

## Geotechnical characterization of soft soil deposits in Northern Poland

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### Highlights

- Case study of soil classification and geotechnical properties
- Discrepancies between CPTU, DMT and USCS classifications
- Local empirical correlations for soft soil compressibility parameters
- Shear strength parameters of organic soils from in-situ and laboratory tests

### Abstract

This paper presents a geotechnical characterization of deltaic soft soil deposits in the Vistula Marshlands, northern Poland. It shows the limited applicability of organic soil classifications based on Cone Penetration Tests (CPTU) and Dilatometer Tests (DMT). None of the in-situ-based classifications correctly identifies peat. Analysis of the behaviour of contractive/dilative soil layers according to Robertson's updated classification (2016) is shown to be in agreement

26 with volumetric changes observed during triaxial compression tests. The coefficient of  
27 primary compression  $C_c$  is found to decrease exponentially with the initial bulk density ( $\rho_{d0}$ )  
28 and to increase linearly with the in-situ water content ( $w_c$ ). The presented geotechnical  
29 characterization and reference data can be used for foundation design and soil improvement in  
30 the soft organic soils of northern Poland.

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32 KEYWORDS: compressibility, shear strength parameters, soil classification, soft soil

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34

## 1. Introduction

35 Some regional correlations concerning the interpretation of in-situ tests in the  
36 Holocene organic soils of Poland were proposed by Lechowicz (1997), Młynarek et al. (2008,  
37 2010) and Rabarijoely (2018). The geotechnical parameters of Eemian peats were described  
38 by Zawrzykraj et al. (2017). However, these studies consider mainly central and western  
39 Poland. The aim of this paper is to provide a comprehensive geotechnical investigation  
40 concerning the Vistula Marshlands (Figure 1) and to propose some local correlations for  
41 geotechnical design parameters in the Gdańsk region.

42 The study is divided into three parts. The first concerns the determination of soil  
43 classification with laboratory tests and using CPTU and DMT classification charts,  
44 particularly with regard to soft organic soils such as clays, silts and peats. The second part  
45 deals with soil compressibility in one-dimensional conditions and discusses sample  
46 disturbances resulting from the probing. Particular attention was drawn to the estimation of  
47 compression coefficient  $C_c$  and its relation to the physical properties of the soft soil. In the  
48 third part, shear strength parameters of the considered soft soils are discussed, taking into  
49 account in-situ test results and CIU and CID triaxial tests. The observed dilative/contractive



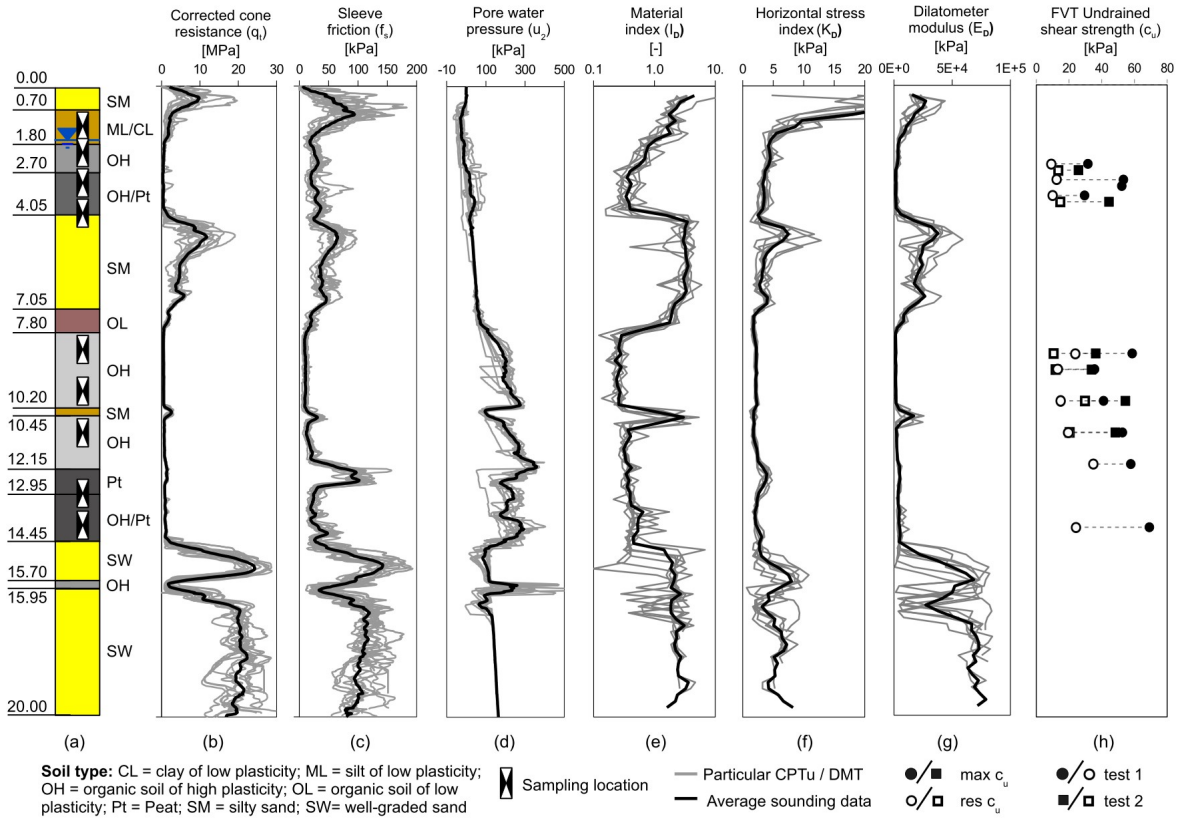
50 phenomena in the triaxial tests is compared to soil behaviour type according to Robertson's  
51 (2016) chart.

## 52 2. Study site description

53 The test site was in Jazowa, next to the S7 expressway in the Vistula Marshlands, near  
54 Elbląg and c. 50 km to the Southeast of Gdańsk. Two soft soil deposits interbedded with a  
55 sand layer were found (Figure 2). The first one (approximately 3 m thick), at 0.7 m to 4.05 m  
56 depth, contained a mixture of low plasticity silts and clays (ML/CL), organic silty clays (OH)  
57 and peats (Pt). A layer of loose to medium-dense sand (SM) was found at 4.05 m to 7.05 m  
58 depth. The second soft soil layer, between 7.05 m and 14.45 m, contained mainly organic silt  
59 (OH) with some peat (Pt). A compacted layer of sand was found below 14.45 m with a 0.25 m  
60 inclusion of organic soil at 15.7 m. The water table was approximately 1.7 m below the  
61 surface. The analyzed soft soil is generally normally consolidated with slight  
62 overconsolidation in the upper part of the deposits, due to water level changes and climate  
63 action.



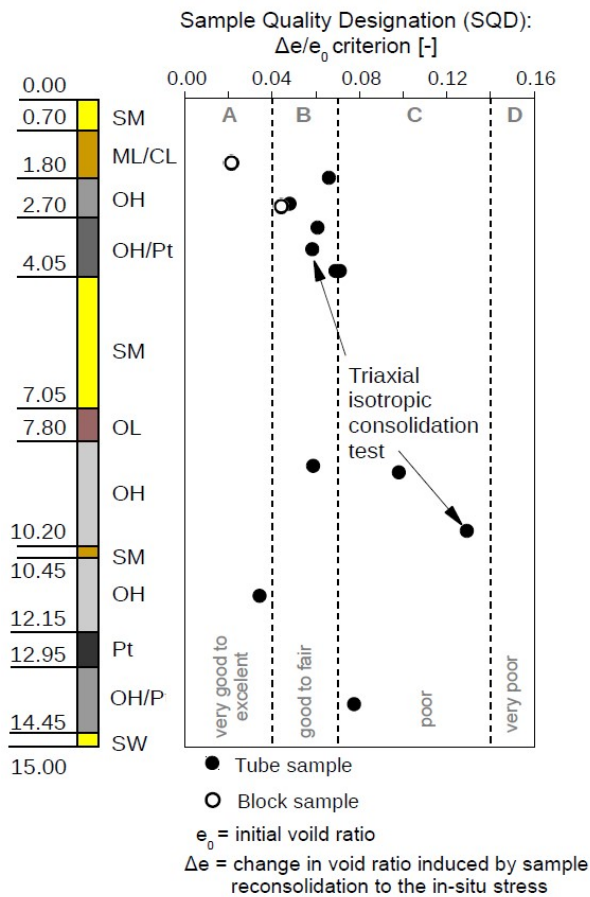
64  
65 **Figure 1.** Location of the testing site. [no colour]



66

67 **Figure 2.** (a) Jazowa site soil profile, (b)-(d) CPTU probing results, (e)-(g) DMT results, (h)

68 FVT sounding results. [no colour]



69

70 **Figure 3.** Sample Quality Designation class (A-D) based on  $\Delta e/e_0$  criterion. [no colour]

71

## 72 2.1. Field investigation

73 Fifteen CPTU tests with a 10 cm<sup>2</sup> electric piezocone were carried out down to  
 74 approximately 20 m, in accordance with ASTM D5778 (2012). The test results for corrected  
 75 cone resistance ( $q_t$ ), friction sleeve ( $f_s$ ) and pore water pressure ( $u_2$ ) are presented in Figures  
 76 2b-d, with average values in bold. The corrected cone resistance is defined as:

$$77 \quad q_t = q_c + u_2(1-a) \quad (1)$$

78 where:  $q_c$  = cone resistance,  $u_2$  = pore water pressure measured at shoulder filter position,  $a$  =  
 79 cone correction factor (equal to 0.84).

