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Studia Geotechnica et Mechanica, 2019; 41(3); 143–150

Research Article

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Effective Friction Angle Of Deltaic Soils In The Vistula Marshlands

https://doi.org/10.2478/sgem-2019-0016
received January 28, 2019; accepted May 29, 2019.

Abstract: This article presents the results of laboratory tests on soft, normally consolidated soils from the Vistula Marshlands. Samples of high-plasticity organic soils (muds) taken from 3.2–4.0 m and 9.5–10.0 m depth, as well as peat deposit at 14.0 m, are analysed. Presented case study confirms the applicability of the Norwegian Institute of Technology (NTH) method based on Cone Penetration Tests (CPTU) and allows for a conservative estimation of effective friction angle for muds. The plastification angle equal to 14.5° for organic silt, applied in the modified NTH method, fits well the triaxial test (TX) results. Moreover, the dilative-contractive behaviour according to the CPTU soil classification based on the Robertson's proposal from 2016 corresponds well with volumetric changes observed in the consolidated drained triaxial compression tests. The internal friction angles of the Vistula Marshlands' muds and peats are lower in comparison with the database of similar soft soils.

Keywords: Angle of internal friction; CPTU; triaxial testing; soft soils; peat.

1 Introduction

1.1 Aim of research

This research is focused on effective angle of internal friction and compares the results for the Vistula Marshlands muds and peats with similar soft soils. Effective shear strength parameters of the deltaic soils near Gdańsk are measured in drained and undrained triaxial compression tests and estimated with the Norwegian Institute of Technology (NTH) method using the Cone Penetration Tests (CPTU) sounding. The observed dilative-contractive soil behaviour is discussed taking into account the CPTU classification chart proposed by Robertson (2016). The aim of the research presented herein is to verify the applicability of the NTH method for the estimation of effective friction angle of soft soils in the Vistula Marshlands.

1.2 Testing site description

The testing field is located near the Jazowa village, in the Vistula Marshlands, Northern Poland. Intensive geotechnical investigations related with the construction of S-7 expressway were carried out in the studied area. Fifteen CPTU soundings, performed at every 2 m spacing, proved the regularity of the subsoil. Soil layers, distinguished according to the Unified Soil Classification System (USCS), are presented in Figure 1 along with the results of the CPTU soundings. The soil profile at the site contains the following layers:

- 0.00–0.70 m – silty sand (working platform)
- 0.70–1.80 m – low-plasticity silt
- 1.80–2.70 m – organic silty clay (mud) of high-plasticity
- 2.70–4.05 m – mixture of organic silty clay (mud) and peat
- 4.00–7.05 m – silty sand (loose to medium dense)
- 7.05–12.15 m - organic silt (mud) of high plasticity intersected with thin sand layer
- 12.15–14.45 m – peat with organic silt inclusions
- below 14.45 m – well-graded sand

In this paper, the study is focused on the samples taken from 1.8–4.0 m (organic silty clay), 7.80–12.15 m (organic silt), and 12.15–14.45 m (peat). Selected index properties of these soils are presented in Table 1.

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Table 1: Selected index properties of the Vistula Marshlands soft soils.

Soil layer	Sampling depth	w_c	γ	G_s	*PL*	*LL*	*IP*	*LOI*
	[m]	[%]	[kN/m3]	[g/cm3]	[%]	[%]	[%]	[%]
Organic silty clay (OH)	3.2÷4.05	54.4 ÷75.9	14.22 ÷14.52	2.54 ÷2.61	40.7 ÷55.3	90.4 ÷119.0	49.7 ÷63.7	11.4 ÷16.2
Organic silt (OH)	9.5÷10.5	45.4 ÷57.3	15.6÷16.6	2.54 ÷2.67	228.3 ÷38.0	53.7÷57.1	15.7 ÷27.55	4.2÷7.1
Peat (Pt)	13.0÷14..0	179.2	10.5	1.57	N/A	N/A	N/A	87.2

