applied sciences

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Evaluation of the Undrained Shear Strength of Organic Soils from a Dilatometer Test Using Artificial Neural Networks

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Received: 23 July 2018; Accepted: 13 August 2018; Published: 17 August 2018

Abstract: The undrained shear strength of organic soils can be evaluated based on measurements obtained from the dilatometer test using single- and multi-factor empirical correlations presented in the literature. However, the empirical methods may sometimes show relatively high values of maximum relative error. Therefore, a method for evaluating the undrained shear strength of organic soils using artificial neural networks based on data obtained from a dilatometer test and organic soil properties is presented in this study. The presented neural network, with an architecture of 5-4-1, predicts the normalized undrained shear strength based on five independent variables: the normalized net value of a corrected first pressure reading $(p_o - u_o)/\sigma'_v$, the normalized net value of a corrected second pressure reading $(p_1 - u_o)/\sigma'_v$, the organic content I_{om}, the void ratio e, and the stress history indictor (*oc* or *nc*). The neural model presented in this study provided a more reliable prediction of the undrained shear strength in comparison to the empirical methods, with a maximum relative error of ±10%.

Keywords: organic soils; undrained shear strength; dilatometer test; artificial neural networks

1. Introduction

The methodology of a standard dilatometer test (DMT) is widely known and a detailed procedure for conducting the test was presented by Marchetti [1] and Marchetti et al. [2]. Until now, numerous studies have been performed to evaluate and improve some of the original correlations proposed by Marchetti [1], but most of them have been limited to mineral soils. Comprehensive investigations have been made to assess and expand the application of DMT in geotechnical engineering [3–17]. In most cases, the relationships used to evaluate geotechnical parameters from the dilatometer test such as the corrected first reading p_o or corrected second reading p_1, or index parameters such as the material index I_D, horizontal stress index K_D, and dilatometer modulus E_D, are commonly applied.

Undrained shear strength is the basic parameter in the geotechnical design of different structures. Determination of this parameter using dilatometer tests is usually based on empirical formulas. However, it should be noted that most of these formulas have been established in different countries; therefore, regional geotechnical conditions could have substantially affected the empirical relationships and the values of empirical coefficients.

In geotechnical engineering, Artificial Neural Networks (ANNs) have been used to analyse many issues, as reviewed by: Adeli [18], Rafiq et al. [19], Shahin et al. [20,21], Dihoru et al. [22], and

Sulewska [23]. The use of ANNs for the prediction of the lateral earth pressure ratio K_o based on a dilatometer test and undrained shear strength of soft clays was presented by Das and Basudhar [24] and Byeong et al. [25], respectively. However, Artificial Neural Networks have not yet been applied to evaluate the undrained shear strength of organic soils from dilatometer tests.

This paper presents the results of field and laboratory tests of organic soils such as peat (amorphous and pseudo-fibrous), calcareous soil called "gyttja" (calcareous and calcareous-organic), mud, and organic mud. The undrained shear strength of organic soils can be evaluated based on measurements obtained from the dilatometer test using single- and multi-factor empirical correlations presented in the literature. However, the empirical methods may sometimes show relatively high values of maximum relative error. Therefore, a method for evaluating the undrained shear strength of organic soils using artificial neural networks based on data obtained from a dilatometer test and organic soil properties is presented in this study. The presented neural network, with an architecture of 5-4-1, predicts the normalized undrained shear strength based on five independent variables: the normalized net value of a corrected first pressure reading $(p_o - u_o)/\sigma'_v$, the normalized net value of a corrected second pressure reading $(p_1 - u_o)/\sigma'_v$, the organic content I_{om}, the void ratio e, and the stress history indictor (*oc* or *nc*). The neural model presented in this study provided a more reliable prediction of the undrained shear strength in comparison to the empirical methods, with a maximum relative error of ±10%.

2. Methods and Materials

2.1. Dilatometer Test Procedure

The flat dilatometer was developed in Italy by Silvano Marchetti [1,26] as an in situ penetration test. The basic DMT equipment consists of a flat blade-shaped tip, 95 mm wide and 14 mm thick, with a sharp edge, and a 60 mm diameter steel membrane centred on and flushed with one side of the blade. The test procedure involves pushing the blade vertically into the ground with readings at selected test depths. The readings are generally made at every 0.2 m of depth. The first *A*-reading pressure occurs at membrane "lift-off" and the second *B*-reading pressure after 1.1 mm movement, with both movements being prompted by an audio signal [16,27,28]. After appropriate corrections, the values of *A* and *B* yield the values of the corrected first reading p_o (0.00 mm expansion) and the corrected second reading p_1. Based on the corrected readings p_o and p_1, as well as in situ hydrostatic pore pressure u_o and in situ effective vertical stress σ'_{vo}, the following index parameters were proposed by Marchetti [1]:

Material index

$$I_D = (p_1 - p_o)/(p_o - u_o) \tag{1}$$

Horizontal stress index

$$K_D = (p_o - u_o)/\sigma'_v \tag{2}$$

Dilatometer modulus

$$E_D = 34.7 \cdot (p_1 - p_o) \tag{3}$$

2.2. Evaluation of Undrained Shear Strength From DMT

2.2.1. Marchetti Relationship

Marchetti [1] developed a correlation between the normalized undrained shear strength τ_{fu}/σ'_{vo} and the horizontal stress index K_D based on the relationship between the normalized undrained shear strength and the overconsolidation ratio (*OCR*) proposed by Ladd et al. [29] and the correlation of *OCR* and K_D. Marchetti [1] proposed the following basic correlation between the normalized undrained shear strength and the horizontal stress index K_D for cohesive soils (for I_D < 1.2):

$$\frac{\tau_{fu}}{\sigma'_{vo}} = 0.22 \cdot (0.5 \cdot K_D)^{1.25} \tag{4}$$

Analysis of the DMT and the triaxial test results carried out by Lechowicz [30,31] 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 [1] and can be modified as follows:

$$\frac{\tau_{fu}}{\sigma'_{vo}} = S\cdot(0.45\cdot K_D)^{1.20} \tag{5}$$

where $S=(\tau_{fu}/\sigma'_{vo})_{nc}$ is the normalized undrained shear strength for normally consolidated soil. The value of the S parameter for amorphous peat is equal to 0.5, but for calcareous gyttja and calcareous-organic gyttja, it is at 0.40 and 0.45, respectively [32].

