

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 (ρ_{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.

31

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



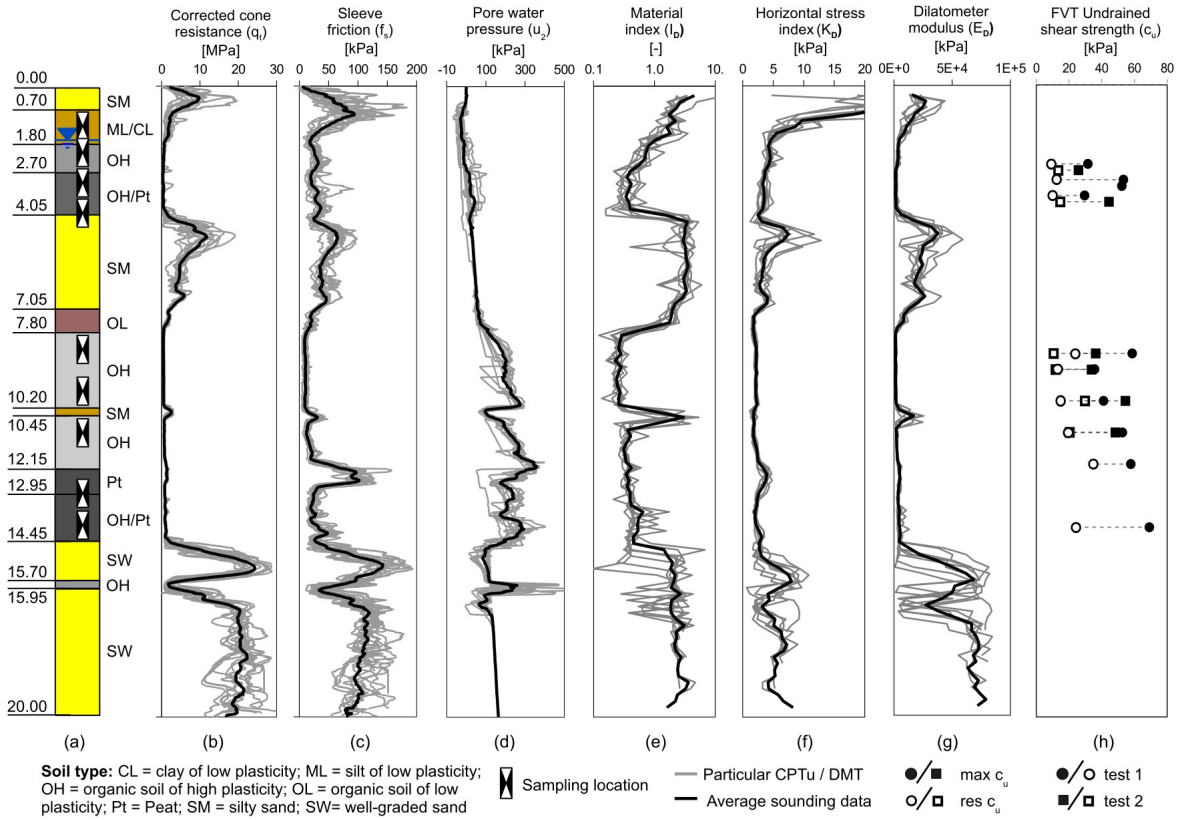
50 phenomena in the triaxial tests is compared to soil behaviour type according to Robertson's
51 (2016) chart.

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.



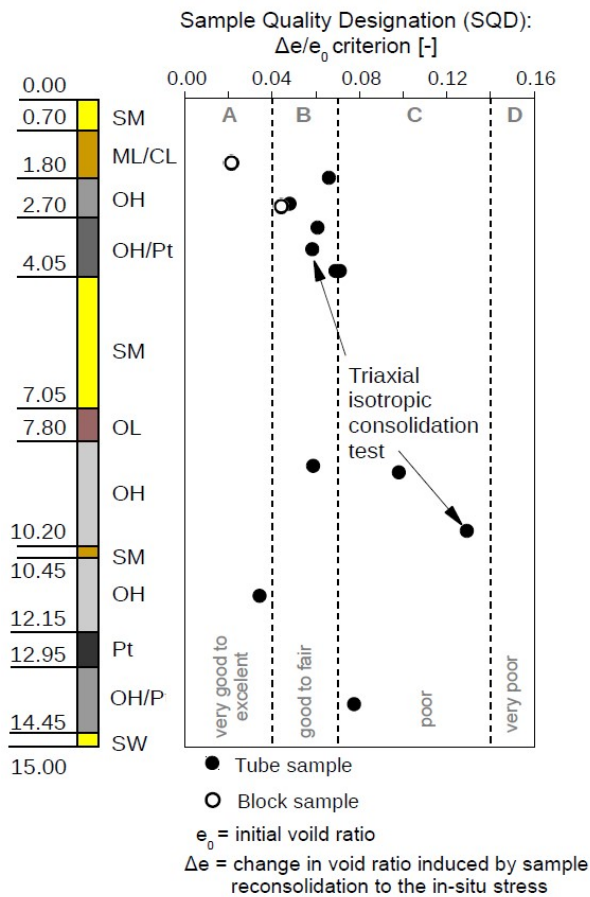
64
65 **Figure 1.** Location of the testing site. [no colour]



