dilatometer data with the results of oedometer tests indicates that the relationship between the compression index C_c for normally

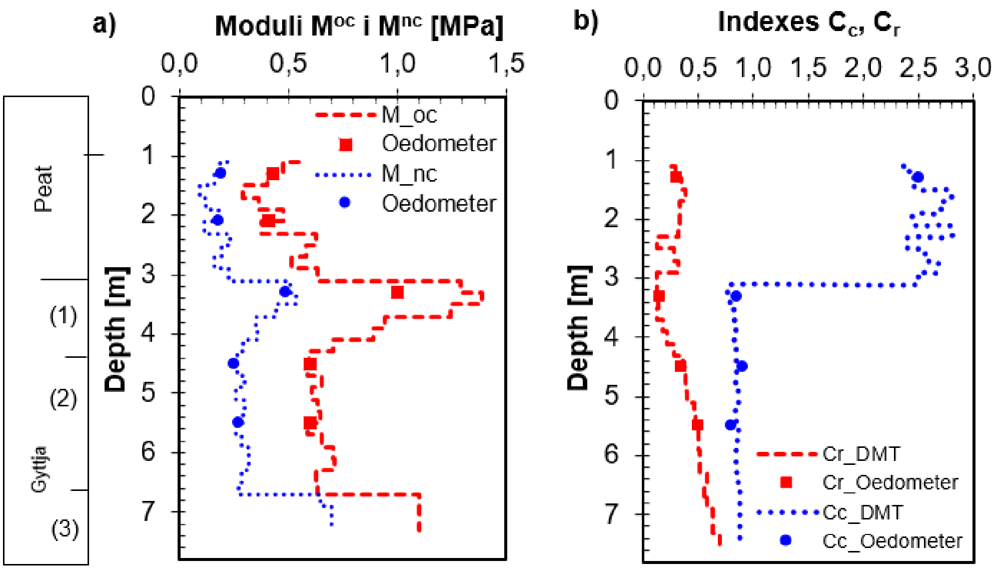


Figure 1. Compression moduli and compression indexes for Holocene organic subsoil at the Antoniny site based on DMT dilatometer tests: a – moduli M^{oc} and Mnc, b – compression indexes C_r and C_c.

consolidated Holocene organic soils and material index I_D can be expressed in the form [19]:

$$C_c = a(I_D)^m. \tag{7}$$

The obtained values of empirical coefficients a and m for peat and gyttja are equal to 1.8, 0.7 and −0.30, −0.20, respectively.

Analysis of test results indicates that the recompression index C_r can be calculated from the relationship between the ratio C_r/C_c and the lateral stress index K_D in the form [19]:

$$\frac{C_c}{C_r} = b(K_D)^n. \tag{8}$$

For Holocene organic soils the values of empirical coefficients are $b = 0.27$ and $n = 1.9$.

The profiles of the recompression index C_r and the compression index C_c for the normally consolidated state for organic subsoil at the Antoniny site evaluated on the basis of the Equation (7) and (8) using the values of empirical coefficients mentioned above are shown in Figure 1b and are compared with the values obtained from the oedometer tests.

Analysis of DMT and triaxial test results carried out by Lechowicz indicates that, particularly for peat and gyttja, the relationship between the normalized undrained shear strength and the horizontal stress index K_D differs from that proposed by Marchetti [20, 21] and can be modified as follows [22, 23]:

$$\frac{\tau_{fu}}{\sigma'_{v0}} = S, \tag{9}$$

where $S = (\tau_{fu}/\sigma'_{v0})_{nc}$ is the normalized undrained shear strength for normally consolidated soil. The value of parameter S for peat is equal to 0.5, but for calcareous gyttja and calcareous-organic gyttja, it is at 0.40 and 0.45, respectively.