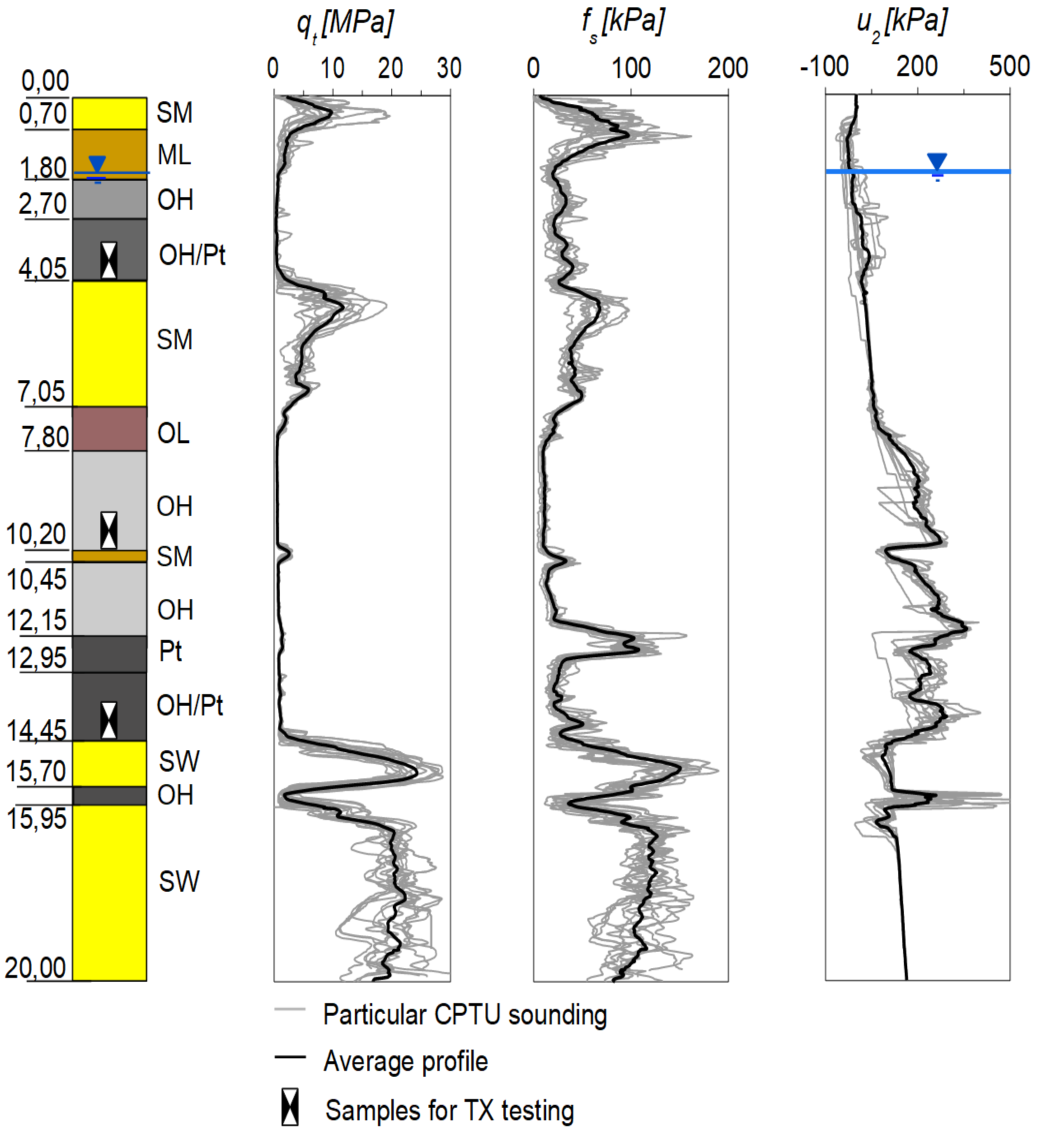

Figure 1: Soil profile and CPTU sounding results.