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 cm² 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, σ'_{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/cm³. In

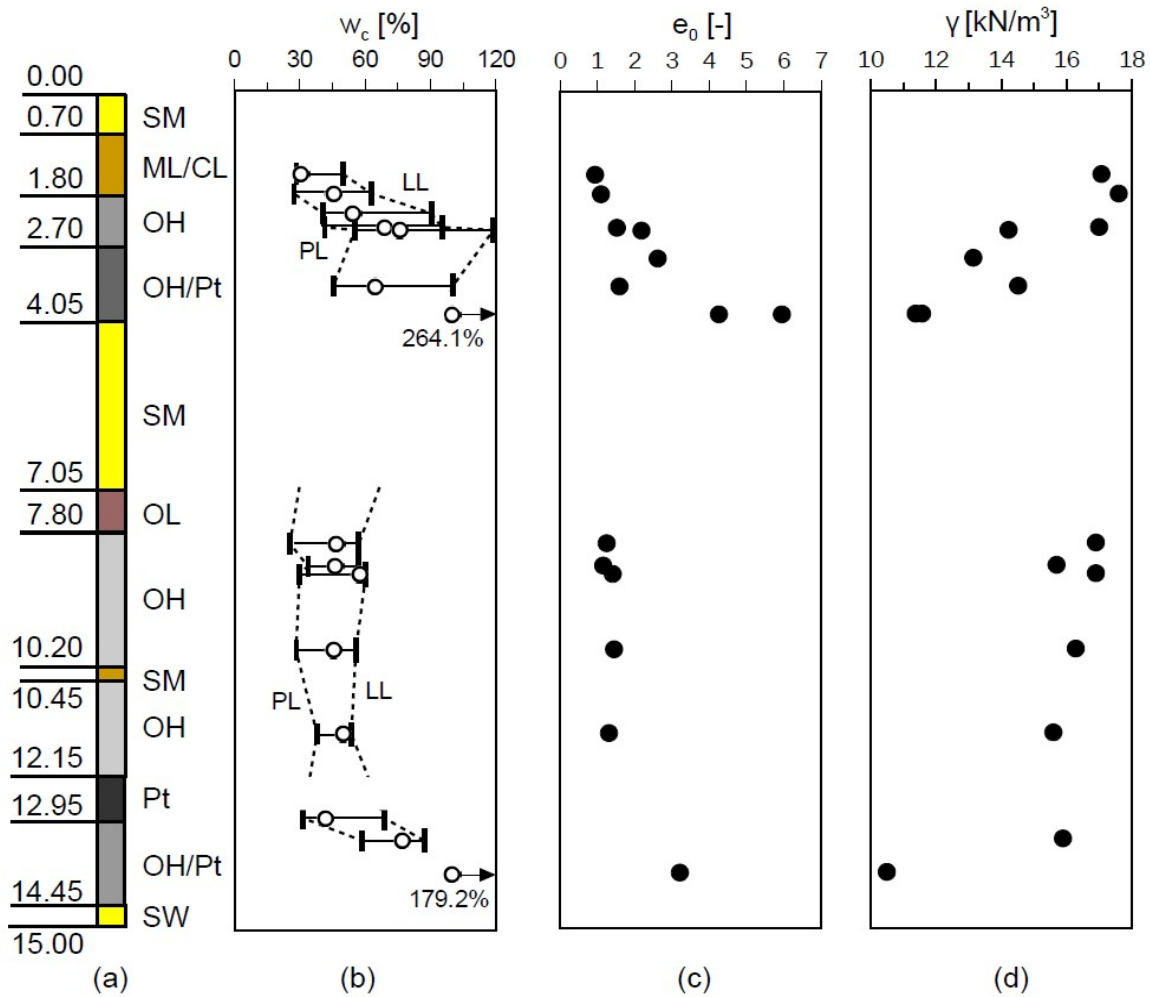


132 the case of peats, the specific gravity was much lower (between 1.6 and 1.7 g/cm³), on
 133 account of its fibrous structure (e.g., Cheng et al., 2007; Mesri and Ajlouni, 2007). The peat
 134 layers had a several times higher content of organic matter than the muds. This is in line with
 135 most 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> ⁽¹⁾	<i>Silt content</i> ⁽¹⁾	<i>LOI</i> ⁽²⁾	<i>pH</i> ⁽²⁾	<i>CaCO₃ content</i> ⁽¹⁾