2.2.2. Roque et al. Relationship

Roque et al. [33] proposed an alternative approach for estimating the undrained shear strength based on the correlation using the corrected second reading p_1 and the bearing capacity factor N_c:

$$\tau_{fu} = (p_1 - \sigma_{ho})/N_c \tag{6}$$

where σ_{ho} is the in situ horizontal stress, and N_C is the dilatometer factor for clays that varies from about 4 to 7. The value of the bearing capacity factor N_C equals 6 and 7 for gyttja and peat, respectively, and 5 for mud and organic mud [32].

2.2.3. Smith and Houlsby Relationship

Different approaches have been proposed by Smith and Houlsby [34], in which the undrained shear strength was a function of the corrected first reading p_o and the bearing capacity factor N_D:

$$\tau_{fu} = (p_o - \sigma_{ho})/N_D \tag{7}$$

where N_D is the dilatometer factor, which varies from about 4 to 7 for clays, and from about 3 to 4 for peat, gyttja, mud, and organic mud.

2.2.4. Rabarijoely Relationship

A multi-factor relationship was proposed by Rabarijoely [35] to evaluate the undrained shear strength τ_{fu} of organic soils:

$$\tau_{fu} = \alpha_o\cdot\sigma'^{\alpha_1}_{vo}\cdot(p_o - u_o)^{\alpha_2}\cdot(p_1 - u_o)^{\alpha_3} \tag{8}$$

where α_0, α_1, α_2, α_3 are the empirical coefficients. In this relationship, three factors are taken into account: the net value of the corrected first pressure reading ($p_o - u_o$), the net value of the corrected second pressure reading ($p_1 - u_o$), and the effective vertical stress σ'_v. The empirical coefficients in Equation (8) for organic soils can be evaluated as a function of the void ratio e and empirical coefficients C_i and D_i shown in Table 1, according to the following formula:

$$\alpha_i = C_i\cdot e + D_i \tag{9}$$

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

Table 1. Values of empirical coefficients C_i and D_i for Equation (9).

Coefficients	$\alpha_i = C_i \times e + D_i \;\; i = 0, 1, 2, 3$			
	$i = 0$	$i = 1$	$i = 2$	$i = 3$
C_i	0.149	−0.0233	0.0065	0.0114
D_i	1.003	0.3406	0.1104	0.1847

2.3. Characteristics of the Tested Organic Soils

2.3.1. Antoniny Site

The Antoniny test site is located in north-western Poland in the Noteć River valley, where the Department of Geotechnical Engineering of the Warsaw University of Life Sciences in cooperation with the Swedish Geotechnical Institute performed extensive field and laboratory investigations in the 1980s [36,37]. Two test embankments (with and without vertical drains) were constructed in three stages between 1983 and 1987. The fill without vertical drains was then brought to failure by successively increasing the height of the fill. The field investigations included dilatometer tests and field vane tests (FVT).

At this site, the virgin organic subsoil, 7.8 m thick, consists of a 3.1 m thick peat layer and a 4.7 m gyttja layer. Based on the index properties, the peat layer was sub-divided into two layers: the first one being pseudo-fibrous peat, occurring from the surface to the depth of 1.0 m, and the second one being amorphous peat, occurring below 1.0 m to the depth of 3.1 m. The gyttja layer was sub-divided into three layers, with the first being calcareous-organic gyttja occurring from the depth of 3.1 m to 4.5 m and the second and third layer being calcareous gyttja occurring from the depth of 4.5 m to 6.8 m and below the depth of 6.8 m, respectively. The organic subsoil is underlined by a sand layer. Organic soils are overconsolidated with an overconsolidation ratio, *OCR*, decreasing from 5 to 2 with depth. The results of the index properties of organic soils are summarised in Table 2. Soil profiles of organic subsoil at the Antoniny site for overconsolidated subsoil (*oc*) and normally consolidated subsoil (*nc*) are shown in Figure 1.

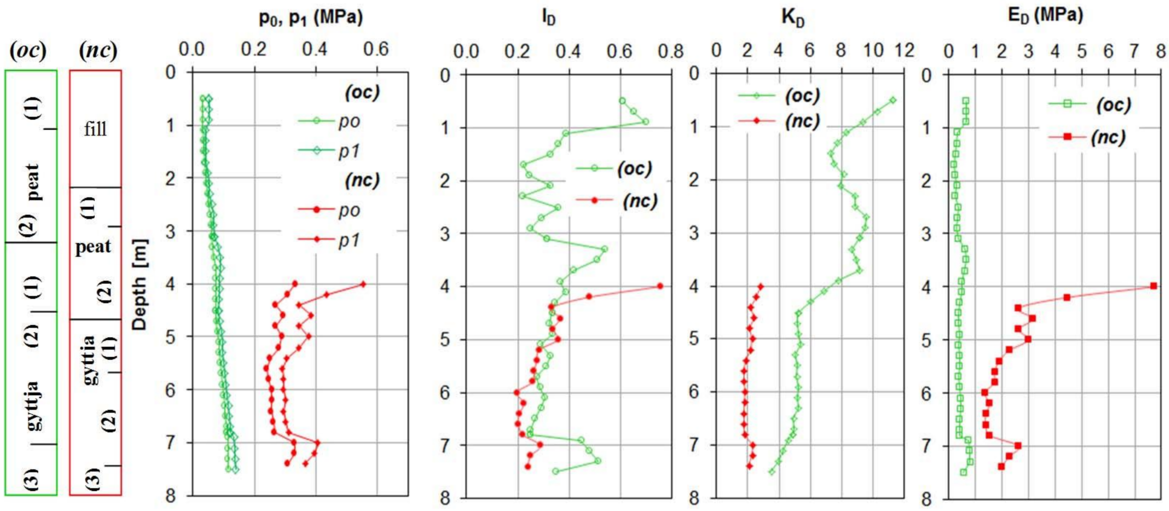


Figure 1. Profiles of the corrected readings p_o and p_1 and index parameters I_D, K_D, and E_D from dilatometer tests obtained for organic subsoil at the Antoniny site; (*oc*): overconsolidated subsoil, (*nc*): normally consolidated subsoil.