80 Eight DMT tests were conducted in accordance with ASTM D6635 (2015) in the  
 81 vicinity of the CPTU soundings. The obtained material index ( $I_D$ ), horizontal stress index ( $K_D$ )

82 and dilatometer modulus ( $E_D$ ) with calculated average values are presented in Figures 2e-g.

83 The DMT indexes are defined as:

$$84 \quad I_D = (p_1 - p_0) / (p_0 - u_0) \quad (2)$$

$$85 \quad K_D = (p_0 - u_0) / (\sigma'_{v0}) \quad (3)$$

$$86 \quad E_D = 34.7(p_1 - p_0) \quad (4)$$

87 where:  $p_0$  = corrected first reading,  $p_1$  = corrected second reading,  $u_0$  = in-situ pore water  
88 pressure,  $\sigma'_{v0}$  = in-situ effective vertical stress.

89 Two electrical Field vane tests (FVT) with an unprotected tapered 13.0 x 6.5 cm vane  
90 and electronic measurement system were performed in terms of ASTM D2573 (2015). During  
91 the tests, the vane instrument rotates the extension rods from the surface. Downhole, the  
92 torque is taken up during the first 15 degrees of rotation by the slip-coupling on top of the  
93 vane. Thereafter, the torque is transmitted to the vane. The maximum and residual values of  
94 undrained shear strength measured at the site are given in Figure 2h.

95 The sampling depths are presented in Figure 2a. The tube samples were extracted  
96 using a Piston Sampler ST:1 equipped with three 170 mm long liners and an inner diameter of  
97 50 mm. The cubical block samples were taken from a shallow excavation. The block samples  
98 were carefully separated from the parent material, placed in a rigid box, wrapped with  
99 cheesecloth and covered with melted wax.

100 The quality of the specimens, often denoted as Sample Quality Designation (SQD), is  
101 an important aspect when interpreting laboratory data. The undrained shear strength,  
102 compressibility parameters and sensitivity are influenced by the sample quality (Karlsrud and  
103 Hernandez-Martinez, 2013). The SQD can be verified in one-dimensional or isotropic  
104 consolidation tests. Taken into account was the change in the void ratio ( $\Delta e/e_0$ ) due to  
105 disturbance during sampling, in accordance with the Lunne et al. (1997) criterion. Eleven  
106 oedometer and two triaxial tests were used to evaluate the SQD. A good sample quality



107 (0.04 <  $\Delta e/e_0$  < 0.08) was generally observed (Figure 3), apart from the peat (~14 m depth) and  
108 organic silt (~10 m depth) specimens, where the ratio was  $\Delta e/e_0 > 0.08$ . The excavated block  
109 samples were of better quality than the tube samples. The void ratio criterion may not  
110 necessarily be valid for silt and peat sample quality, because this criterion was not originally  
111 meant for these types of soils. As it was already observed by Ladd et al. (1999), the measured  
112  $\Delta e/e_0$  ratios increase generally with depth, see Figure 3. As overburden stress increases,  
113 greater stress relief during sampling should be expected, resulting in a larger  $\Delta e/e_0$  ratio  
114 (deJong et al., 2018).

115

## 116 **2.2. Basic soil properties**

117 The basic physical soil properties, such as water content, soil unit weight and specific  
118 gravity, were determined at the sampling depths. The dataset of the index properties of the  
119 Vistula Marshland soft soils is presented as a result of comprehensive laboratory tests. The  
120 organic matter in the soft soil deposits was measured with the loss on ignition method for  
121 twelve selected samples according to ASTM D2974 (2014). The consistency limits were  
122 determined in terms of ASTM D4318 (2017) on thirteen selected specimens. The soil pH was  
123 measured on eight samples, using the reference electrode Sentix 41. The 50 g soil samples  
124 were diluted in 100 ml of distilled water and the pH analysis was carried out after 24 hours. A  
125 granulometric analysis was performed using the laser diffraction method (e.g., Eshel et al.,  
126 2004), which considers five repeated measurements. Consequently, the Particle Size  
127 Distribution (PSD) for eight samples was determined.

128 The soft soils analyzed in this paper are high-plasticity organic silts (silty muds),  
129 organic silty clays (clayey muds) and peats. The selected index properties of these soils are  
130 summarized in Table 1 and Figure 4. The water content varied from 47% to 76% for muds and  
131 was over 170% for peats. The specific gravity of the muds was approximately 2.57 g/cm<sup>3</sup>. In



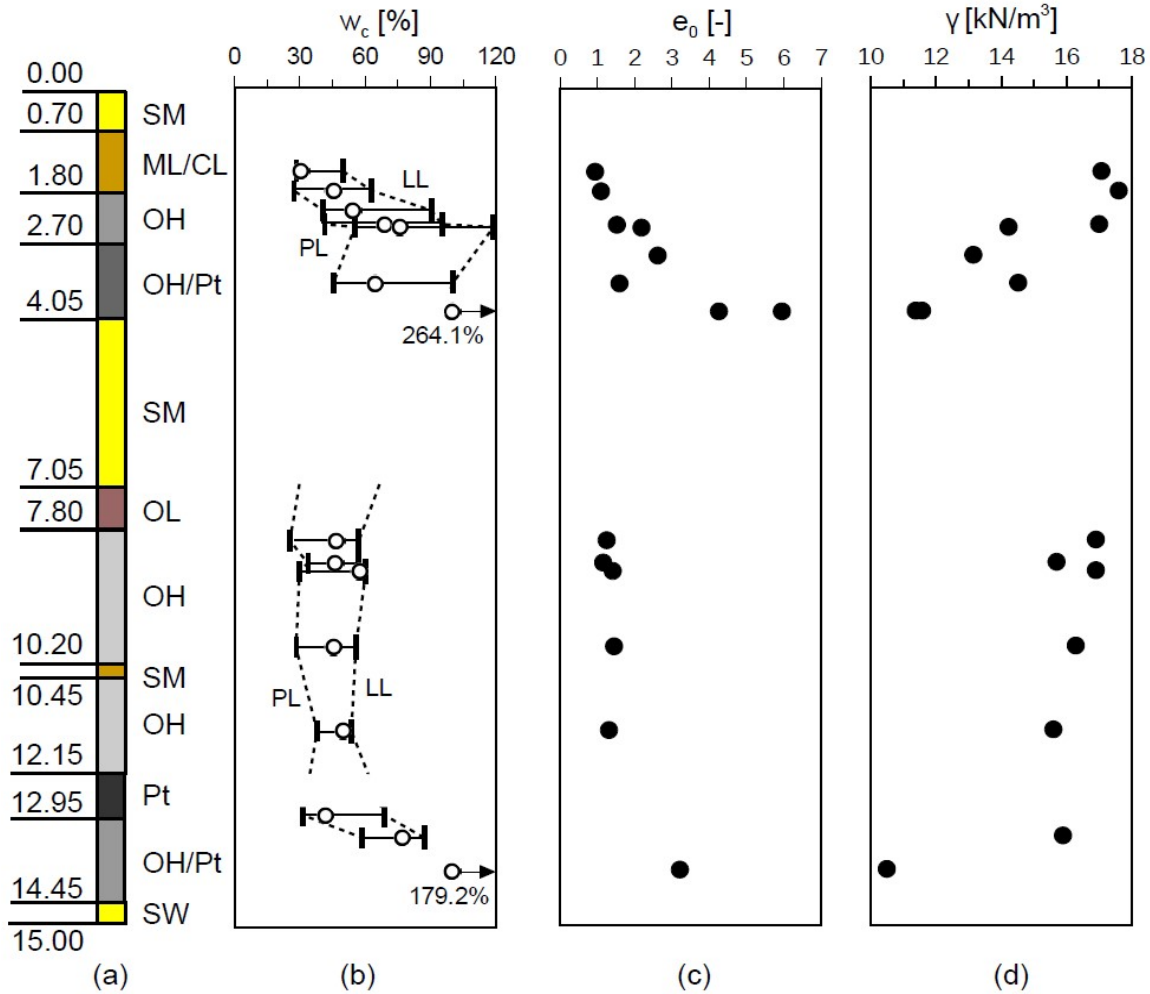
132 the case of peats, the specific gravity was much lower (between 1.6 and 1.7 g/cm<sup>3</sup>), on  
 133 account of its fibrous structure (e.g., Cheng et al., 2007; Mesri and Ajlouni, 2007). The peat  
 134 layers had a several times higher content of organic matter than the muds. This is in line with  
 135 most of the classification systems, where the boundary between organic soils (muds) and  
 136 highly organic soils (peats) is usually fixed at 30% of the organic matter content. The pH  
 137 ranged from 5.8 (moderately acidic) to 7.9 (moderately alkaline). The majority of the  
 138 examined soils did not react to hydrochloric acid. Only the highly organic soils from 8 m to  
 139 12 m started to effervesce, which indicates a calcium carbonate content of up to 3% at 8.5 m,  
 140 and over 5% at approximately 12 m, where sea shell traces were noticed. The dataset of the  
 141 Jazowa site, including the geotechnical parameters, is provided as an electronic supplement to  
 142 this paper.