2 Testing Methodology

2.1 Triaxial tests

The consolidated undrained (CU) triaxial compression test (ASTM D4767, 2011) was conducted on muds (organic silty clay and organic silt) taken from 3.2–4.0 m and 9.5–10.0 m and on peat from approximately 14 m. The specimens were sheared at the rate of 0.011 mm/min. The three CU tests on mud samples were made at different level of cell pressure. However, only two samples of peat have been sheared due to limited amount of material. The consolidated drained (CD) triaxial compression test (ASTM D7181, 2011) was conducted only on organic silt samples, sheared at the rate of 0.002 mm/min. Standard triaxial device was used. The angle of internal friction has been determined using the stress ratio M in the *p*'-*q* (*p*' = effective mean stress; *q* = deviatoric stress) plane defined as:

$$M = \frac{6 \cdot \sin \phi'}{3 - \sin \phi'} \quad (1)$$

where: ϕ' = effective angle of internal friction.

2.2 CPTU soundings

The CPTU estimation of internal friction angle using the NHT method was calculated with the following equations (Mayne, 2007):

$$\phi' = 29.5 \cdot B_q^{0.121} \left(0.256 + 0.336 \cdot B_q + \log Q_t\right) \quad (2)$$

where:

$$Q_t = \frac{q_t - \sigma_{v0}}{\sigma'_{v0}} \quad (3)$$

$$B_q = \frac{u_2 - u_0}{q_t - \sigma_{v0}} \quad (4)$$

q_t = corrected cone resistance, σ_{v0} = in-situ vertical total stress, σ_{v0} = in-situ vertical effective stress, Q_t = normalized cone resistance, B_q = normalized pore-water pressure, u_o = hydrostatic pressure based on the water table level.

The values of effective angle of internal friction based on CPTU results were adjusted with those determined from the triaxial tests using the modified NTH method (Ouyang & Mayne, 2017) with the angle of plastification β being fitting parameter:

$$\phi' = 29.5 \cdot 10^{0.0035 \cdot \beta} \left[B_q^{0.121} \cdot \left(0.256 + 0.336 \cdot B_q + \log Q_t\right)\right] \quad (5)$$

The modified NTH method can be applied for soils ranging from sands to clays, where the angle of plastification β = (-20°; 20°). The modified NTH method should not be adopted to peats.

The dilative-contractive soil behaviour type parameters required in the Robertson (2016) classification are:

- normalized sleeve friction:

$$F = \frac{f_s}{\sigma'_{v0}} \quad (6)$$

- normalized cone resistance:

$$Q_{tn} = \left[\frac{q_t - \sigma_{v0}}{p_a}\right] \cdot \left(\frac{p_a}{\sigma'_{v0}}\right)^n \quad (7)$$

and:

$$n = 0.38 \cdot I_c + 0.05 \cdot \left(\frac{\sigma'_{v0}}{p_a}\right) - 0.15 \quad (8)$$

$$I_c = \left[(3.47 - \log Q_t)^2 + (\log F_r + 1.22)^2\right]^{0.5} \quad (9)$$

$$F_r = \left[(f_s / q_t - \sigma_{v0})\right] \cdot 100\% \quad (10)$$

where: f_s = sleeve friction, p_a = atmospheric reference pressure equal to 100 kPa, n = variable stress exponent; $n \leq 1.0$, I_c = soil behaviour type index, F_r = friction ratio.

3 Results And Interpretation

Frictional strength of soil in terms of effective angle of internal friction ϕ' depends on soil particles interference and interlocking (Terzaghi et al., 1996). For normally consolidated soils, the critical value of effective angle of internal friction (ϕ'_c) is equal to the maximum value (ϕ'_{max}). The determination of ϕ'_{max} in TX tests is related to the choice of failure criterion. There are three standard criterions: (i) maximum deviatoric stress $qmax = \max(\sigma_1 - \sigma_3)$, (ii) maximum obliquity: $\max(\sigma_1/\sigma_3)$, (iii) $\max(\sigma_1 - \sigma_3)$ or $\max(\sigma_1/\sigma_3)$ at predefined value of axial strain (usually 15%). The choice of failure criterion for organic soils is not obvious