Table 2. Index properties of organic soils at the Antoniny site.

Properties	Peat		Gyttja		
	(1)	(2)	Calcareous-Organic (1)	Calcareous (2)	Calcareous (3)
Thickness (m)	0–1.0	1.0–3.1	3.1–4.5	4.5–6.8	6.8–7.8
Water content w_n (%)	420–450	310–340	130–140	105–110	110–115
Bulk density ρ (t/m^3)	1.05–1.1	1.05–1.1	1.25–1.30	1.35–1.40	1.40–1.45
Specific density ρ_s (t/m^3)	1.4	1.45	2.2	2.3	2.4
Liquid limit w_L (%)	450	305–310	100–110	80–90	90–100
Organic content I_{om} (%)	80–85	65–75	15–20	8–10	5–7
$CaCO_3$ content (%)	5–10	10–15	65–75	80–85	85–90

2.3.2. Koszyce site

The Koszyce test site is located in north-western Poland in the Ruda River valley, where a laboratory and field testing program was performed below and outside of the main dam embankment of the Koszyce reservoir [38]. Due to the presence of deep soft organic subsoil, the dam embankment was constructed as a reinforcement mattress. At the Koszyce site, the central part of the dam embankment is founded on organic subsoil with a variable thickness. The soft subsoil consists of organic sediments with a thickness ranging from 4 to 27 m. The uppermost 2.5 m consists of peat. Below the peat layer, there is a layer of calcareous soil called gyttja with a thickness ranging from 2 to 25 m, divided into four sub-layers. The organic subsoil is underlined by a fine sand layer. The field investigations included dilatometer tests and field vane tests (FVT). The index properties of the initial state of organic soils are summarised in Table 3. Soil profiles of organic subsoil at the Koszyce site for overconsolidated subsoil (*oc*) and normally consolidated subsoil (*nc*) are shown in Figure 2.

Table 3. Index properties of organic soils at the Koszyce site.

Properties	Peat	Gyttja			
	(1)	Calcareous-Organic (1)	Calcareous (2)	Calcareous (3)	Calcareous (4)
Thickness (m)	2.5	2.5–6.0	2.0–5.0	3.0–5.0	5.0–15.0
Water content w_n (%)	400–500	150–160	105–115	120	105–110
Bulk density ρ (t/m^3)	1.03–1.05	1.20–1.25	1.35–1.40	1.40	1.45
Specific density ρ_s (t/m^3)	1.45	2.10	2.25	2.20	2.30
Liquid limit w_L (%)	450	100–110	80–95	95–100	80–90
Organic content I_{om} (%)	80–85	15–20	8–10	10–12	6–8
$CaCO_3$ content (%)	5–10	65–70	75–80	70–75	75–80

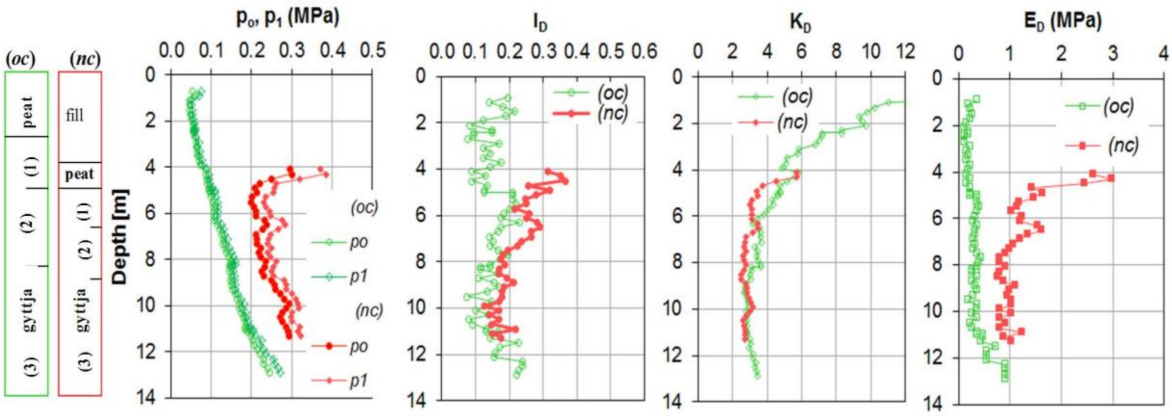


Figure 2. Profiles of the corrected readings p_o and p_1 and index parameters I_D, K_D, and E_D from dilatometer tests obtained for organic subsoil at the Koszyce site; (*oc*): overconsolidated subsoil, (*nc*): normally consolidated subsoil.

2.3.3. Nielisz Site

The Nielisz test site is located in south-eastern Poland in the Wieprz River valley where an extensive testing program was performed between 1994 and 1996 [32,35,39], which included laboratory tests and in situ tests such as dilatometer tests and field vane tests (FVT). Due to the appearance of soft soils, the main dam embankment of the Nielisz reservoir was constructed in stages, utilising the increase in shear strength due to consolidation. The main dam embankment was constructed in two stages with preloading fills.

At the Nielisz site, the soft subsoil consists of mineral and organic sediments. The original thickness of soft soils at the site varied from 1.0 to 5.0 m. The upper 0.5–1.0 m mainly consists of sandy silt or silt. Further below, there is a layer of mud or organic mud with a thickness of 1.0–4.0 m, divided into two parts by a layer of silt. A fine sand layer occurs below soft subsoil. The results of the index properties of organic soils are summarised in Table 4. Soil profiles of organic subsoil at the Nielisz site for overconsolidated subsoil (*oc*) and normally consolidated subsoil (*nc*) are shown in Figure 3.

Table 4. Index properties of organic soils at the Nielisz site.