143 **Table 1.** Selected index properties of Jazowa soft soil deposits

<i>Soil symbol</i>	<i>Sampling depth</i>	$w_c^{(1)}$	$\gamma^{(1)}$	$G_s^{(1)}$	<i>PI</i>	<i>Clay content</i> <sup>(1)</sup>	<i>Silt content</i> <sup>(1)</sup>	<i>LOI</i> <sup>(2)</sup>	<i>pH</i> <sup>(2)</sup>	<i>CaCO<sub>3</sub> content</i> <sup>(1)</sup>
	[m]	[%]	[kN/m <sup>3</sup> ]	[g/cm <sup>3</sup> ]	[%]	[%]	[%]	[%]	[-]	[%]
ML	1.3÷1.6	30.6	17.07	2.65	21.6	33.1	66.6	5.8	8.0	<1
ML/OH	1.85	45.4	17.6	-	-	-	-	4,4	-	-
OH	2.2	54.4	-	-	49.7	-	-	-	-	-
OH	2.45	68.9	17.0	-	-	-	-	8,3	-	-
OH	2.3÷2.6	75.9	14.22	2.54	63.7	51.3	48.7	11.4	5.8	<1
OH	3.2÷4.2	64.4	14.52	2.61	54.8	44.6	55.1	16.2	6.0	<1
Pt	~4	264.1	11.58	1.71	-	-	-	69.9	5.2	<1
OH	8.10	46.8	16.9	-	-	-	-	6,7	-	-
OH	8.1÷8.9	46.3	15.7	2.59	23.3	5.8	94.2	4.2	7.0	1-3
OH	8.65	57.3	16.9	-	-	-	-	4.5	-	-
OH	9.5÷10.5	45.4	16.3	2.67	27.5	2.3	97.6	-	-	3-5
OH	11.1÷11.9	49.8	15.6	2.54	15.7	1.8	96.8	7.1	7.9	>5
OH	13.0	41,8	-	-	37,4	-	-	-	-	-
OH	~13.4	77.2	15.9	-	28.5	5.6	93.5	7.0	8.2	>5
Pt	~14	179.2	10.5	1.57	-	-	-	87.2	7.0	<1

144 (1) = average value, (2) = point value,  $w_c$  = water content,  $\gamma$  = soil unit weight,  $G_s$  = specific soil gravity, PI = plasticity index,  
 145 LOI= Loss on Ignition





146

147 **Figure 4.** Soil properties of Jazowa soft soil deposits: (a) soil profile, (b) Atterberg's limits,

148 (c) initial void ratio, (d) soil unit weight. [no colour]

149

150

### 3. Soil classification

#### 3.1. Methods

152 Three different soil classification systems were applied: USCS, CPTU- and DMT-  
 153 based. The Unified Soil Classification System (USCS), according to ASTM D2487 (ASTM  
 154 D2487, 2017), uses the Casagrande's plasticity chart. The other two are in-situ behavioural  
 155 soil classifications.

156 The soft soils were classified according to the CPTU charts proposed by Robertson  
 157 (1990), Schneider et al. (2008) and Robertson (2016). The normalized cone resistance  $Q_t$  and  
 158 friction ratio  $F_r$  were calculated as follows (Robertson, 1990):

$$159 \quad Q_t = (q_t - \sigma_{v0}) / \sigma'_{v0} \quad (5)$$

$$160 \quad F_r = [(f_s / q_t - \sigma_{v0})] \times 100\% \quad (6)$$

161 where:  $q_t$  = corrected cone resistance,  $\sigma_{v0}$  = in-situ vertical total stress,  $\sigma'_{v0}$  = in-situ vertical  
 162 effective stress,  $f_s$  = sleeve friction.

163 The normalized pore water pressure parameter  $B_q$  and net cone resistance  $q_n$  are defined:

$$164 \quad B_q = (u_2 - u_0) / (q_t - \sigma_{v0}) \quad (7)$$

$$165 \quad q_n = q_t - \sigma_{v0} \quad (8)$$

166 where  $u_0$  = in-situ pore water pressure.

167 The contractive/dilative soil behaviour type (SBT) was determined using the updated  
 168 Robertson's classification (Robertson, 2016), with the following variables:

$$169 \quad Q_m = [(q_t - \sigma_{v0}) / p_a] (p_a / \sigma'_{v0})^n \quad (9)$$

$$170 \quad n = 0.381 \times I_c + 0.05 \times (p_a / \sigma'_{v0}) - 0.15 \quad (10)$$

$$171 \quad I_c = [(3.47 - \log Q_t)^2 + (\log F_r + 1.22)^2]^{0.5} \quad (11)$$

172 where:  $Q_m$  = normalized cone resistance,  $p_a$  = atmospheric reference pressure equal to 100  
 173 kPa,  $n$  = variable stress exponent,  $I_c$  = soil behaviour type index.

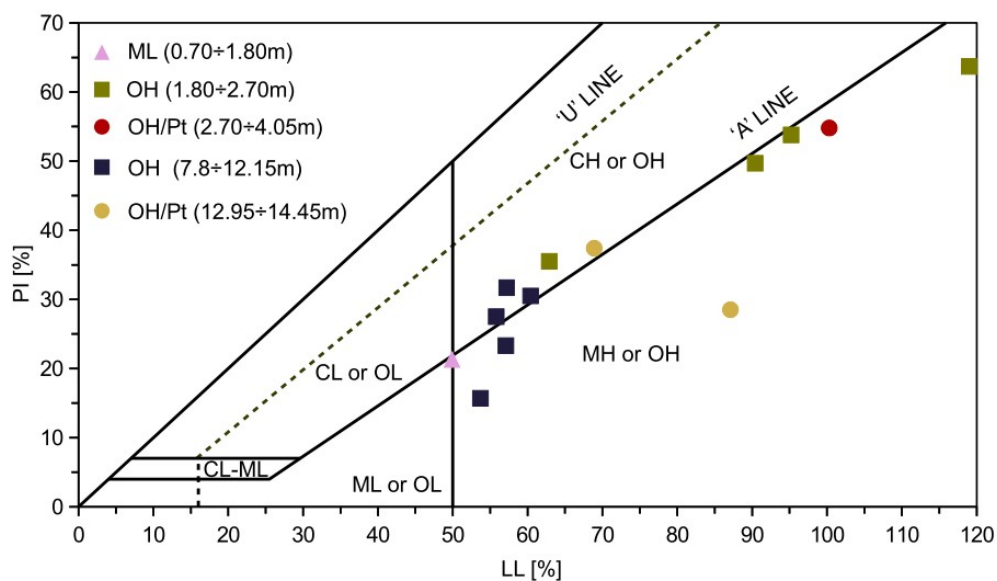
174 The last classification system was based on the Marchetti and Crapps (1981) DMT chart.

175 The statistical evaluations of the CPTU and DMT readings were performed for  
 176 classification purposes. The required parameters, such as  $Q_t$ ,  $Q_m$ ,  $F_r$ ,  $B_q$ ,  $q_n$ ,  $\Delta u_2$  for CPTU and  
 177  $I_D$ ,  $E_D$  for DMT, were averaged within the soil layers presented in Figure 2a. Next, the global  
 178 average values and corresponding standard deviations (SD) for each soil layer were  
 179 calculated. Finally, the global average values and SD error boxes were plotted in the  
 180 classification charts.



### 181 3.2. Results and interpretation

182 The Jazowa soft soils, classified according to USCS, are presented in Figure 5. The  
183 graph is based on the data given in Figure 4, where Atterberg's limits are shown. The soil  
184 layer from 0.7÷1.8 m has a liquid limit ( $LL$ ) of less than 50% and lies below the A-line and  
185 can be defined as low plastic silt (ML) according to ASTM D2487 (2017). Soils sampled from  
186 the 2.3÷4.05 m and most of the samples from 7.8÷14.45 m have a liquid limit exceeding 50%,  
187 and are classified as organic silts (OH). Samples taken from approximately 4 m and 14 m are  
188 classified as peats (Pt) due to their high organic matter content (Table 1). The layers at  
189 2.7÷4.05 m and 12.95÷14.45 m contain mixtures of interlaying muds and peats and are  
190 denoted as OH/Pt.