A multi-factor relationship was proposed by Rabarijoely [25] to evaluate the undrained shear strength τ_{fu} of organic soils from DMT dilatometer tests based on the net value of the corrected first pressure reading $(p_0 - u_0)$, the net value of the corrected second pressure reading $(p_1 - u_0)$, and the effective vertical stress σ'_{v0}; and it is as follows:

$$\tau_{fu} = \alpha_0 \cdot (\sigma'_{v0})_1^{\alpha} \cdot (p_0 - u_0)_2^{\alpha} \cdot (p_1 - u_0)_3^{\alpha}, \tag{10}$$

where α_0, α_1, α_2, α_3 are empirical coefficients, σ'_{v0} is the *in situ* effective vertical stress, p_0 and p_1 are corrected pressures from DMT tests, and u_0 is the in situ pore water pressure.

The empirical coefficients in Equation (10) for organic soils can be evaluated as functions of the void ratio e and empirical coefficients C_i and D_i shown in Table 3 according to the following formula [25]:

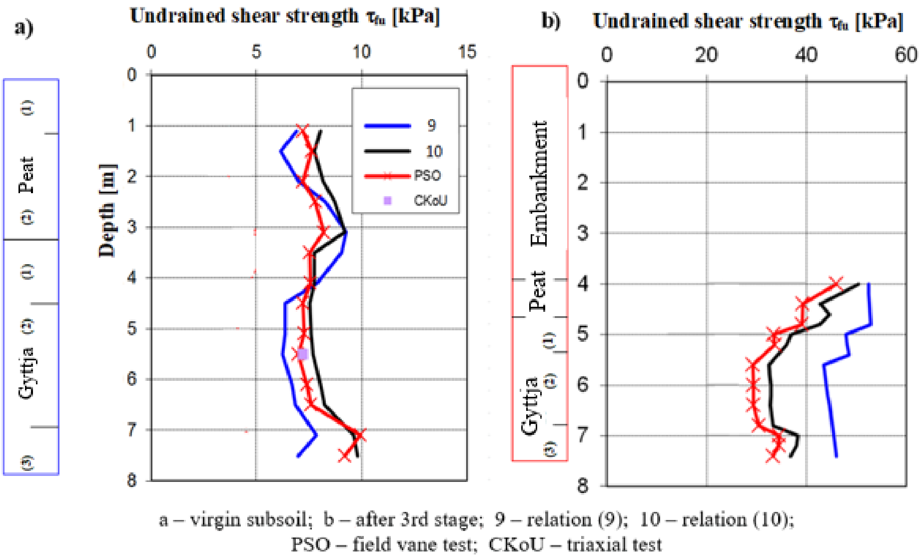
$$\alpha_i = C_i \cdot e + D_i, \tag{11}$$

where subscript $i = 0,\ 1,\ 2,\ 3$.

1.1.1 Coefficients	$\boldsymbol{\alpha_i = C_i \cdot e + D_i}$ **$\boldsymbol{i = 0,\ 1,\ 2,\ 3}$**			
	$i = 0$	$i = 1$	$i = 2$	$i = 3$
C_i	0.149	−0.0233	0.0065	0.0114
D_i	1.003	0.3406	0.1104	0.1847

Table 3. Values of empirical coefficients C_i and D_i for Equation (11).

The profiles of the undrained shear strength of Holocene organic soils at the Antoniny site before



a – virgin subsoil; b – after 3rd stage; 9 – relation (9); 10 – relation (10);
PSO – field vane test; CKoU – triaxial test

FIGURE 2. Undrained shear strength of Holocene organic soils at the Antoniny site based on DMT dilatometer tests.

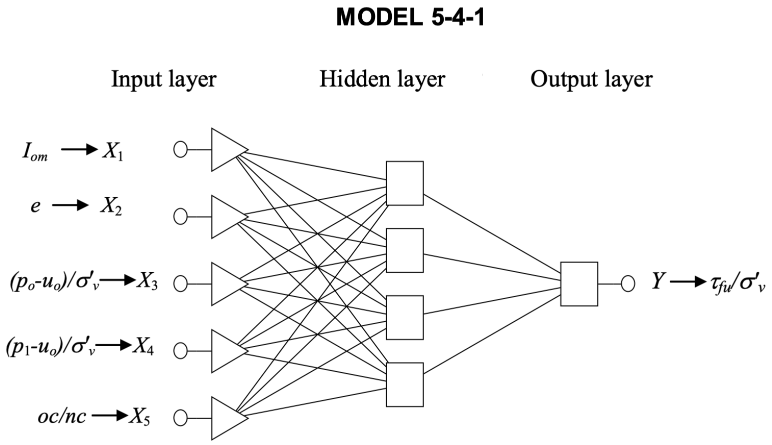


FIGURE 3. Architecture of the two-layer artificial neural network 5–4–1 for the evaluation of undrained shear strength of Holocene organic soils based on DMT dilatometer tests [24].