	[m]	[%]	[kN/m ³]	[g/cm ³]	[%]	[%]	[%]	[%]	[-]	[%]
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, γ = 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, σ_{v0} = in-situ vertical total stress, σ'_{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.

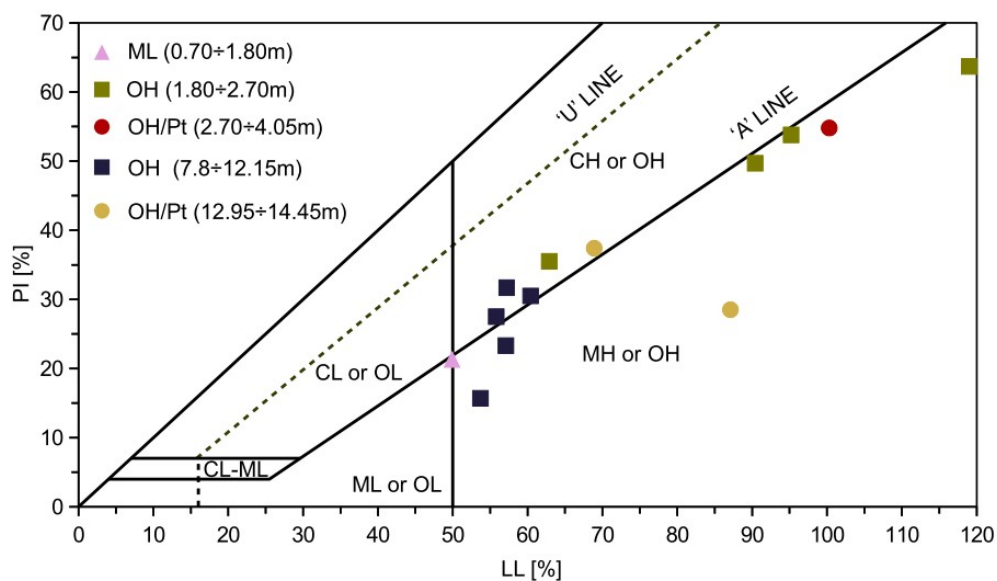
174 The last classification system was based on the Marchetti and Crapps (1981) DMT chart.

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 , Δu_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.



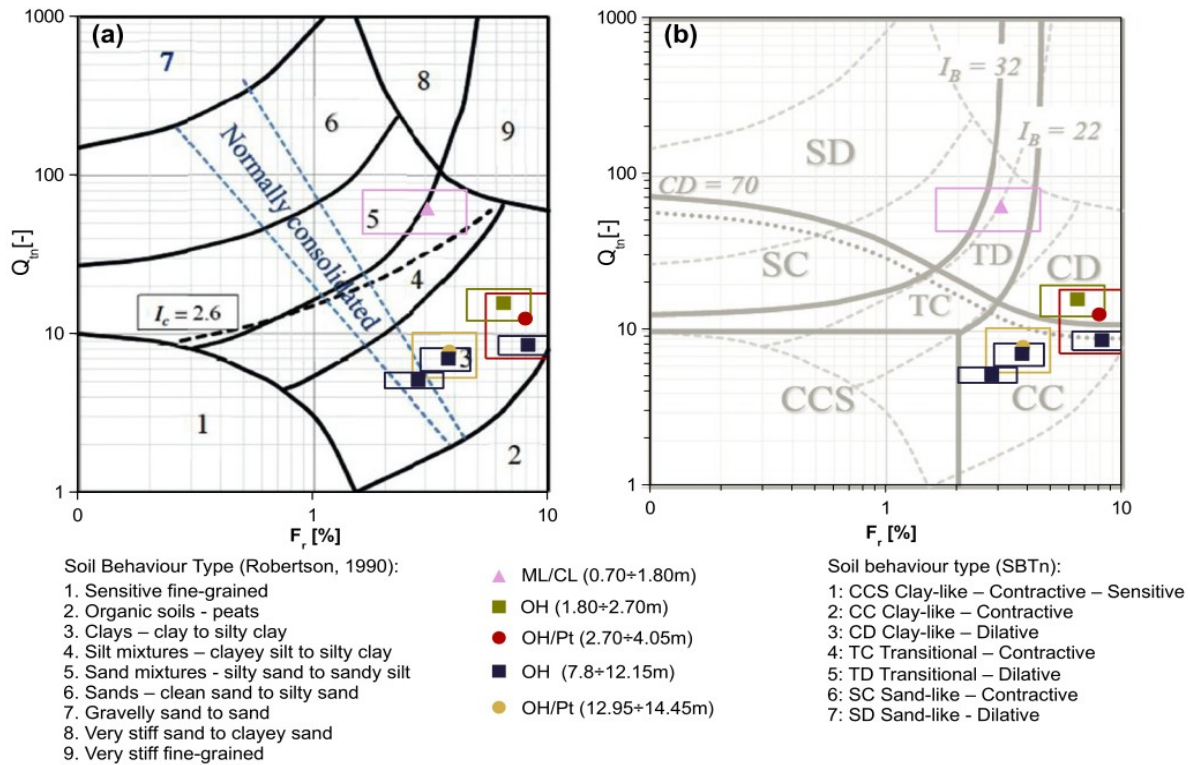
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192 **Figure 5.** Classification of layers according to ASTM D2487 (2017). [no colour]