Properties	Organic Mud	Mud
Water content w_n (%)	120–200	65–120
Bulk density ρ (t/m^3)	1.2–1.3	1.3–1.5
Specific density ρ_s (t/m^3)	2.1–2.3	2.3–2.5
Liquid limit w_L (%)	130–220	70–130
Organic content I_{om} (%)	21–35	8–20

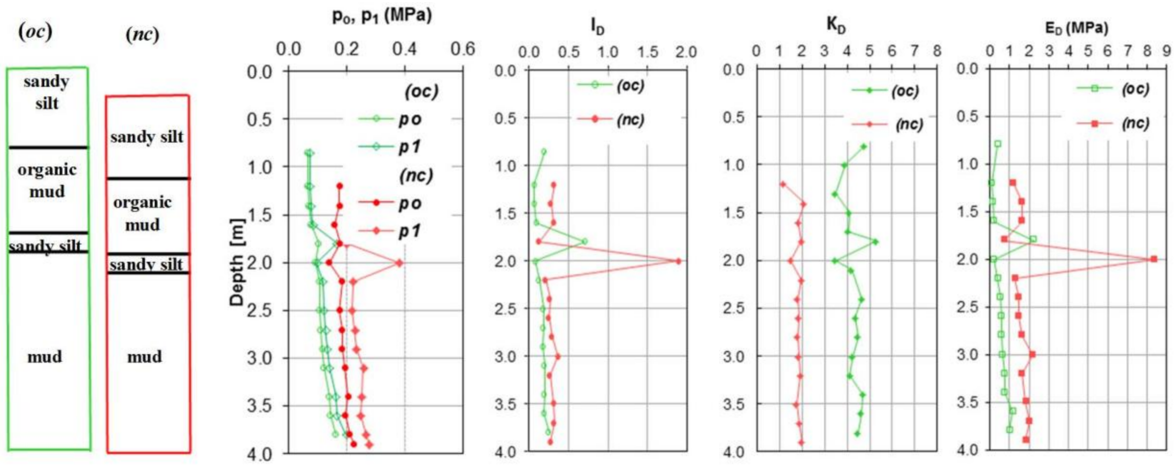


Figure 3. Profiles of the corrected readings p_o and p_1 and index parameters I_D, K_D, and E_D from dilatometer tests obtained for organic subsoil at the Nielisz site; (*oc*): overconsolidated subsoil, (*nc*): normally consolidated subsoil.

3. Results

3.1. Results of Dilatometer Tests

The DMT data profiles including the corrected readings p_o and p_1, as well as the index parameters I_D, K_D, and E_D from dilatometer tests obtained for the overconsolidated subsoil and for normally consolidated organic subsoil at the Antoniny, Koszyce, and Nielisz sites, respectively, are presented in Figures 1–3.

3.2. Results of Field Vane Tests

The shear strength of the organic soils at the Antoniny, Koszyce, and Nielisz sites was measured by the field vane test (FVT). In order to evaluate the undrained shear strength τ_{fu} of organic soils from FVT, the measured shear strength τ_{fv} has to be corrected by using the correction factor μ according to Bjerrum [40]:

$$\tau_{fu} = \mu \cdot \tau_{fv} \tag{10}$$

The correction factors for the organic soils from the Antoniny site were evaluated according to the method elaborated by the Swedish Geotechnical Institute (SGI) [41] based on the liquid limit w_L, and also by the average correction factors determined from the following laboratory tests: triaxial compression, triaxial extension, and direct simple shear (Table 5).

Table 5. Correction factors for field vane tests obtained at the Antoniny site.

Type of Soil	$\mu(w_L)$	$\mu(lab)$
peat (1.0–3.1 m)	0.50	0.51
gyttja 1 (3.1–4.5 m)	0.70	0.56
gyttja 2 and 3 (4.5–7.8 m)	0.80	0.61

For organic soils from the Koszyce site, the correction factors for peat, gyttja (calcareous-organic), and gyttja (calcareous), evaluated according to the SGI method based on the liquid limit w_L, were $\mu(w_L) = 0.5$, $\mu(w_L) = 0.65$, and $\mu(w_L) = 0.75$, respectively. For organic mud and mud from the Nielisz site, the correction factors evaluated according to the SGI method based on the liquid limit w_L were: $\mu(w_L) = 0.6$ and $\mu(w_L) = 0.65$, respectively.

Shown in Table 6 are the values of the undrained shear strength τ'_{fv} of organic soils obtained from FVT using the corrected value of measured shear strength τ'_{fv}.

Table 6. Summary of calculated maximum relative error max *RE* of the evaluated undrained shear strength τ_{fu} for organic soils from Antoniny, Koszyce, and Nielisz sites.

Sites		Soil Type	Maximum Relative Error Max *RE* of Evaluated Undrained Shear Strength τ_{fu} (kPa) for:				
			Single-Factor Relationships by				Multi-Factor Relationship by
			Marchetti [1] Equation (4)	Modified Marchetti Lechowicz [30,31] Equation (5)	Roque et al. [33] Equation (6)	Smith and Houlsby [34] Equation (7)	Rabarijoely [35] Equations (8) and (9)
			max *RE* (%)	max *RE* (%)	max *RE* (%)	max *RE* (%)	max *RE* (%)
Antoniny	*oc*	peat	56.9	19.2	19.0	47.0	13.4
		gyttja [1]	48.4	20.3	40.6	31.3	12.1
		gyttja [2]	42.3	12.1	31.3	13.0	10.3
	nc	peat	49.9	35.1	50.9	8.0	9.5
		gyttja [1]	29.9	23.4	14.0	19.4	10.6
		gyttja [2]	27.6	22.1	31.5	25.1	12.0
Koszyce	*oc*	peat	58.7	24.0	28.4	25.3	0.9
		gyttja [1]	50.0	14.0	19.4	8.0	7.7
		gyttja [2]	47.7	18.6	20.3	7.4	7.2
	nc	peat	47.5	25.3	23.9	22.2	2.9
		gyttja [1]	40.6	13.8	7.2	8.6	7.8
		gyttja [2]	38.8	3.3	14.5	4.8	9.5
Nielisz	*oc*	organic mud	50.7	10.4	13.5	17.0	-
		mud	48.8	43.1	21.5	14.0	-
	nc	organic mud	48.4	6.2	17.5	16.0	-
		mud	50.8	10.5	7.7	12.0	-

[1] calcarous–organic; [2] calcareous.

4. Evaluation of the Undrained Shear Strength Based on Empirical Relationships

Evaluation of the undrained shear strength τ'_{fu} of overconsolidated and normally consolidated organic soils from dilatometer tests was carried out on the basis of single- and multi-factor empirical relationships proposed by Marchetti [1], Lechowicz [30,31], Roque et al. [33], and Smith and Houlsby [34], as well as the three-factor relationship of Rabarijoely [35] using Equations (4)–(8), and empirical coefficients determined on the basis of the void ratio e from Equation (9). In order to compare the undrained shear strength evaluated based on empirical relationships with undrained shear strength obtained from field vane tests, the measurements from dilatometer tests were taken from the same depth where FVT was carried out.