embankment construction and after the 3$^{\text{rd}}$ embankment stage based on DMT dilatometer tests, using the Equations (9) and (10), are shown in Figure 2. Obtained values of undrained shear strength are compared with the values of corrected undrained shear strength from the field vane tests and the values from CKoU triaxial tests.

The method of evaluating the undrained shear strength of organic soils from DMT dilatometer tests using the Artificial Neural Network was presented by Lechowicz et al. [24] based on the normalized net value of the corrected first pressure reading $(p_0 - u_0)/\sigma'_v$ and the normalized net value of the corrected second pressure reading $(p_1 - u_0)/\sigma'_v$ from dilatometer tests and organic soil properties such as the organic content I_{om}, void ratio e, and a stress history indicator (o_c/n_c). The architecture of the two-layer artificial neural network 5–4–1 for the evaluation of undrained shear strength of Holocene organic soils based on DMT dilatometer tests is shown in Figure 3.

3.2. EEMIAN ORGANIC SOILS

For design of deep excavations supported by diaphragm walls, the evaluation of the undrained shear strength τ_{fu}, the deformation modulus $E_{0.1\%}$ at vertical strain ε_1 of 0.1 % and the initial shear modulus G_0, are needed. The deformation modulus $E_{0.1\%}$ of Eemian organic soils from SDMT seismic dilatometer tests using the dilatometer modulus E_D and the empirical coefficient R_E can be evaluated based on Equation 12 [26]:

$$E_{0.1\%} = R_E \cdot E_D, \tag{12}$$

for Eemian organic mud:

$$R_E = 2.4 + 2.36 \cdot \log K_D, \tag{13}$$

and for Eemian gyttja:

$$R_E = 2.15 + 2.10 \cdot \log K_D. \tag{14}$$

The initial shear modulus G_0 from SDMT seismic dilatometer tests using soil density ρ and shear wave

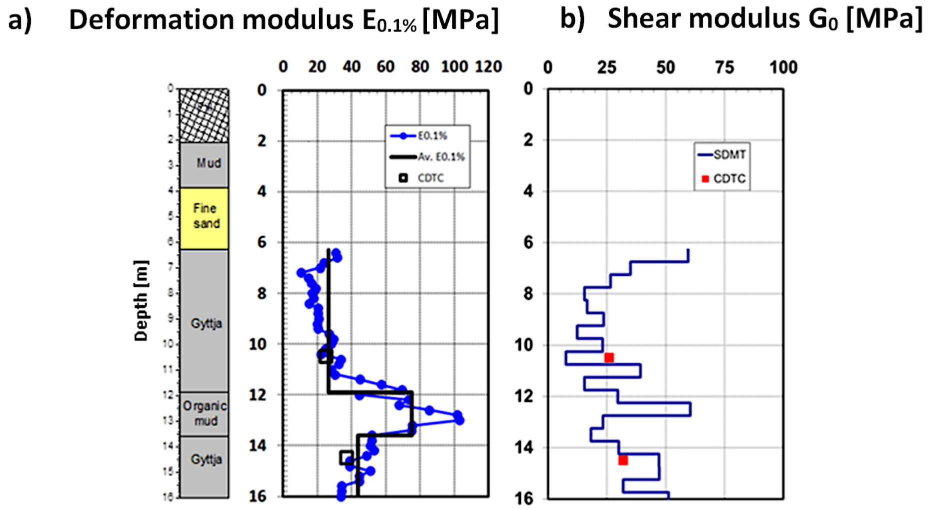


Figure 4. Profiles of the deformation modulus $E_{0.1\%}$ and shear modulus G_0 from SDMT seismic dilatometer tests and the modulus values obtained from triaxial tests C_D with measurements of shear wave velocity V_s for the Eemian gyttja from the Płocka underground station.