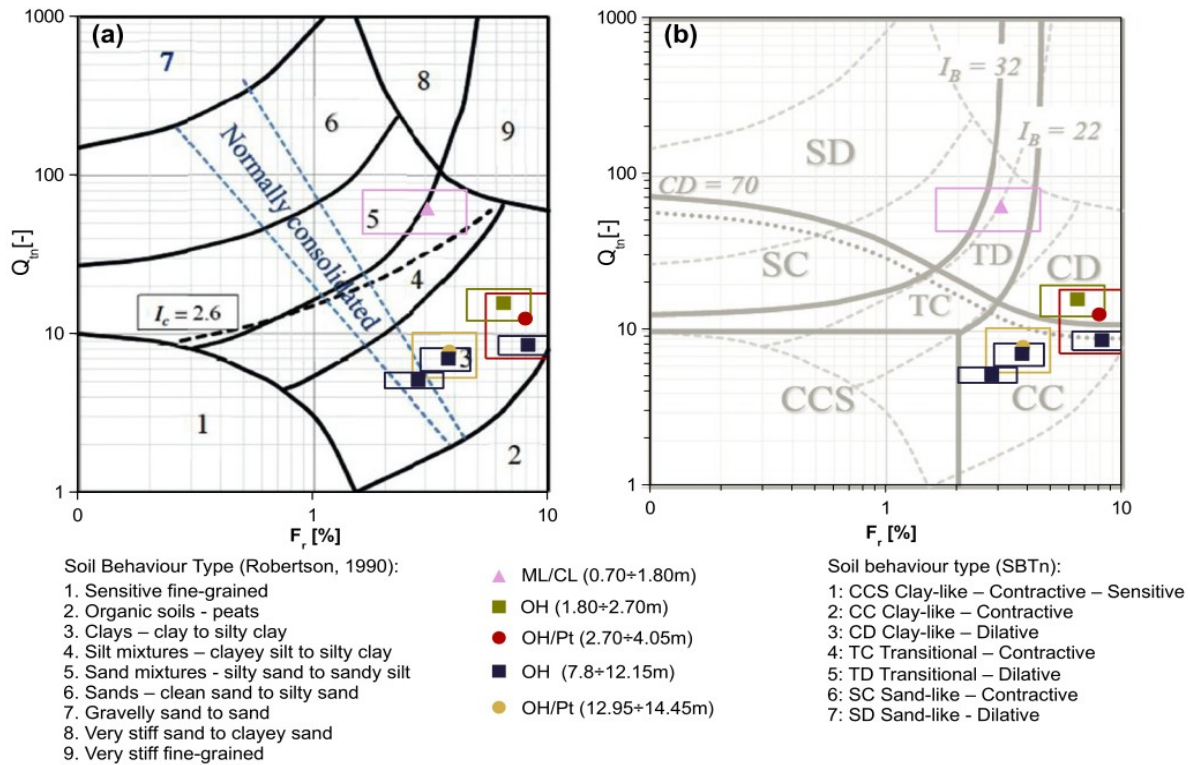
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192 **Figure 5.** Classification of layers according to ASTM D2487 (2017). [no colour]

193  
194 Soil classifications based on the Robertson (1990) and Schneider et al. (2008)  
195 approaches are presented in Figure 6. Only Figure 6a classifies ML correctly as a mixture of  
196 silt and clay, while Figure 6b classifies it as having a high sand content, which was not  
197 confirmed in the PSD, see Table 1. As can be seen in Figure 6a, Robertson's chart classifies  
198 peat and organic soils as clay, which is only partially correct for the organic silty clay from

199 1.8 to 2.7 m (Table 1). Moreover, the muds (OH soils) with low clay fraction at this depth  
200 range and the soils with high silt fraction content in the 7.8÷12.15 m layer are positioned  
201 close to one another in the diagram. The SBTn for Jazowa site according to Robertson (2016)  
202 is shown in Figure 6b. Most of the examined soils are clay-like contractive, which was  
203 confirmed with consolidated drained triaxial tests (Fig 13). The muds at shallow depths  
204 (0.7÷4.05 m) are, however, classified as dilative.

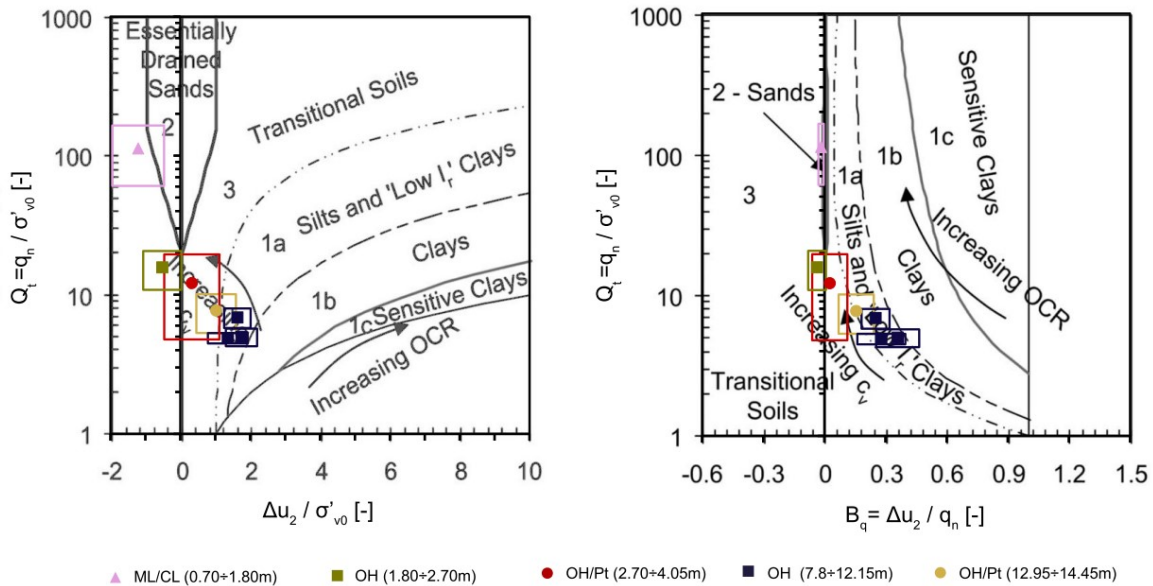
205 The results for Jazowa soft soils in Schneider's classification are presented in Figure 7.  
206 In Schneider's  $\Delta u_2/\sigma'_{v0}$  nomogram (Fig.7a), muds are classified as silts and silty clays, the  
207 peats and ML soils from shallow depths are denoted as sands. In the  $B_q = \Delta u_2/q_n$  nomogram  
208 (Fig. 7b), ML soils from a shallow depth are classified as having a high sand content, which  
209 was not confirmed in the PSD, see Table 1. Here, muds are classified as silts and silty clays.  
210 However, peats are denoted as sand mixtures or clays but not as organic soils.

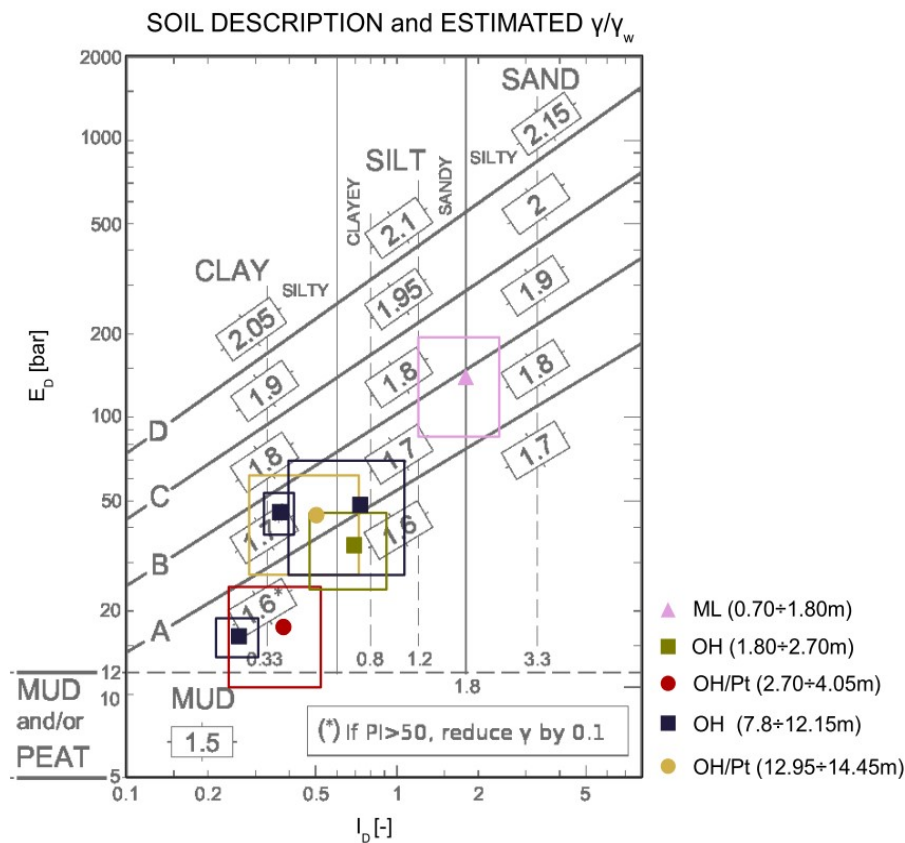
211 The results of DMT-based classification (Marchetti and Crapps, 1981) are presented in  
212 Figure 8. Similarly to Robertson's classification, the organic clay layer at 0.7÷1.8 m is  
213 classified as silty sand/sandy silt. The muds are classified as clayey silts, silty clays or clays,  
214 and peats are denoted as silty clays. The dilatometer modulus  $E_D$  of the considered muds and  
215 peats is considerably higher than the upper bound proposed for such soils according to the  
216 Marchetti and Craps diagram.