For each relationship, the maximum relative error max *RE* (Table 6) for particular organic soil was selected from values of the relative errors *RE* calculated according to the formula:

$$RE = \left| \left(d^{(p)} - y^{(p)} \right) / d^{(p)} \right| \cdot 100\%, \quad (11)$$

where P is the number of cases, $p \in \{1, \ldots, P\}$, $d^{(p)}$ is the measured value, and $y^{(p)}$ is the calculated value.

Analysis of the calculation results indicates quite high maximum relative error values obtained for the undrained shear strength evaluated on the basis of the single-factor empirical relationship of Marchetti ranging between 47.5–58.7% for peat, 27.6–50.0% for gyttja, and 48.4–50.8% for mud. The max *RE* values calculated for undrained shear strength evaluated from the Roque et al. relationship with the bearing capacity factor N_c determined for organic soils are smaller, and range between 19.0–50.9% for peat, 7.2–40.6% for gyttja, and 7.7–21.5% for mud. The max *RE* values calculated for undrained shear strength evaluated from the Smith and Houlsby relationship with the bearing capacity factor N_D determined for organic soils are slightly smaller, and range between 8.0–47.0% for peat, 4.8–31.3% for gyttja, and 12.0–17.0% for mud. The comparison carried out for the version of the Marchetti relationship modified by Lechowicz for organic soils indicates that the max *RE* values obtained for the undrained shear strength of organic soils for the Antoniny, Koszyce, and Nielisz sites vary between 3.3 and 35.1%.

The comparison carried out for the three-factor relationship of Rabarijoely, from which the empirical coefficients were determined on the basis of the void ratio, indicates much smaller max *RE* values of the undrained shear strength for peat at 0.9–13.4% and for gyttja at 7.2–12.1%. This shows that the evaluation of the undrained shear strength from dilatometer tests for the tested peat and gyttja from the three-factor relationship of Rabarijoely results in a better accuracy; however, it requires the use of empirical coefficients individually determined on the basis of the void ratio. In the case of mud and organic mud, the evaluation of the undrained shear strength from the dilatometer test using the Rabarijoely relationship (Equation (8)) requires additional determination of the empirical coefficients α_0, α_1, α_2, α_3.

5. Artificial Neural Networks Analysis

5.1. Determination of the Architecture of the Neural Network

The class of neural network used in this study includes multilayer perceptrons (MLPs) with one hidden layer. The architecture of the *N-H-M* type network is defined by the number of nodes N in the input layer X_1–X_N, the number of nodes H in one hidden layer, and the number of nodes $M = Y$ in the output layer. Neural networks were constructed according to the criterion of minimization of the error function, which was the sum of squares of differences (*SOS*) expressed by the formula:

$$E_{SOS} = \sum_{p=1}^{P} \left(d^{(p)} - y^{(p)} \right)^2 \quad (12)$$

where P is the number of cases of the set P, $p \in \{1, \ldots, P\}$, $d^{(p)}$ represents the measured values, and $y^{(p)}$ represents the corresponding values predicted from neural networks.

5.2. Database Used in the Development of the ANN Method

The dataset used in the ANN analysis consisted of $n = 88$ cases of results of index properties tests (organic content and void ratio) and results of dilatometer tests and stress history indicators (*oc* or *nc*) as independent variables and as dependent variables of normalized undrained shear strength from field vane tests shown in Table 7. The dataset was described by five independent variables: X_1 = organic content $I_{om} \in \{8\text{–}85\%\}$; X_2 = void ratio $e \in \{1.9\text{–}7.4\}$; X_3 = normalized net value of corrected first pressure reading $(p_o - u_o)/\sigma'_v \in \{1.41\text{–}20.0\}$; X_4 = normalized net value of corrected second pressure reading $(p_1 - u_o)/\sigma'_v \in \{1.87–27.35\}$; X_5 = code of overconsolidated state (*oc*) or normally consolidated state (*nc*), respectively $\in \{0; 1\}$, and one dependent variable $Y = \tau_{fu}/\sigma'_v \in \{0.26–5.00\}$. Variable X_3 is the same as the horizontal stress index K_D. Variable X_5 was treated as a quantitative variable since it was a zero-one variable [42].

Sensitivity analysis of the Neural Network was performed based on the network error quotient, with one of the input variables for the basic error of the network calculated for the neural network having all input variables. A larger ratio of errors in the absence of a given input variable means that a larger error is created in the neural network devoid of this input variable. This indicates how the variable is important in the model. In the proposed neural network, the relevant importance of input variables is: X_5 = *oc* or *nc* (with Ratio = 9.73), $X_3 = (p_o - u_o)/\sigma'_v$, (with Ratio = 9.62), $X_4 = (p_1 - u_o)/\sigma'_v$, (with Ratio = 5.04), $X_2 = e$ (with Ratio = 3.29), and $X_1 = I_{om}$ (with Ratio = 2.28).

Table 7. Summary of input and output values for the ANN analysis.