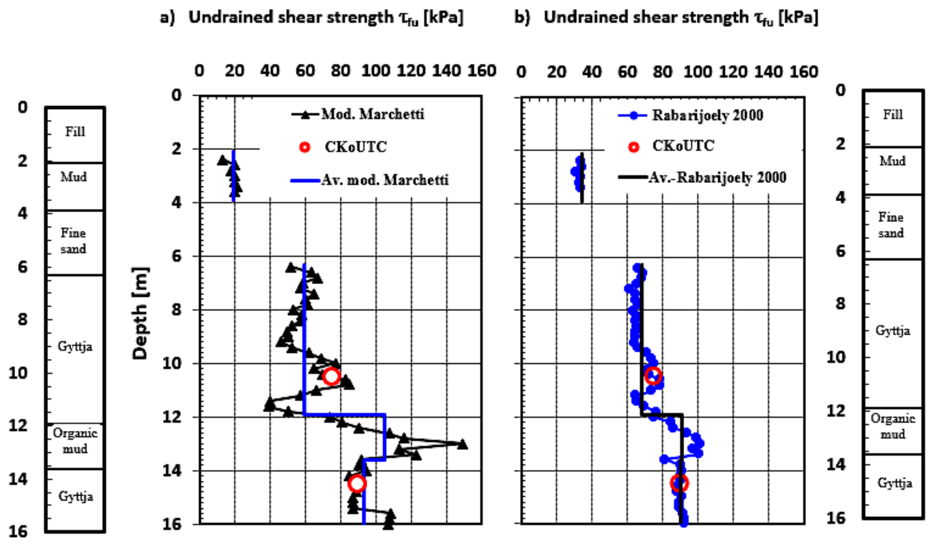


Figure 5. Undrained shear strength profile from DMT dilatometer tests and τ_{fu} values from triaxial tests for the Eemian gyttja from the Płocka underground station.

velocity V_s can be evaluated from the following equation:

$$G_0 = \rho \cdot V_s^2. \tag{15}$$

Figure 4 shows the profiles of the deformation modulus $E_{0.1\%}$ and the initial shear modulus G_0 from SDMT tests and values obtained from the isotropically consolidated drained C_D triaxial tests with shear wave velocity measurements V_s for the Eemian gyttja from the Płocka underground station.

Figure 5 shows the profile of undrained shear strength from anisotropically consolidated undrained CK_0U triaxial tests and from the SDMT test based on the empirical Equation (10). Empirical coefficients for Eemian gytjja are: $\alpha_0 = 1.25$, $\alpha_1 = 0.30$, $\alpha_2 = 0.12$, $\alpha_3 = 0.30$, and for the Eemian organic mud are: $\alpha_0 = 1.12$, $\alpha_1 = 0.13$, $\alpha_2 = 0.10$, $\alpha_3 = 0.44$.

4. Conclusions

The paper presents the problem of evaluating the deformation and strength parameters of Holocene and Eemian organic soils obtained from DMT and SDMT dilatometer tests. Empirical relationships used to evaluate the constrained modulus M^{oc} for the preconsolidated state and the constrained modulus M^{nc} for the normally consolidated state, as well as the recompression index C_r and the compression index C_c of Holocene peat and gyttja, are presented. The evaluation of undrained shear strength τ_{fu} of Holocene peat and gyttja from DMT dilatometer tests based on empirical relationships and the Artificial Neural Network is also shown. The evaluation of undrained shear strength τ_{fu}, deformation modulus $E_{0.1\%}$ and initial shear modulus G_0 of Eemian organic soils from DMT dilatometer tests and SDMT seismic dilatometer tests is then presented. A comparison between the evaluated and obtained values from oedometer tests and triaxial tests shows a good agreement.

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