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.

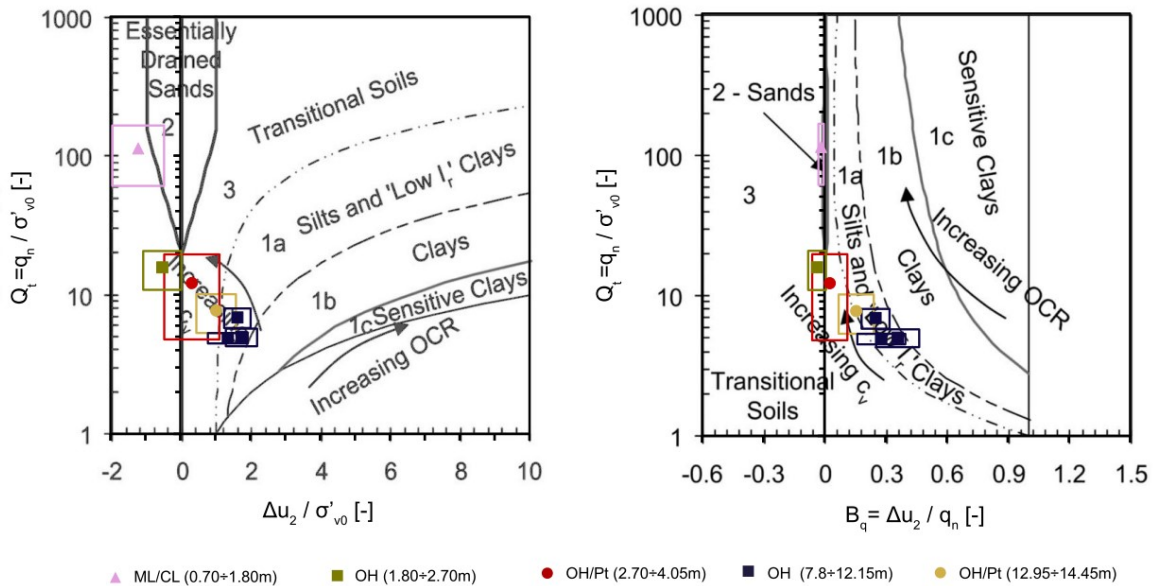


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218 **Figure 6.** CPTU based classification (error boxes based on standard deviation) for Jazowa

219 soft soil deposits: (a) Robertson's nomogram (1990; 2009) and (b) SBTn charts based on Q_{tn} -