217

218 **Figure 6.** CPTU based classification (error boxes based on standard deviation) for Jazowa  
 219 soft soil deposits: (a) Robertson's nomogram (1990; 2009) and (b) SBTn charts based on  $Q_{in}$ -  
 220  $F_r$  (Robertson, 2016). [no colour]





224

225 **Figure 8.** DMT-based classification (Marchetti and Crapps, 1981) for Jazowa soft soil deposit  
 226 (error boxes based on SD). [no colour]

227

### 228 3.3. Discussion

229 One should keep in mind that CPTU and DMT soil classifications describe soil type  
 230 behaviour and are not directly related to the soil granulometry. The difficulties in the soil type  
 231 identification according to CPTU-based classifications were already described by Młynarek et  
 232 al. (1997) and Tumay et al. (2011). One can notice that the CPTU-based classification has no  
 233 relation to the USCS in the case of Jazowa soft soils. Robertson's graph (1990) better  
 234 classifies shallow soil layers (up to 2.7 m), whereas the Schneider et al. nomogram (2008)  
 235 results better match the soil behaviour type for deeper muds. In all cases, muds are not  
 236 recognized as organic soils but as silts and silty clays. As noticed by Młynarek et al. (2008),  
 237 the CPTU system illustrates well the effect of preconsolidation. Slightly overconsolidated

238 muds from the first layer are generally situated above the NC zone on the Robertson (1990)  
239 chart (Figure 6a). DMT classification slightly better reflects the soft soil type than the CPTU  
240 classifications. However, peats are improperly identified here as silty clays. Similar  
241 discrepancies between CPTU and DMT classifications in the case of organic soils were  
242 already found by Młynarek et al. (2008), who argued that organic soils require a separate  
243 classification system. For instance, an attempt of new DMT soil classification including  
244 organic soils was proposed by Rabarijoely (2018). Consequently, only a combined approach,  
245 including local geological maps, drillings, CPTU or DMT classifications and engineering  
246 judgement, will allow for appropriate soil type recognition in the considered organic soils.

247

248

## 4. Compressibility

### 4.1. Methods

249  
250 The compressibility of soft soil deposits was determined with triaxial apparatus using  
251 the isotropic consolidation procedure (ASTM D4767, 2011; ASTM D7181, 2011) on  
252 specimens from approximately 4 m and 10 m. An almost fully saturated soil sample  
253 (Skempton's parameter  $B \geq 0.95$ ) was subjected to isotropic multi-stage consolidation (e.g.,  
254 ASTM D7181, 2011) up to 800 kPa. The preconsolidation pressure  $\sigma'_p$ , swelling index ( $\kappa$ )  
255 and compression index ( $\lambda$ ) were evaluated.

256 The coefficients of the consolidation ( $c_v$ ), recompression ( $C_r$ ), compression ( $C_c$ ) and  
257 swelling ( $C_s$ ) indices and the vertical preconsolidation pressure  $\sigma'_p$  were determined on the  
258 basis of eleven oedometer tests (ASTM D2435, 2011). The end of primary consolidation  
259 (EOP) was determined using the Casagrande method or rectangular hyperbola method  
260 (Sridharan et al., 1987). An extensive study concerning the application of different methods  
261 for the determination of preconsolidation pressure in oedometer tests was presented by Grozic  
262 et al. (2003). Determination of the vertical preconsolidation pressure ( $\sigma'_p$ ) is not always



263 simple, especially in disturbed low plastic overconsolidated clays, and may include subjective  
264 interpretations (Grozic et al., 2005). As the interpretation of consolidation curves requires  
265 experience, preconsolidation pressure can be difficult to define, especially when graphical  
266 methods are used. That is why Paniagua et al. (2016) recommend to evaluate this parameter  
267 using at least three different methods. In this study, the preconsolidation pressure is  
268 interpreted using five methods: Casagrande (1936), Onitsuka et al. (1995); Becker et al.  
269 (1987); Boone (2010) and Pacheco-Silva's (1970). Casagrande (1936) is a traditional semi-  
270 logarithmic method, which is probably applicable only for clays with an overconsolidation  
271 ratio between 1 to 3 and 1 to 4 (Lacasse et al. 2008). The Onitsuka et al. (1995) bilogarithmic  
272 and Becker et al. (1987) work method were recommended by Grozic et al. (2003) in a study  
273 concerning overconsolidated glaciomarine clays of low plasticity. The Boone (2010) approach  
274 uses a bilinear approximation of the compressibility curve in the  $e$ - $\log(\sigma'_{v0})$  plane. It is based  
275 on a simple slope-intercept mechanism and does not require subjective or graphical  
276 interpretations. Pacheco Silva's (1970) method, widely used in Brazil, is considered to be less  
277 influenced by subjective interpretation (Grozic et al., 2005).

278 The overconsolidation ratio ( $OCR$ ) was also estimated with DMT results (Marchetti,  
279 1980) for  $I_D < 1.2$ :

$$280 \quad OCR = (0.5 \times K_D)^{1.56} \quad (12)$$

281 as well with CPTU-based preconsolidation pressure assessment (Chen and Mayne, 1996):

$$282 \quad \sigma'_p / p_a = 0.86 \times \left( \frac{q_t - \sigma_{v0}}{p_a} \right)^{0.93} \times PI^{-0.28} \quad (13)$$

## 284 4.2. Results and interpretation

285 The principal consolidation parameters for the Jazowa site are summarized in Table 2.  
286 The presented values are typical for similar soils. For instance, the  $c_v$  for San Francisco Bay  
287 mud is between  $0.6 \div 1.2$  m<sup>2</sup>/year (Lee et al., 1983), while for Jazowa organic silty clay it is