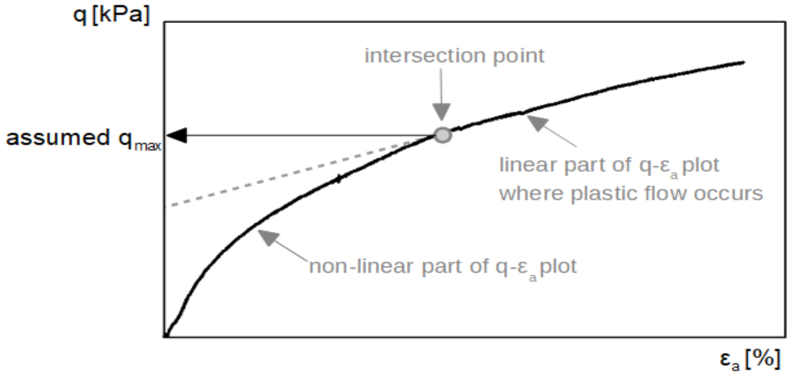

Figure 2: Determination of q_{max} for non-standard q-ε_a curves. Procedure adopted after Hendry et al. (2012).

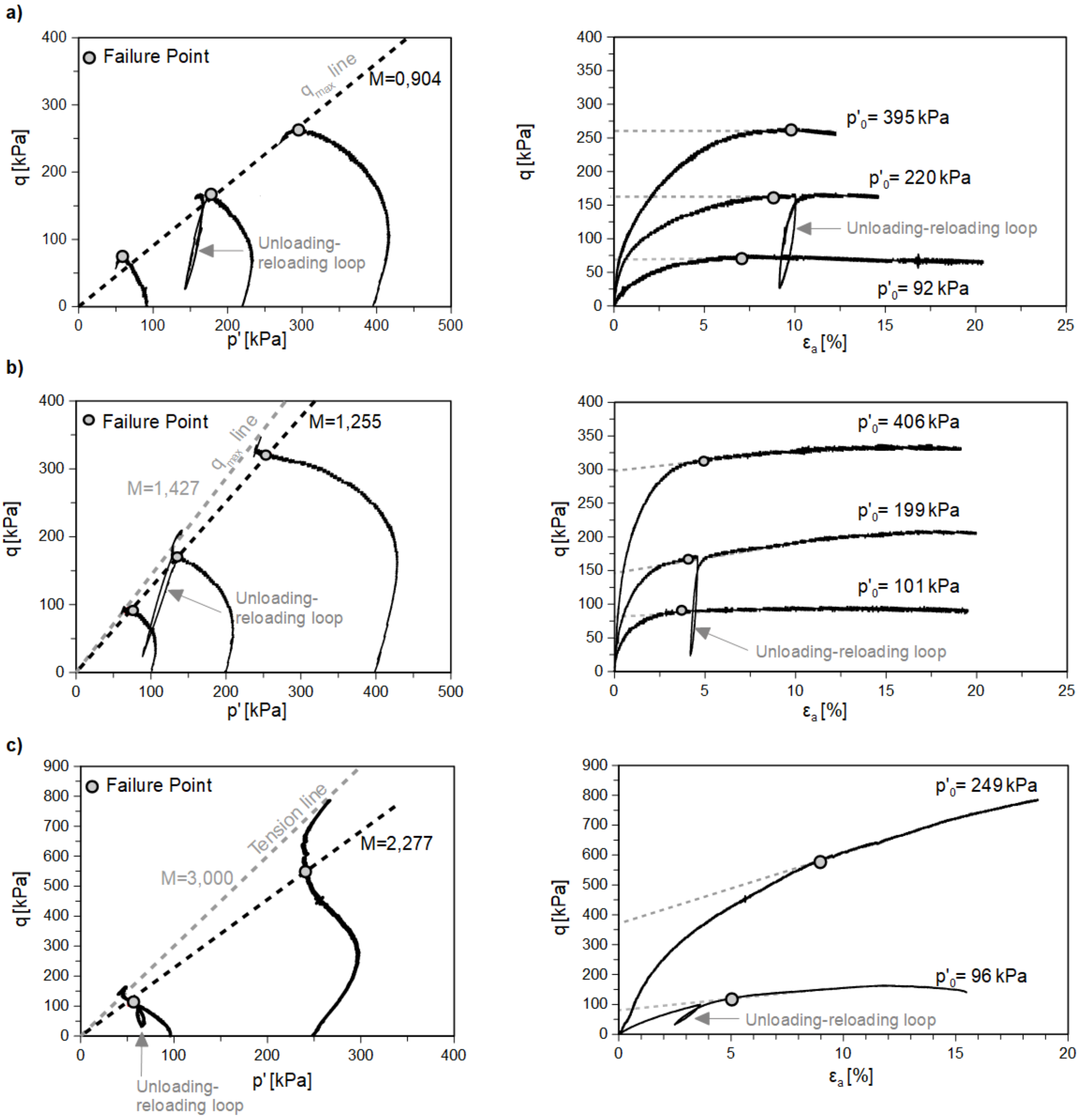

Figure 3: The CU tests results for (a) organic silty clay, (b) organic silt and (c) peat.

as soft soils, and peats in particular, could exhibit plastic flow phenomenon, see Figure 3. For some soils (mostly peats), the q_{max} can even increase up to Rankine's surface. To interpret such behaviour, the procedure adopted after Hendry et al. (2012), and schematically presented in Figure 2, was applied. The plastic flow is usually characterized by almost linear increase of q_{max} with axial strain (ε_a). The q_{max} is assumed as a point of intersection between non-linear and linear part of $q\text{-}_{\varepsilon a}$ plot (see Figure 2). The Authors believe that this interpretation can be satisfactorily applied for non-standard $q\text{-}_{\varepsilon a}$ curves when considerable plastic flow occurs.

The results of CU triaxial compression tests are presented in Figure 3 in terms of the plots in $q\text{-}_{\varepsilon a}$ and p'-q planes. Strength mobilization in the organic silty clay progresses slowly (Figure 3a) and the failure is achieved at the axial strain between 6% and 8%. The achieved M = 0.904 corresponds to the effective angle of internal friction of 23.1°.

For organic silt (Figure 3b), the maximum deviatoric stress is reached at the axial strains of 3-4%. The samples exhibit plastic flow phenomenon and the failure point has been adopted after the procedure described above. The assumed stress ratio M = 1.255, which results in the angle of internal friction equal to 31.3°. The results of CU tests on organic silt have been verified by CD triaxial compression tests, see Figure 4. Almost the same failure envelope has been achieved in CD and CU tests. However, large axial strains are required at the failure in CD tests and the response of specimens during shearing is clearly contractive (Figure 4). This observation confirms the CPTU soil classification based on soil behaviour type (SBT)