Site	Soil Type	I_{om}(%) X_1	e(-) X_2	σ'_v (kPa)	u_0 (kPa)	p_0 (kPa)	$(p_0 - u_0)/\sigma'_v$ (-) X_3	p_1 (kPa)	$(p_1 - u_0)/\sigma'_v$(-) X_4	Stress History *oc* or *nc* X_5	τ_{fu} (from FVT) (kPa)	τ_{fu}/σ'_v (from FVT) (-) Y
Antoniny	peat	75	4.8	2.9	8.9	32.6	8.29	42.0	11.61	*oc*	7.2	2.52
		70	3.6	3.2	23.6	51.5	8.86	62.0	12.19	*oc*	7.8	2.48
		65	3.1	3.4	30.4	61.5	9.14	72.0	12.23	*oc*	8.2	2.41
		75	3.6	99.5	37.0	308.0	2.72	436.1	4.01	*nc*	46.0	0.46
		75	3.6	100.3	41.0	295.0	2.53	386.4	3.44	*nc*	42.3	0.42
		75	3.6	104.9	38.0	333.0	2.81	555.6	4.93	*nc*	39.2	0.37
		75	3.6	105.3	42.0	270.0	2.17	345.6	2.88	*nc*	40.6	0.39
		70	3.2	105.7	46.0	270.0	2.12	345.6	2.83	*nc*	39.1	0.37
Antoniny	gyttja calcareous -organic	20	3.3	3.8	35.2	69.1	8.91	88.0	13.89	*oc*	7.3	1.32
		15	3.1	4.5	42.3	73.4	6.87	87.0	9.89	*oc*	7.0	1.22
		15	3.1	5.1	46.9	73.5	5.21	84.0	7.27	*oc*	7.4	1.21
		20	2.7	106.4	48.0	290.0	2.27	376.1	3.08	*nc*	7.6	1.15
		20	2.7	107.1	50.0	281.0	2.16	346.1	2.76	*nc*	29.2	0.27
		20	2.6	113.6	68.0	330.0	2.31	405.6	2.97	*nc*	29.3	0.27
		20	2.6	115.0	72.0	309.0	2.06	365.7	2.55	*nc*	29.3	0.26
Antoniny	Gyttja calcareous	10	2.7	5.5	54.8	84.5	5.40	95.0	7.31	*oc*	7.3	1.32
		10	2.6	5.7	60.1	89.5	5.14	101.0	7.17	*oc*	7.0	1.22
		10	2.6	6.1	68.0	99.4	5.15	112.0	7.21	*oc*	7.4	1.21
		8	2.6	6.6	73.0	105.5	4.91	117.0	6.66	*oc*	7.6	1.15
		10	2.2	108.5	54.0	242.0	1.73	291.4	2.19	*nc*	29.2	0.27
		10	2.2	110.0	58.0	257.0	1.81	295.9	2.16	*nc*	29.3	0.27
		10	2.2	111.4	62.0	256.0	1.74	295.9	2.10	*nc*	29.3	0.26
		8	2.2	112.9	66.0	267.0	1.78	311.1	2.17	*nc*	30.4	0.27
Koszyce	peat	85	7.4	3.3	6.0	60.0	16.36	71.0	19.70	*oc*	15.0	4.54
		85	7.4	3.5	12.0	46.0	9.86	53.0	11.88	*oc*	12.2	3.54
		85	7.1	42.7	58.0	250.0	4.50	320.0	6.14	*nc*	39.6	0.93
		85	7.1	43.1	62.0	209.0	3.41	256.0	4.50	*nc*	35.1	0.82
		85	7.4	3.4	12.0	80.0	20.00	105.0	27.35	*oc*	17.0	5.00
		85	7.4	4.2	20.0	75.0	13.10	95.0	17.86	*oc*	16.1	3.82
		85	7.0	57.3	61.0	234.0	3.02	285.0	3.91	*nc*	39.5	0.69
		85	7.0	58.9	70.0	250.0	3.06	280.0	3.57	*nc*	38.7	0.66
		80	4.5	106.6	55.0	253.0	1.86	310.0	2.39	*nc*	49.1	0.46
		80	4.5	105.6	45.0	242.0	1.87	330.0	2.70	*nc*	50.3	0.48
		80	6.2	28.2	47.0	113.0	2.34	135.0	3.12	*oc*	24.3	0.86
		80	6.6	5.5	23.0	84.0	11.09	105.0	14.91	*oc*	17.3	3.14
		80	6.6	4.0	7.0	44.0	9.25	62.0	13.75	*oc*	13.5	3.38
		80	6.6	4.5	12.0	65.0	11.78	78.0	14.67	*oc*	15.3	3.39

Table 7. *Cont.*

Site	Soil Type	I_{om}(%) X_1	e(-) X_2	σ'_v (kPa)	u_0 (kPa)	p_0 (kPa)	$(p_0 - u_0)/\sigma'_v$ (-) X_3	p_1 (kPa)	$(p_1 - u_0)/\sigma'_v$(-) X_4	Stress History *oc* or *nc* X_5	τ_{fu} (from FVT) (kPa)	τ_{fu}/σ'_v (from FVT) (-) Y
Koszyce	gyttja calcareous -organic	20	3.2	4.6	22.0	55.0	7.17	58.2	7.86	*oc*	8.3	1.81
		20	3.2	6.6	32.0	66.0	5.15	70.2	5.79	*oc*	9.4	1.42
		20	3.2	9.1	42.0	89.0	5.16	93.2	5.63	*oc*	11.3	1.25
		20	2.9	43.7	68.0	197.0	2.95	230.0	3.71	*nc*	25.5	0.58
		20	2.9	44.6	74.0	211.0	3.07	246.0	3.86	*nc*	26.1	0.59
		20	2.9	46.6	82.0	211.0	2.77	246.0	3.52	*nc*	26.0	0.56
		20	3.2	7.0	32.0	70.0	5.43	85.0	7.57	*oc*	10.5	1.50
		20	3.2	9.0	42.0	86.0	4.89	92.0	5.56	*oc*	11.2	1.24
		20	3.2	12.0	52.0	97.0	3.75	110.0	4.83	*oc*	12.4	1.03
		20	2.8	60.2	75.0	235.0	2.66	260.0	3.07	*nc*	29.5	0.49
		20	2.8	61.0	80.0	225.0	2.38	255.0	2.87	*nc*	29.5	0.48
		20	2.7	77.9	70.0	180.0	1.41	216.0	1.87	*nc*	28.5	0.37
Koszyce	gyttja calcareous	10	2.7	12.1	53.0	104.0	4.30	115.6	5.25	*oc*	12.4	1.02
		10	2.7	15.1	62.0	116.0	3.58	125.5	4.20	*oc*	13.0	0.86
		10	2.7	18.1	72.0	135.0	3.48	145.5	4.06	*oc*	14.5	0.80
		10	2.5	49.7	92.0	223.0	2.64	246.0	3.10	*nc*	25.2	0.51
		10	2.5	53.2	102.0	249.0	2.76	281.0	3.36	*nc*	27.1	0.51
		10	2.7	15.0	62.0	110.0	3.20	125.0	4.20	*oc*	13.0	0.87
		10	2.7	18.0	72.0	130.0	3.22	145.0	4.06	*oc*	14.2	0.79
		10	2.4	66.0	95.0	254.0	2.41	290.0	2.95	*nc*	29.6	0.45
		10	2.4	67.5	100.0	250.0	2.22	275.0	2.59	*nc*	28.9	0.43
		10	2.7	25.3	127.0	204.0	3.04	222.0	3.75	*oc*	17.5	0.69
		10	2.5	70.5	110.0	270.0	2.27	290.0	2.55	*nc*	30.3	0.43
Nielisz	mud organic	20	3.2	32.0	3.0	74.8	2.24	80.0	2.41	*oc*	17.9	0.56
		20	3.2	35.0	9.0	84.3	2.15	100.0	2.60	*oc*	20.4	0.58
		20	3.2	13.0	3.0	65.0	4.77	72.0	5.31	*oc*	16.1	1.24
		20	3.2	16.0	10.0	74.7	4.04	81.0	4.44	*oc*	16.5	1.03
		20	2.6	74.1	18.0	175.0	2.12	196.0	2.40	*nc*	34.0	0.46
		20	2.8	51.0	19.0	186.0	3.27	250.0	4.53	*nc*	39.0	0.76
		20	3.2	18.4	7.0	79.3	3.94	94.0	4.74	*oc*	18.3	1.00
		20	3.2	24.1	13.0	89.3	3.17	104.0	3.78	*oc*	19.5	0.81
		20	2.8	48.0	19.0	165.0	3.04	248.0	4.77	*nc*	38.2	0.80
		20	2.8	49.0	21.0	155.0	2.73	233.0	4.33	*nc*	36.5	0.74
		20	2.8	52.0	25.0	244.0	4.21	348.0	6.21	*nc*	49.0	0.94
		20	2.8	54.0	27.0	235.0	3.85	313.0	5.30	*nc*	45.5	0.84
		20	3.2	76.5	13.0	188.0	2.29	223.0	2.75	*oc*	39.4	0.51
		20	2.3	116.0	38.0	282.0	2.10	426.0	3.34	*nc*	60.0	0.52