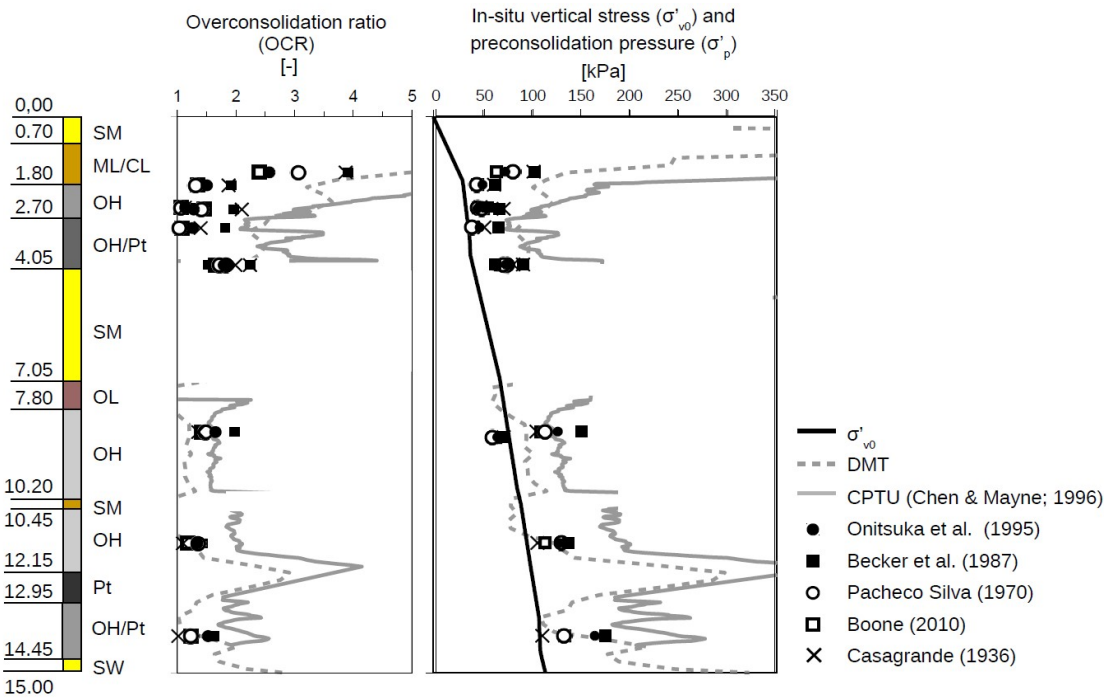
288 between 0.61 and 0.89 m<sup>2</sup>/year. The  $c_v = 0.34 \div 0.62$  m<sup>2</sup>/year for Jazowa organic silt is close to  
 289 the values given by Lowe et al. (1964),  $c_v = 0.6 \div 3.0$  m<sup>2</sup>/year. The  $c_v = 0.21 \div 2.66$  m<sup>2</sup>/year for  
 290 peats are within the range reported by Mesri and Ajlouni (2007) for fibrous peats ( $c_v =$   
 291  $0.8 \div 8.1$  m<sup>2</sup>/year). The  $C_c$  range (0.249  $\div$  0.638) for Jazowa OH soils is also typical for this kind  
 292 of soil. For instance, O’Kelly (2006) reports  $C_c = 0.29 \div 1.4$  for Irish silts and clays. The  
 293 derived  $C_c/C_r$  ratio for muds in Jazowa varies generally between 7 and 15, which is slightly  
 294 higher than that reported by Das (2013) for natural inorganic clays of low to medium  
 295 sensitivity. In natural organic sensitive clays, this ratio may exceed even 15 (e.g, Koskinen  
 296 and Karstunen, 2004; Mataic et al., 2015).

297

298 **Table 2.** Consolidation parameters obtained from oedometer and TX tests

<i>Soil type</i>	<i>Sampling depth [m]</i>	$\sigma'_{v0}$ [kPa]	$c_v^{(1)}$ [m <sup>2</sup> /year]	$C_r$ [-]	$C_c$ [-]	$C_s$ [-]	$\lambda$ [-]	$\kappa$ [-]
ML/CL	1.3 $\div$ 1.6	22.6 $\div$ 27.8	2.91	0.016	0.249	0.036	-	-
ML/OH	1.85	30.6	1.56	0.044	0.392	0.025	-	-
OH	2.45	33.2	0.61	0.044	0.517	0.030	-	-
OH	2.3 $\div$ 2.6	32.5 $\div$ 33.8	0.83	0.056	0.638	0.084	-	-
OH	3.2 $\div$ 4.05	36.7 $\div$ 40.5	0.89	0.085	0.719	0.146	0.227	0.042
Pt	~4	~40.2	2.66	0.180	1.585	0.104	-	-
OH	8.1 $\div$ 8.9	73.9 $\div$ 78.7	0.54	0.029	0.286	0.018	-	-
OH	8.65	77.3	0.62	0.062	0.403	0.019	-	-
OH	9.5 $\div$ 10.5	82.3 $\div$ 89.5	-	-	-	-	0.194	0.038
OH	11.1 $\div$ 11.9	93.1 $\div$ 97.8	0.34	0.012	0.465	0.025	-	-
Pt	~14	~108.4	0.21	0.059	2.249	0.164	-	-

299 (1)= values for in-situ stresses



300

301 **Figure 9.** OCR profile for Jazowa site. [no colour]

302

303 The distribution of *OCR* with depth is presented in Figure 9. According to the  
 304 oedometer test results, the soil is slightly overconsolidated in the upper layers and practically  
 305 normally consolidated at larger depths. The *OCR* interpreted from oedometer tests supports  
 306 the geological history of the Vistula Marshlands, where both soft soil deposits are normally  
 307 consolidated or slightly overconsolidated sediments. The *OCR* distribution obtained from the  
 308 DMT-based estimation overlaps the results from the oedometer tests for deeper layers,  
 309 whereas both the Chen and Mayne (1996) proposal and DMT estimations surpass the results  
 310 at shallow depths. The *OCR* values interpreted using the five methods based on oedometer  
 311 tests are fairly consistent. Pacheco Silva's and Casagrande's methods generally give the  
 312 smallest *OCR* values, whereas Becker's method gives the upper bound of this ratio.

313 **4.3. Discussion**

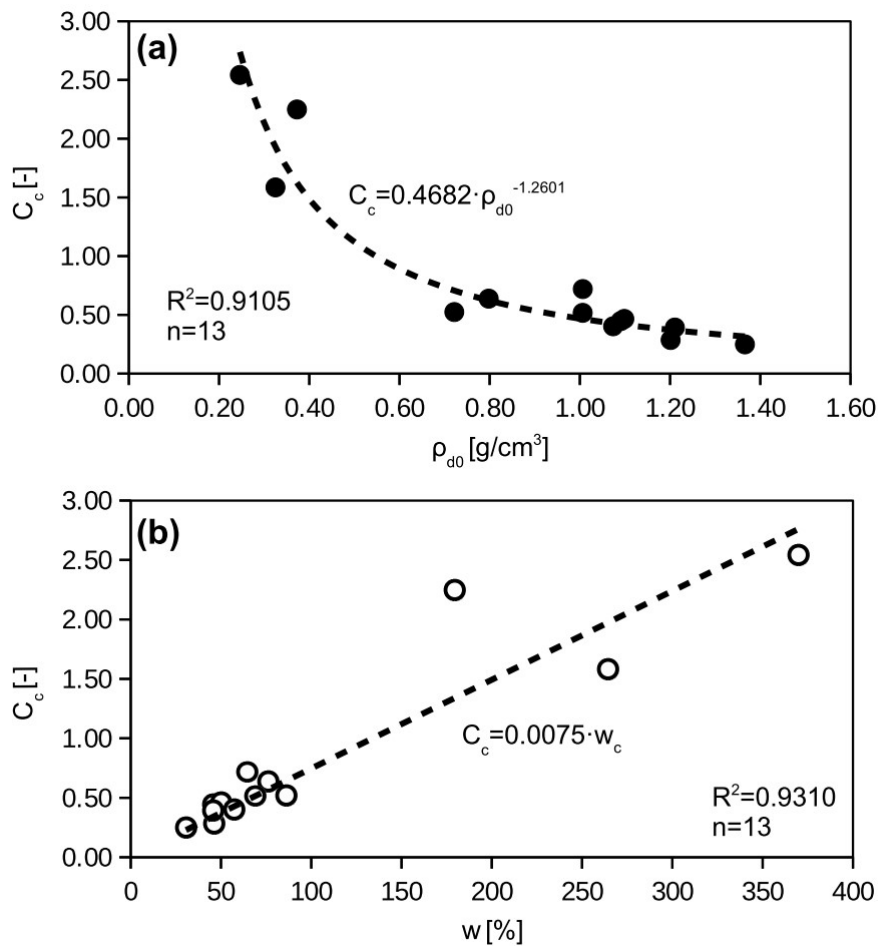
314 Different correlations between  $C_c$  and physical properties of soft soils were examined and the  
 315 most promising relations were presented. For the Jazowa site, the relation between  $C_c$  and  
 316 initial dry density  $\rho_{d0}$  (see Figure 10a) is:

$$317 \quad C_c = 0.4682 \times \rho_{d0}^{-1.2601} \quad (14)$$

318 The relation between  $C_c$  and water content  $w_c$  (see Figure 10b) is:

$$319 \quad C_c = 0.0075 \times w_c \quad (15)$$

320 These equations allow for a rough  $C_c$  estimate at the site when only a limited geotechnical  
 321 investigation is carried out. The coefficient of 0.0075 in Eq. (15) is lower than that proposed  
 322 by Bowles (1984) for organic silts and clays ( $C_c = 0.0115w_c$ ).



323

324 **Figure 10.** The relationships: (a)  $C_c$  versus  $\rho_{d0}$  and (b)  $C_c$  versus  $w_c$ .