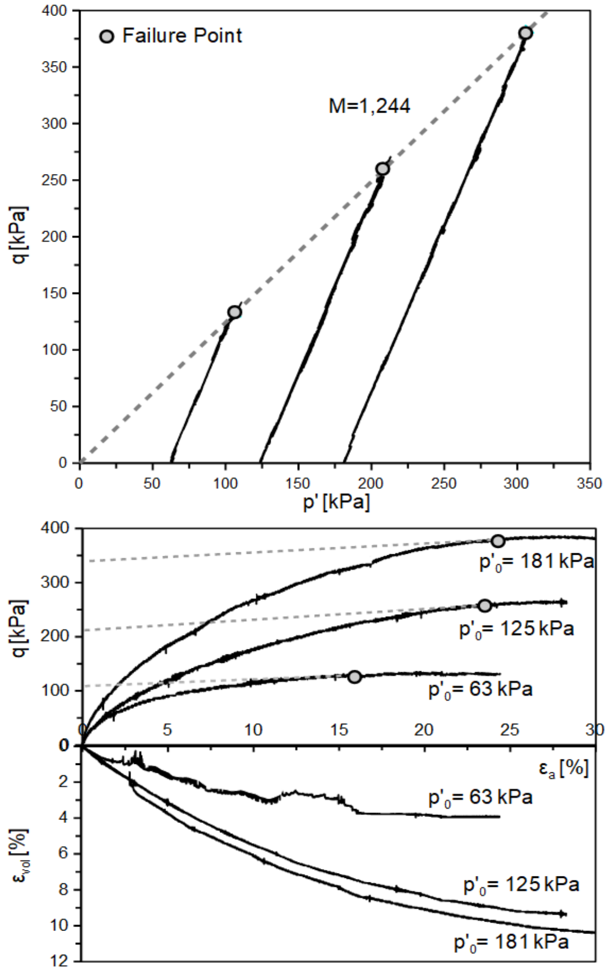

Figure 4: The results of CD tests on organic silt.

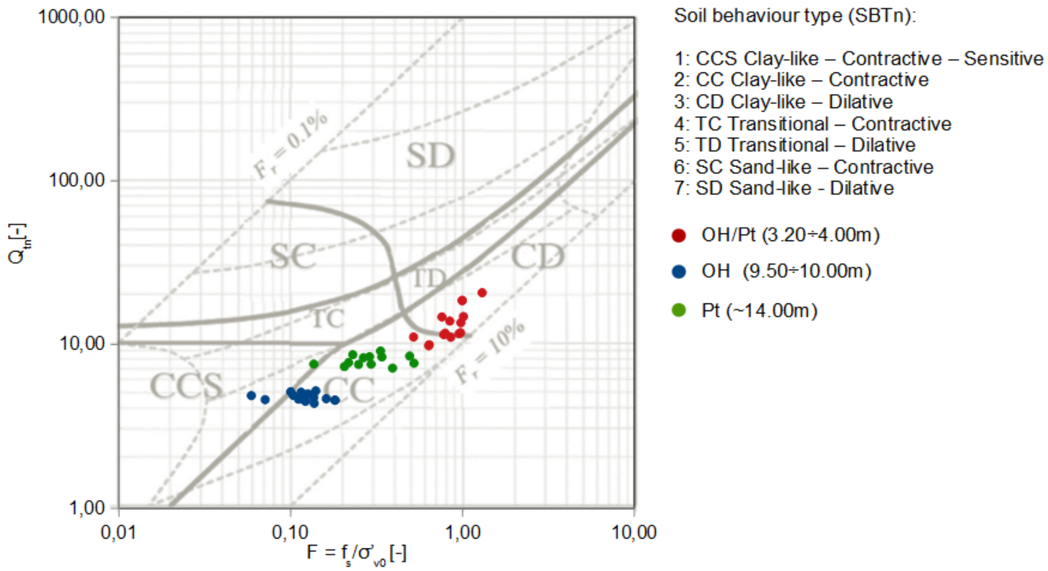

Figure 5: SBTn chart based on Q_{tn}-F (Robertson, 2016).

Table 2: Values of effective friction angle of soft soils in Jazowa.

Soil type	Type of the test			
	CU	CD	CPTU	
			NHT method (Mayne, 2007)	NTH modified method (Ouyang & Mayne, 2017)
Organic silty clay (3.2–4.0 m depth)	23.1°	23.4° *	N/A	N/A
Organic silt (9.5–10.0 m depth)	31.3°	31.0°	27.9°±1.2	31.3°±1.4
Peat (~14.0 m depth)	55.7°	N/A	29.0°±2.4	N/A

*Value obtained from lab tests, conducted by an external company, and summarized in geotechnical documentation for the S-7 expressway.

Table 3: Effective friction angle of soft soils deposits.