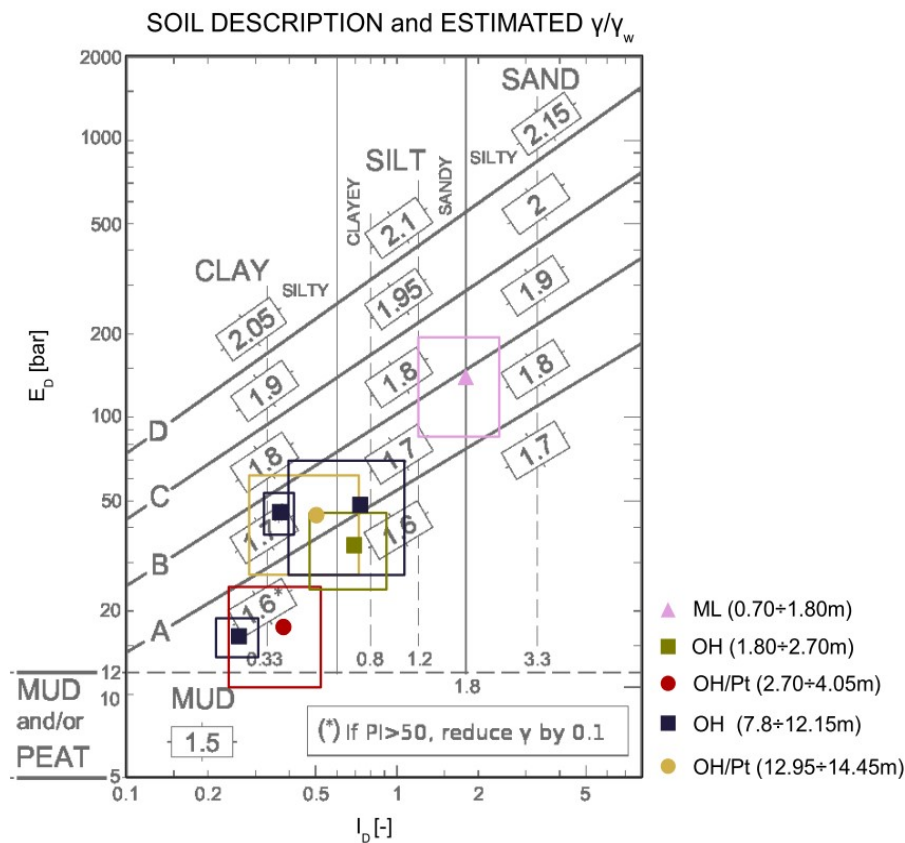
220 F_r (Robertson, 2016). [no colour]



221

222 **Figure 7.** Schneider et al. CPTU classification (2008) (error boxes based on standard

223 deviation). [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 σ'_p , swelling index (κ)
255 and compression index (λ) 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 σ'_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 (σ'_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 $0.6 \div 1.2$ m²/year (Lee et al., 1983), while for Jazowa organic silty clay it is

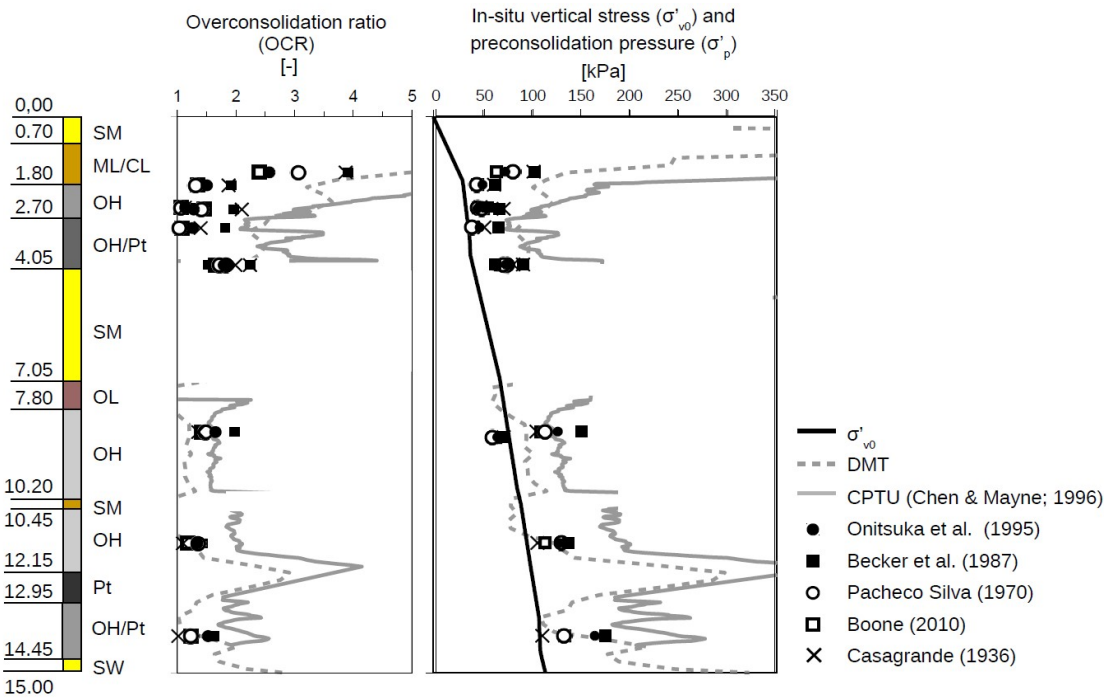
288 between 0.61 and 0.89 m²/year. The $c_v = 0.34 \div 0.62$ m²/year for Jazowa organic silt is close to
 289 the values given by Lowe et al. (1964), $c_v = 0.6 \div 3.0$ m²/year. The $c_v = 0.21 \div 2.66$ m²/year for
 290 peats are within the range reported by Mesri and Ajlouni (2007) for fibrous peats ($c_v =$
 291 $0.8 \div 8.1$ m²/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>	σ'_{v0} [kPa]	$c_v^{(1)}$ [m ² /year]	C_r [-]	C_c [-]	C_s [-]	λ [-]	κ [-]
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**