Table 7. *Cont.*

Site	Soil Type	I_{om}(%) X_1	e(-) X_2	σ'_v (kPa)	u_0 (kPa)	p_0 (kPa)	$(p_0 - u_0)/\sigma'_v$ (-) X_3	p_1 (kPa)	$(p_1 - u_0)/\sigma'_v$(-) X_4	Stress History *oc* or *nc* X_5	τ_{fu} (from FVT) (kPa)	τ_{fu}/σ'_v (from FVT) (-) Y
Nielisz	mud	10	2.4	19.0	16.0	105.0	4.68	121.0	5.53	*oc*	19.6	1.03
		10	2.4	21.0	20.0	109.2	4.25	126.0	5.05	*oc*	20.8	0.99
		10	2.4	23.0	24.0	119.1	4.13	138.0	4.96	*oc*	21.2	0.92
		10	2.4	25.0	28.0	114.0	3.44	166.0	5.52	*oc*	23.4	0.93
		10	2.0	79.0	25.0	184.0	2.01	226.0	2.54	*nc*	34.0	0.43
		10	2.0	81.8	29.0	193.0	2.00	256.0	2.78	*nc*	36.0	0.44
		10	2.0	71.0	51.0	255.0	2.87	348.0	4.18	*nc*	40.9	0.58
		10	1.9	111.3	32.0	313.0	2.52	449.0	3.75	*nc*	52.0	0.47
		10	1.9	111.5	38.0	281.0	2.18	459.0	3.78	*nc*	51.0	0.46
		10	1.9	116.0	38.0	282.0	2.10	426.0	3.34	*nc*	50.0	0.43
		10	1.9	119.0	42.0	262.0	1.85	416.0	3.14	*nc*	48.5	0.41
		10	1.9	120.5	44.0	254.0	1.74	356.0	2.59	*nc*	44.5	0.37
		10	2.4	38.8	35.0	186.0	3.89	269.0	6.03	*oc*	32.5	0.84
		10	2.4	31.6	7.0	99.6	2.93	109.0	3.23	*oc*	21.0	0.67

5.3. Training and Testing

The quality of prediction of the neural regression model was evaluated on the basis of error analysis, calculated independently for the following subsets: learning *L*, testing *T*, and validation *V*. Neural networks were optimized for the number of neurons in the hidden layer, the activation function in the neurons of the hidden layer and the output layer, and the learning method. The Broyden-Fletcher-Goldfarb-Shanno algorithm (BFGS) was chosen for network learning. An early-stopping method of training was used [43]. Learning was stopped after 108 learning cycles (epochs). The subsets of learning *L*, testing *T* for periodic checking of the generalizability acquired by the network, and validation *V* for the final evaluation of the trained neural network, were randomly assigned to 75%, 15%, and 15% of the data set, respectively. Neural networks with the best predictive quality were determined on the basis of the highest values of determination coefficients R^2, the lowest mean values of relative errors *RE* according to Equation (11) [43], and the lowest values of mean squared errors *MSE* according to the formula:

$$MSE = \frac{1}{P}\sum_{p=1}^{P}\left(d_i^{(p)} - y_i^{(p)}\right)^2 \quad (13)$$

Based on the analysis of many neural networks, a neural network of 5-4-1 was selected (Figure 4). Activation functions have been identified: hidden neurons-logistic function (binary sigmoid) and output neuron-exponential function (with a negative exponent). The prediction errors in the subsets *L*, *T*, and *V* are presented in Table 8.