325

326

## 5. Shear strength parameters

### 327 5.1. Undrained shear strength

#### 328 5.1.1. Methods

329 The undrained shear strength profiles were obtained from field tests, including CPTU,  
330 DMT and FVT, as described below:

331 1. The CPT-based  $c_u$  estimation was calculated using the following empirical formula:

$$332 \quad c_u = (q_t - \sigma_{v0}) / N_{kt} \quad (16)$$

333 where:  $c_u$  = undrained shear strength of soil,  $\sigma_{v0}$  = vertical in-situ total stress,  $N_{kt}$  = cone  
334 factor. For the analyzed deltaic soft soils, a local correlation (with FVT as a reference) linking  
335 the cone factor with the friction ratio was used (Bałachowski et al., 2018):

$$336 \quad N_{kt} = 1.242 \times F_r + 7.803 \quad (17)$$

337 For the considered soils,  $N_{kt}$  varies between 11 and 18 according to Eq. (17). This is similar to  
338 the values for normally consolidated marine clays obtained by Lunne and Kleven (1981), who  
339 propose an average  $N_{kt}$  value of 15 with reference to FVT. The recommended values of the  $N_{kt}$   
340 factor depends on the shearing mode. Aas et al. (1986) suggest that the correlation between  
341 the cone factor and the average laboratory undrained shear strength obtained from triaxial  
342 compression, triaxial extension and direct simple shear tests ranges from 8 to 16. Assuming  
343 average shearing mode, an  $N_{kt}$  value of 14 can be assumed for soft soils (Robertson, 2009).

344 2. The DMT  $c_u$  estimation was calculated using Lechowicz (1997) formula for soft  
345 organic soil deposits in Poland, which is a modified version of Marchetti (1980):

$$346 \quad \frac{c_u}{\sigma'_{v0}} = S \times (0.45 \times K_D)^{1.20} \quad (18)$$

347 where:  $S$  = normalized undrained shear strength;  $S$  is equal to 0.4 for normally consolidated  
348 organic soils (Lechowicz, 1997).



349 3. FVT  $c_u$  measurements are affected by several factors, including rate effects and  
350 anisotropy (e.g., Bjerrum, 1972; Chandler, 1988). Therefore, the measured undrained shear  
351 strength was corrected with the factor  $\mu_v$  (Chandler, 1988):

$$352 \quad c_u = \mu_v c_{u-FV} \quad (19)$$

353 where  $c_{u-FV}$  = undrained shear strength measured directly with FVT,  $\mu_v$  = correction factor.

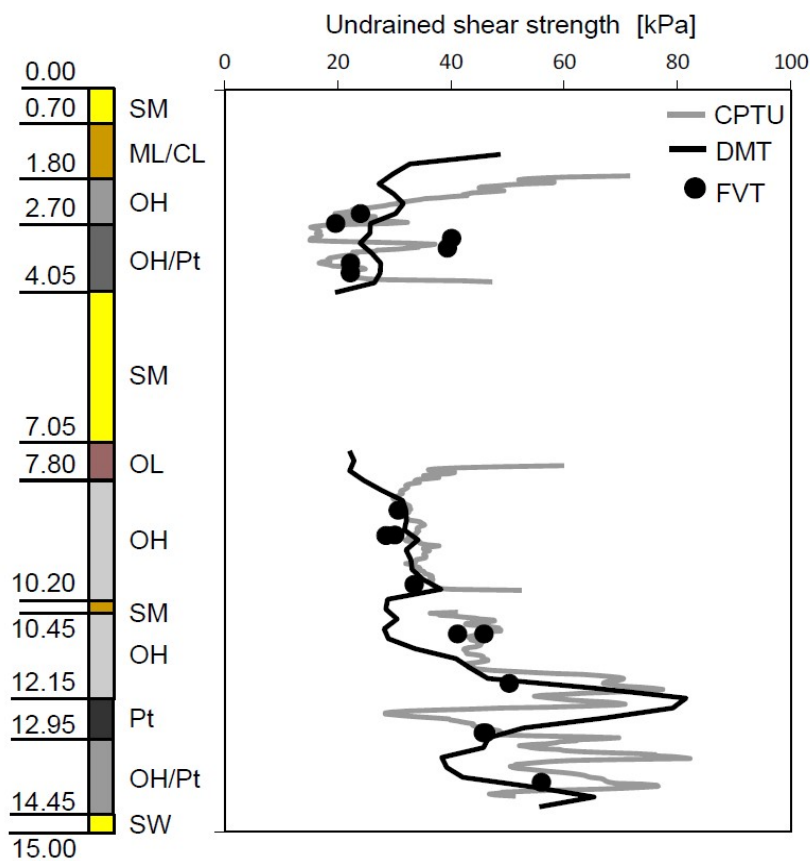
354 For muds, the  $\mu_v$  was defined as:

$$355 \quad \mu_v = 1.05 - b \times (PI)^{0.5} \quad (20)$$

356 where:  $b$  = time to failure coefficient equal to 0.045, as suggested by ASTM 2573 (2015),  
357 which corresponds to time to failure equal 10 000 minutes. For peat  $\mu_v = 0.5$  (e.g.,  
358 Gołębiewska, 1983).

### 359 5.1.2. Results

360 The undrained shear strength profiles obtained from the CPT, DMT and FVT tests are  
361 consistent (Figure 11). The  $c_u$  values are generally constant in the upper lightly  
362 overconsolidated layer and increase with depth in the lower normally consolidated deposit.