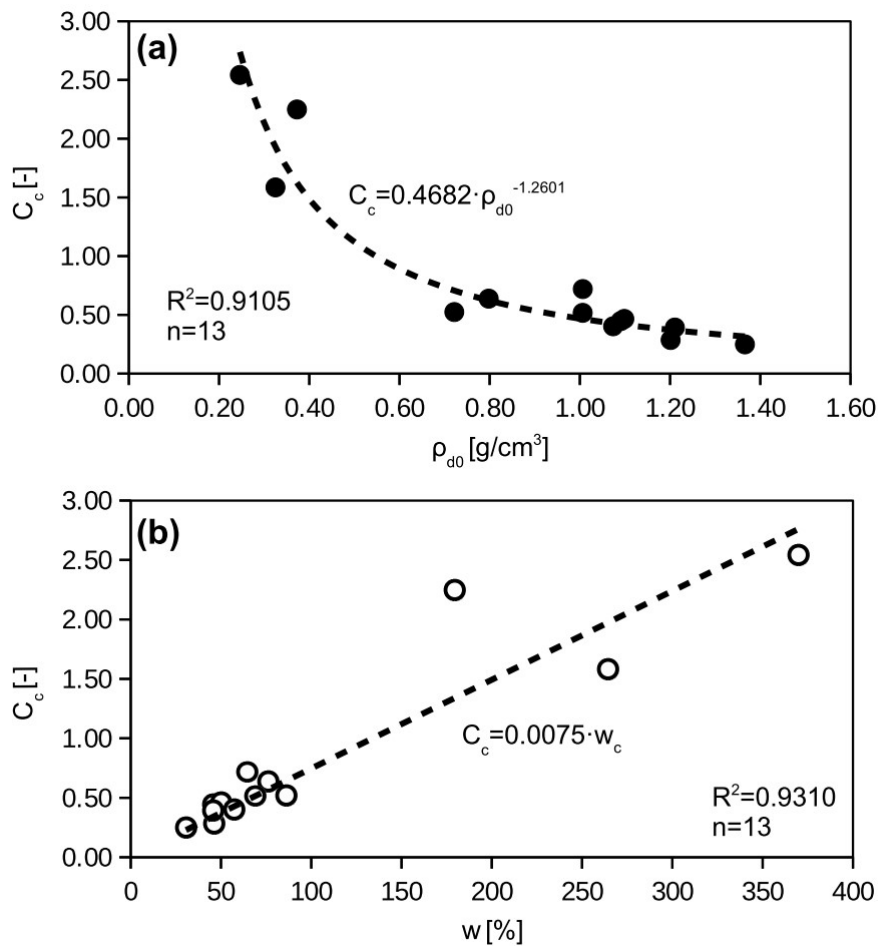
314 Different correlations between C_c and physical properties of soft soils were examined and the
 315 most promising relations were presented. For the Jazowa site, the relation between C_c and
 316 initial dry density ρ_{d0} (see Figure 10a) is:

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

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 ρ_{d0} and (b) C_c versus w_c .

325



326

5. Shear strength parameters

5.1. Undrained shear strength

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, σ_{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 μ_v (Chandler, 1988):

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

353 where c_{u-FVT} = undrained shear strength measured directly with FVT, μ_v = correction factor.