	Soil	ϕ’	Reference
CLAYS	Bothkennar clay	34°	(Hight et al., 1992)
	Osaka bay clay	25–40°	(Tanaka and Locat, 1999)
	Omono clay	50–60°	(Yasuhara and Takenaka, 1977)
	Muck clay	52–60°	(Tsushima et al., 1977)
	Juturnaiba organic clay	23–57°	(Coutinho and Lacerda, 1989)
	Soft organic clay	32.0°	(Danziger, 2007)
	Organic clay	30.0°	(Larsson et al., 2007)
	Organic clay	38–46°	(Cheng et al., 2007)
	Organic clay from Cubzac-les-Ponts	28–34°	(Shahanguian, 1981)
	Various organic clays	44–74°	(Krieg, 2000)
	Alluvial clay	31.5°	(Sandroni et al., 2015)
	Soft alluvial clay	36°	(Takemura et al., 2006)
	Soft alluvial Atchafalaya clay	20.2°	(Donaghe and Townsend, 1978)
	Soft deltaic clay	36.0°	(Sultan et al., 2004; Dan et al., 2007)
SILTS	Alluvial clayey silt	28°	(Lambson et al., 1993; Powell and Lunne, 2005)
	Organic silt	38–56°	(Cheng et al., 2007)
PEAT	Swedish clayey gyttja	60–90°	(Larsson, 1990)
	Eemian gyttja	29–44°	(Pietrzykowski, 2004)
	peat	63–65°	(Cheng et al., 2007)
	Middleton peat	60°	(Ajlouni, 2000)
	Ohmiya peat	51–55°	(Yamaguchi et al., 1985)
	Edson peat	28.8–50.1°	(Hendry et al., 2012)
THIS STUDY	Jazowa silty clay	23°	
	Jazowa organic silt	31°	
	Jazowa peat	56°	

proposed by Robertson (2016) (Figure 5). The organic silt and peat layers are classified as clay-like contractive, while the silty clay layer is mostly dilative.

The angle of internal friction equal to 55.7° was obtained in CU tests for peat taken from 14 m. High value of ϕ' is typical for fibrous peat (Mesri and Ajlouni, 2007) due to its microstructure (Cheng et al., 2007). The assumed q_{max} for peats is achieved at approximately 10% of axial strain.

Using CPTU results, the ϕ' was determined with Equations 2 and 5. Only the results for organic silt and peat layers from 7.80–14.45 m depth could be taken into consideration. In the shallow layers (up to 4.05 m), negative u_2 readings were obtained, which results in $B_q < 0$. The ϕ' according to the Equation 2 almost perfectly fits the TX value for organic silts. However, the CPTU based ϕ' underestimates the TX value of ϕ' for peats.

In organic silt, the angle of plastification equal to *14.5°* provides a fitting match between the modified NHT and the TX tests. The effective internal friction angles obtained in the laboratory tests and mean value derived from the fifteen CPTU tests are summarized in Table 2.

The effective friction angels for soft soil deposits in the Jazowa site are compared with the other soft soils in Table 3. As one can see, the organic soft soil in the Jazowa are characterized by similar frictional parameters as observed for other sites. However, the angles of the internal friction of organic silty clay and organic silt form the lower bound of the reported database.

4 Conclusions

The high values of effective angle of internal friction are obtained for organic silts, organic silty clays and peats. However, the full shear strength is achieved at relatively large strains (ε_a > 10% in most cases). The angles of internal friction are lower in comparison with database. The ϕ' according to NTH (Mayne, 2007) almost fits the value of effective friction angle for silty layers, but significantly underestimates the ϕ' for peats. However, the good estimation of ϕ' requires reliable measurement of u_2 reading, which was not be fulfilled for shallow layers of soft soils in the reported testing site. The presented research shows that the NTH method can be treated as a conservative estimation of effective friction angle for soft soils. In case of organic silt, perfect agreement between the CPTU and the modified NTH method is achieved for the angle of plastification $\beta = 14.5°$. The CD triaxial tests on organic silt confirmed the updated Robertson's (2016) classification as a practical tool for qualitative description of soil behaviour type (SBT).

Acknowledgements: The research is supported by the National Centre for Research and Development grant PBS3/B2/18/2015. Some of the geotechnical data was provided by the General Directorate for National Roads and Motorways in Poland.

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