363

364 **Figure 11.** Undrained shear strength profiles

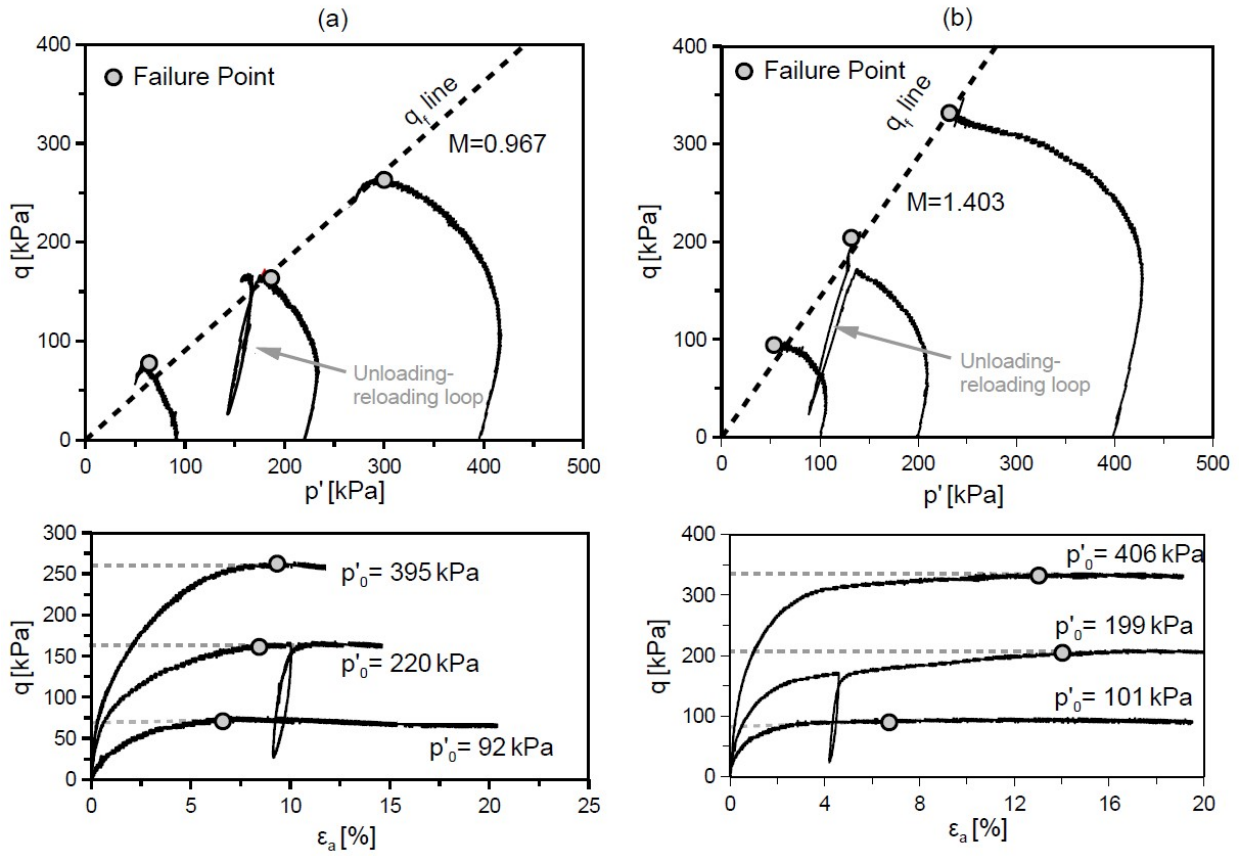
365

## 366 5.2. Frictional strength parameters

### 367 5.2.1. Methods

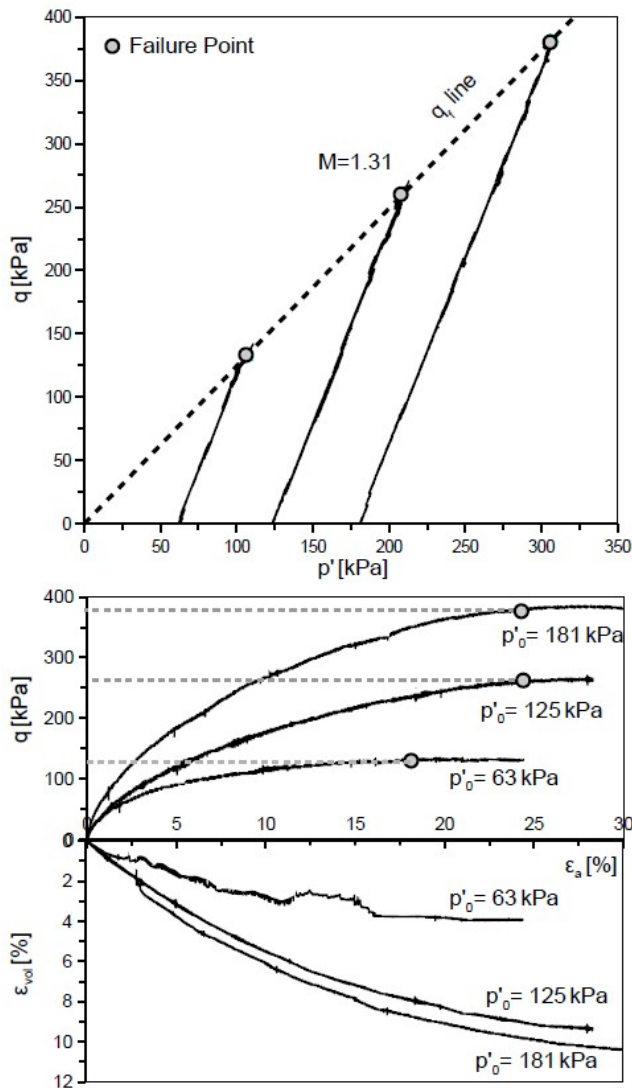
368 A CIU triaxial compression test (ASTM D4767, 2011) was conducted on mud samples taken  
 369 from 3.2÷4.0 m and 9.5÷10.5 m. Specimens were sheared at a rate of 0.011 mm/min. Three  
 370 CIU tests on mud were performed in both samples. The CID triaxial compression test (ASTM  
 371 D7181, 2011) was conducted only on specimens taken from 8.1÷8.9 m (organic silt) with a  
 372 shearing rate of 0.002 mm/min. All the tests were carried out using a standard triaxial device  
 373 and the maximum deviatoric stress criterion was used to determine the angle of internal  
 374 friction. The angle of internal friction  $\varphi'$  is related to the stress ratio  $M$  (slope of failure  
 375 surface in the  $p'$ - $q$  plane, where  $p'$  = mean effective stress and  $q$  = deviatoric stress) as:

$$376 \quad M = \frac{6 \cdot \sin \varphi'}{3 - \sin \varphi'} \quad (21)$$



377

378 **Figure 12.** The CIU test results for (a) organic silty clay and (b) organic silt.



379

380 **Figure 13.** The CID test results for organic silt.

381

### 382 5.2.2. Results and interpretation

383

384

385

386

387

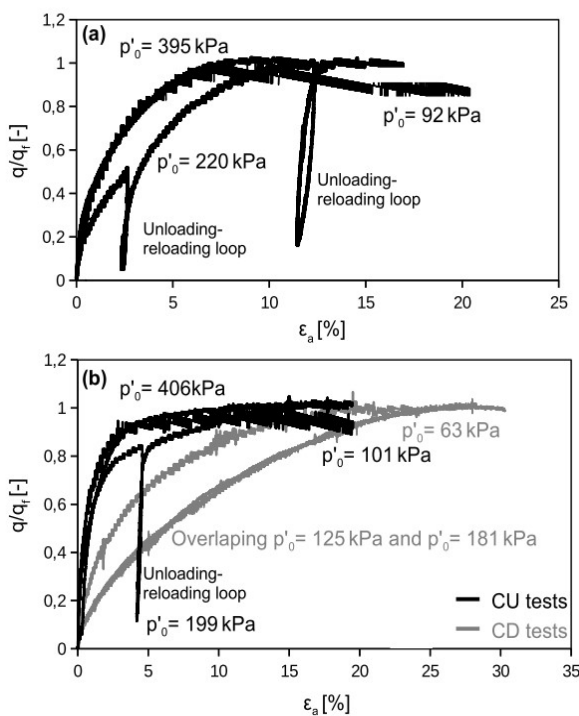
388

389

The results of the CIU triaxial compression tests are presented in Figure 12 in terms of deviatoric stress ( $q$ ) versus axial strain ( $\epsilon_a$ ) and stress paths in the  $p'$ - $q$  plane. Full strength mobilization in the organic silty clay required an axial strain of approximately 10%. The elastic modulus  $E_{50}$  (secant modulus corresponding to  $q = 0.5q_f$ ) normalized with respect to undrained shear strength ( $c_u = q_f/2$ , where  $q_f$  is deviatoric stress at failure) ranges between 76 and 102. The ratio between the unloading-reloading modulus  $E_{ur}$  and the  $E_{50}$  is equal to 1.74. The  $M = 0.967$  corresponds to an angle of internal friction of  $24.6^\circ$ . The maximum strength of



390 the organic silt (Figure 12b) is also mobilized at large values of axial strain. Stress ratio  $M =$   
 391 1.403 results in an angle of internal friction equal to  $34.6^\circ$ . The  $E_{50}/c_u$  ratio for organic silt  
 392 ranges between 180 and 234, while  $E_{ur}/E_{50} = 2.17$ . The CID triaxial compression tests on  
 393 organic silt (Figure 13) give almost the same failure envelope as the one obtained from the  
 394 CIU tests, with  $M = 1.31$  and  $\varphi' = 32.6^\circ$ . The response of specimens during shearing is clearly  
 395 contractive (Figure 13) and confirms the results of the updated CPTU classification according  
 396 to Robertson (2016).



397  
 398 **Figure 14.** Mobilization of deviatoric stress ratio with axial strains; (a) organic silty clay and  
 399 (b) organic silt.

### 401 5.3. Discussion

402 The organic soft soil in Jazowa has similar frictional parameters to soils from other  
 403 sites. For instance,  $\varphi' = 28^\circ$  for alluvial clayey silt is reported by Lambson et al. (1993), and  
 404  $\varphi' = 23\div 57^\circ$  for Juturnaiba organic clay is given by Coutinho and Lacerda (1989). However,

405 the angle of internal friction in soft deltaic soils is mobilized at an axial strain larger than  
406 10%, see Figure 14. The reported  $E_u/c_u$  ratios are slightly higher than those given for similar  
407 soils. For instance, for Osaka Bay mud,  $E_u/c_u \approx 40$  (Watabe et al., 2002). The organic silt  
408 behaviour in the CID triaxial compression test was contractive, which confirms the Robertson  
409 (2016) CPTU classification. This classification may, therefore, be considered a practical tool  
410 for qualitative descriptions of SBTn and comparison between drained and undrained shear  
411 strength.

412

413

## 6. Conclusions

414 A comprehensive geotechnical characterization of Vistula Marshlands deltaic soft soil  
415 from the Jazowa test site has been presented in this paper. The investigation concerned  
416 organic silty clay, organic silt, and peat interbeddings. The wide scope of the combined field  
417 and laboratory tests allows for the following conclusions to be drawn:

- 418 1. In case of organic soils, the CPTU and DMT classification test results do not match  
419 the USCS soil types. The discrepancies are smaller in the case of the Schneider et al.  
420 (2008) charts. It is worth noting that none of the in-situ-based classifications identifies  
421 peat as an organic soil.
- 422 2. The  $OCR$  values derived from oedometer tests are consistent with DMT and CPTU  
423 estimations. Five interpretation methods were applied to oedometer test results to  
424 determine preconsolidation stress. Pacheco Silva (1970) generally gives the lowest  
425 values of  $OCR$ , whereas the Becker et al. (1987) method gives the highest values.
- 426 3. Local empirical correlations between  $C_c$  and basic physical parameters (water content  
427 and bulk density) are proposed.
- 428 4. Similar  $c_u$  values are obtained using CPT, DMT and FVT soundings. The soil  
429 sensitivity based on FVT varies from low to moderate, i.e. 1.5 to 4.5.



430 5. The effective angle of internal friction equals  $24.6^\circ$  (CIU) for organic silty clay and is  
431 between  $32.6^\circ$  (CIU) and  $34.6^\circ$  (CID) for organic silt. The maximum shear strength in  
432 the considered organic soils is mobilized at an axial strain higher than 10%.

433 6. The Robertson's SBTn (2016) updated chart for dilative/contractive soil behaviour  
434 type can be used for soft soils in the Vistula Marshlands.

435 The above described research will improve geotechnical design in the Vistula Marshland  
436 area. It presents a wide range of geotechnical properties for deltaic soft soil deposits. The  
437 geotechnical characterization can be employed as reference data for foundation design and  
438 soil improvement in the soft organic soils of northern Poland.

439

440

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444

445

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