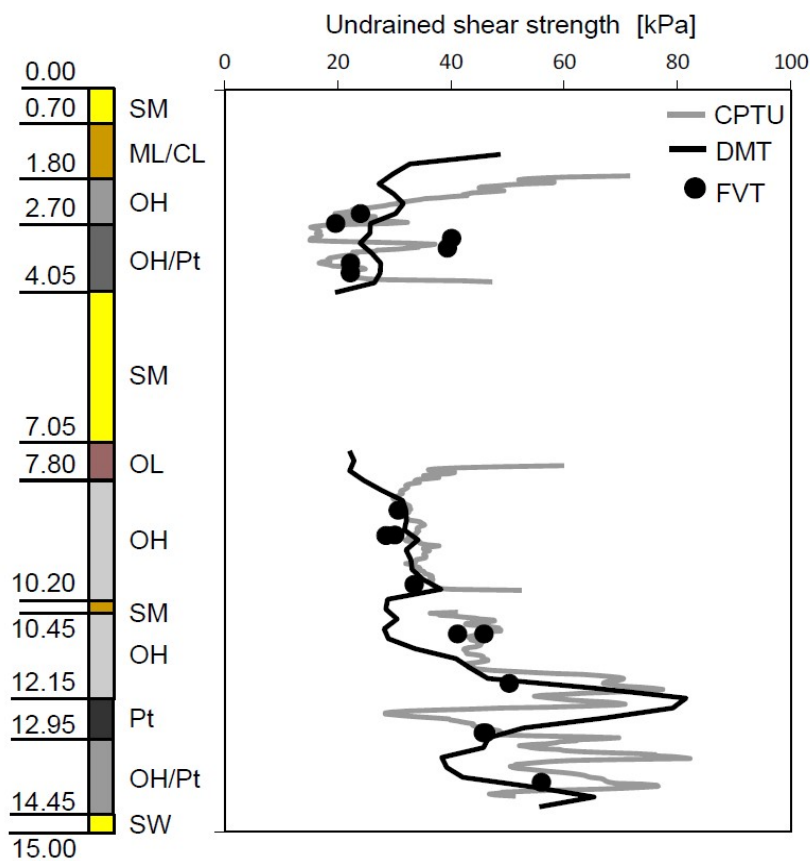
354 For muds, the μ_v was defined as:

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

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

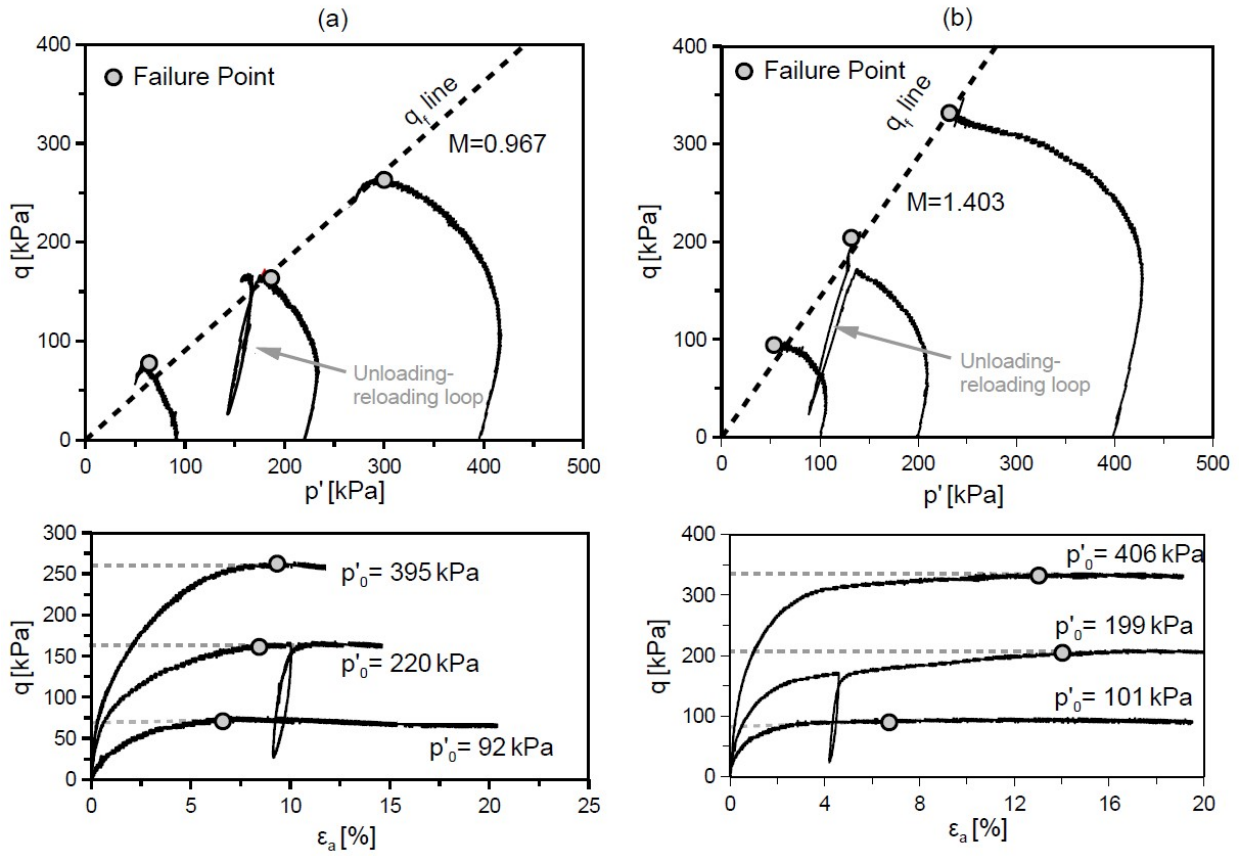
366 5.2. Frictional strength parameters

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 φ' 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:

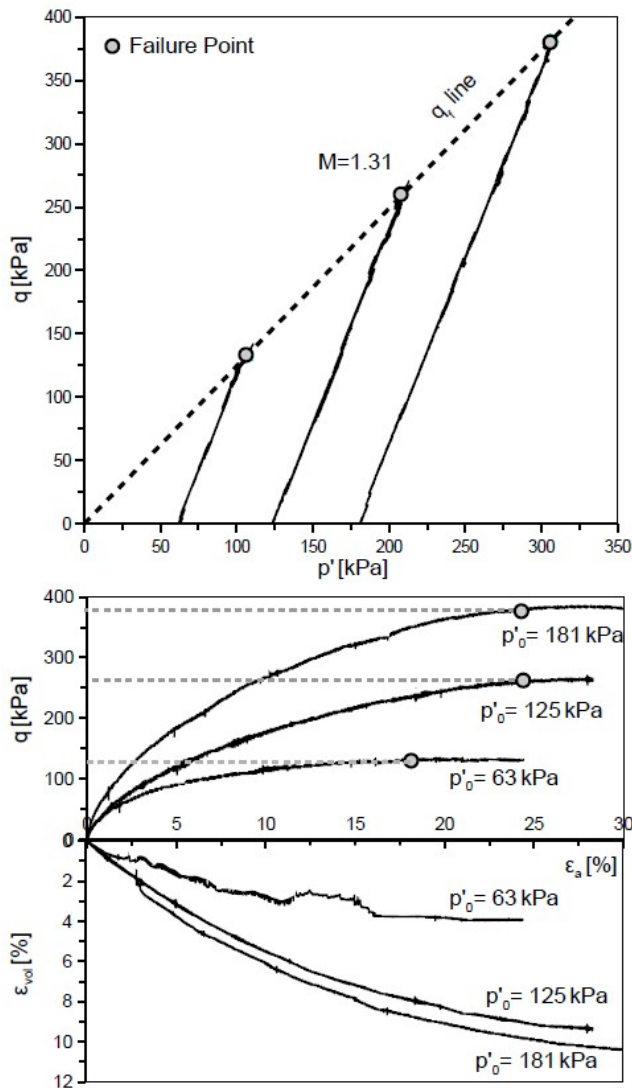
376

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



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

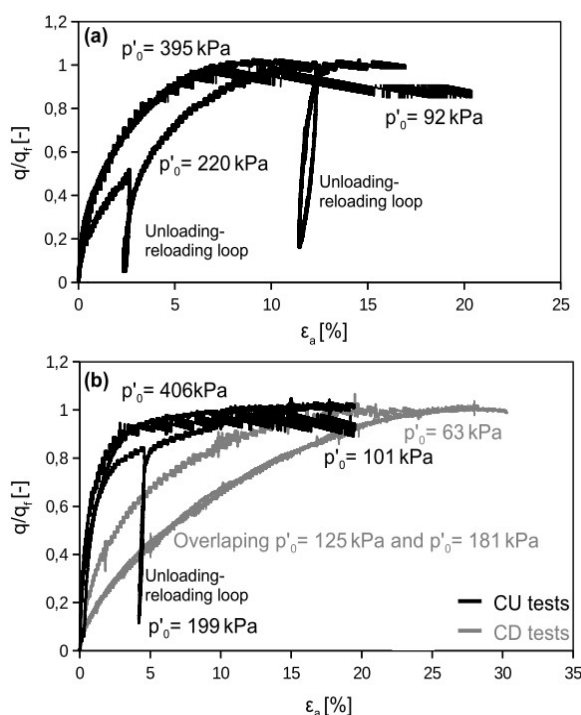
387

388

389

The results of the CIU triaxial compression tests are presented in Figure 12 in terms of deviatoric stress (q) versus axial strain (ϵ_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° . 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° . 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° (CIU) for organic silty clay and is
431 between 32.6° (CIU) and 34.6° (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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