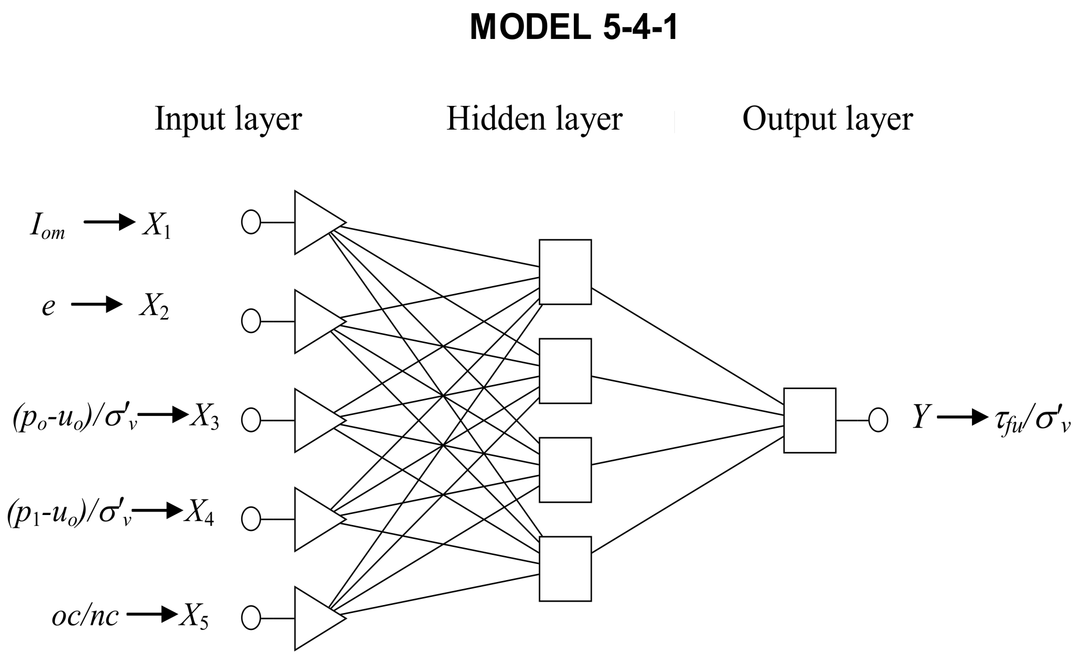


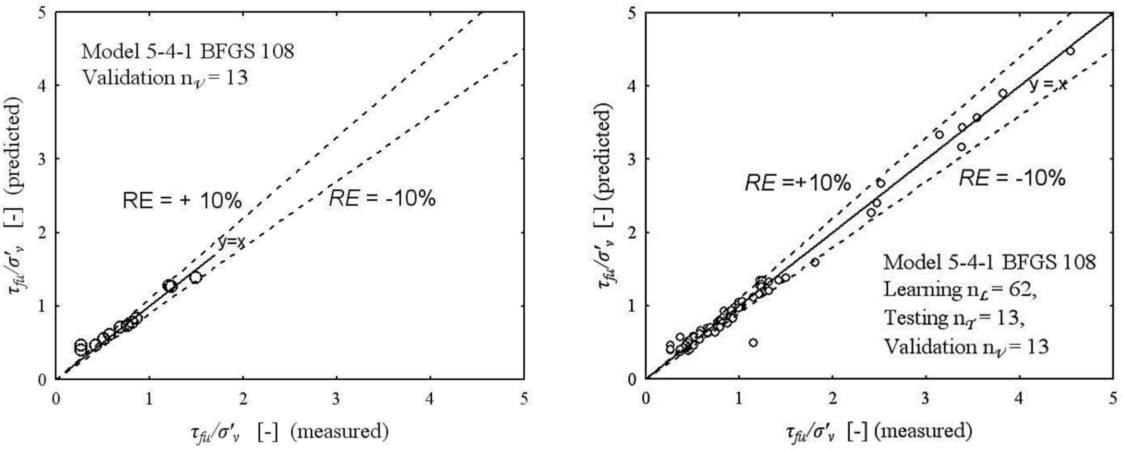
Figure 4. Architecture of the two-layer artificial neural network 5-4-1.

Table 8. Measures of network errors 5-4-1 BFGS 108 in the subsets *L*, *T*, and *V*.

Measures of Errors	Subset *L*	Subset *T*	Subset *V*
R^2	0.990	0.982	0.968
MSE	0.0058	0.0068	0.0352

5.4. Evaluation of the Undrained Shear Strength Using a Neural Network

The trained neural network 5-4-1 was tested by applying it for the prediction of the normalized undrained shear strength τ_{fu}/σ'_v of organic soils based on data from subset validation *V* and on all data. The accuracy of the prediction using the developed network is illustrated by a graph of the dependence of the measured τ_{fu}/σ'_v values and τ_{fu}/σ'_v values predicted by the neural network (Figure 5). The maximum relative prediction error of the network 5-4-1 of normalized undrained shear strength τ_{fu}/σ'_v based on the data subset *V* and all data is approximately max *RE* = ±10%.



(**a**) (**b**)

Figure 5. Relative error *RE*: (**a**) in the data subset *V*, (**b**) in the whole data set.

6. Conclusions

The analysis carried out for the tested organic soils indicates quite high values of the maximum relative error max *RE* for the evaluated undrained shear strength τ_{fu} from the dilatometer test on the basis of single-factor empirical relationships: Marchetti, Roque et al., Smith and Houlsby, and the Marchetti relationship modified by Lechowicz. It shows that the evaluation of the undrained shear strength τ_{fu} from a dilatometer test for the tested peat and gyttja from the three-factor relationship of Rabarijoely presents a better accuracy; however, it requires the use of empirical coefficients individually determined on the basis of the void ratio.

The normalized undrained shear strength τ_{fu}/σ'_v of organic soils from the dilatometer test can be predicted using the neural model 5-4-1 based on measurements from the dilatometer test as the normalized net value of a corrected first pressure reading $(p_o - u_o)/\sigma'_v$ and the normalized net value of a corrected second pressure reading $(p_1 - u_o)/\sigma'_v$, and organic soil properties as the organic content I_{om}, void ratio *e* and the stress history indicator (*oc* or *nc*). A neural model 5-4-1 with values within the data range provides a prediction of relative variable values, with a maximum relative error of approximately ±10%. Further research is needed for organic soils with a higher variability of the organic content I_{om}, void ratio *e*, and stress history to extend the proposed neural network by these variables.

Author Contributions: Z.L. and S.R. prepared the research program, performed in situ tests, analysed the test results, and prepared the manuscript. M.F. analysed the test results and prepared the manuscript. M.J.S. performed Artificial Neural Network analysis and prepared the manuscript.

Acknowledgments: This work was carried out in cooperation with the partners from the Warsaw University of Life Sciences, Poland, and the Tokai University, Japan, and between 2017–2018 at the Warsaw University of Life Sciences—SGGW and the Bialystok University of Technology, it was supported by the Polish Ministry of Science and Higher Education.

Conflicts of Interest: The authors declare no conflict of interest.

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