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Influence of Soft Soil Samples Quality on the Compressibility and Undrained Shear Strength – Seven Lessons Learned From the Vistula Marshlands

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Abstract: This technical article presents the influence of sample quality on the compressibility parameters and undrained shear strength (c_u) of soft soils from the Vistula Marshlands. The analysis covers: (1) quality of soft soil according to three criteria: void ratio ($\Delta e/e_0$ index), volumetric strain ($\Delta\varepsilon_v$) and C_r/C_c ratio; (2) influence of storage time on quality; (3) influence of sample quality on undrained shear strength (c_u), and (4) reliability of compression and undrained shear strength parameters estimation. The sample quality of three different soft soils (peat, organic clays, and organic silts) was investigated using dataset of geotechnical investigations from the Vistula Marshlands. The reliability of oedometer tests and compressibility parameters determination was shown. Different undrained shear strength estimates (from lab and field tests) were juxtaposed with sample quality. In situ estimates of undrained shear strength were compared with results of triaxial tests and direct simple shear test on reconstituted samples as well as SHANSEP estimates.

The results of research are grouped in seven lessons. The most important outcomes are: (1) the quality of samples is at best moderate or poor and there is no significant influence of storage time on sample quality, (2) regardless of testing method, the undrained shear strength natural variability of the Vistula Marshlands soft soils is between 20% and 50% depending on deposit depth and soil type, (3) the most accurate estimation of undrained shear strength can be obtained from field vane test (FVT) while unconsolidated, undrained compression (UUC) triaxial tests should be avoided, (4) SHANSEP approach can be considered as a valuable estimate of c_u (next to the FVTs), which additionally allows in relatively easy way to establish lower and upper bounds of c_u.

Keywords: soft soils; soil sample quality; constrained modulus; deformation properties; undrained shear strength.

1 Introduction

Large infrastructure projects involving geotechnical design are a great opportunity to collect data that allow to evaluate currently used procedures. They also provide some guidelines to improve geotechnical design in the future. Such a critical analysis is in common interests for Academia and Industry as it can reduce costs, improve spending money for particular parts of geotechnical investigation process, and allow to optimize currently used procedures. This article aims for analysis of geotechnical investigation done in the past decade in the Vistula Marshlands involving soft soil deposits. The study is mostly concerned on the quality of soil sample taken from the region, its influence on compressibility parameters and undrained shear strength, i.e. the most crucial aspects involving soft soils. This article is divided into four major sections. The first one introduces problems related with sample quality, undrained shear strength, and compressibility parameters. The second invokes influence of soil sample quality on compressibility parameters. The third is focused on undrained shear strength, sensitivity of this parameter determination due to soil sample quality and its natural variability. The last (fourth) part summarizes this research and provides conclusions. Presented research and its outcomes can be someway treated as a continuation of the geotechnical description of the Vistula Marshlands soft soils that had started in the 1970s and 1980s. The soil investigation performed

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at that time by Gdańsk University of Technology, Polish Academy of Science and Geoprojekt were summarized in geotechnical reports by Gwizdała et al. (1983) and Stępkowska (1986). Since that time, to the best of author's knowledge, no comprehensive concerns was paid to Vistula Marshlands soft soils.

1.1 Soil sample quality

Soil sample quality is a crucial factor for proper estimation of soil strength and deformation parameters. Sample quality is usually related to cohesive, clay-like soils (Andresen & Kolstad, 1979; Hight, 2003; Karlsrud & Hernandez-Martinez, 2013; Karlsson et al., 2016; La Rochelle et al., 1981; La Rochelle & Lefebvre, 1971; Ladd & DeGroot, 2003; Lunne et al., 1997, 2006; Santagata & Germaine, 2002; Shogaki & Kaneko, 1994; Skempton & Sowa, 1963; Tanaka et al., 1996, 2002). The research conducted in the past years has shown that samples of lower quality exhibit lower strength and deformation parameters (i.e., lower constrained modulus M_0 and undrained shear strength c_u) than samples of higher quality (Karlsrud & Hernandez-Martinez, 2013; Lunne et al., 1997; Tanaka et al., 2002; Tsuchida, 2000). This is schematically presented in Figure 1. Consequently, the evaluation of sample quality and, therefore, reliability of design parameters become a crucial factor in infrastructure projects. Assessment of sample quality resulted in development commonly accepted quality criteria such as sample quality designation (SQD) (Terzaghi et al., 1996), change in void ratio (Lunne et al., 1997), oedometer stiffness ratio (Karlsrud & Hernandez-Martinez, 2013) and work-based criteria (DeJong et al., 2018). Most of them are designated to clay-like soils (Lunne et al., 1997; Terzaghi et al., 1996). The evaluation of sample quality in intermediate soils (silts) is less understood (DeJong et al., 2018; Viana da Fonseca & Pineda, 2017). Outside of the abovementioned criteria, there are methods that estimate sample quality based on suction and wave velocity measurements (Donohue & Long, 2010; Landon et al., 2007).

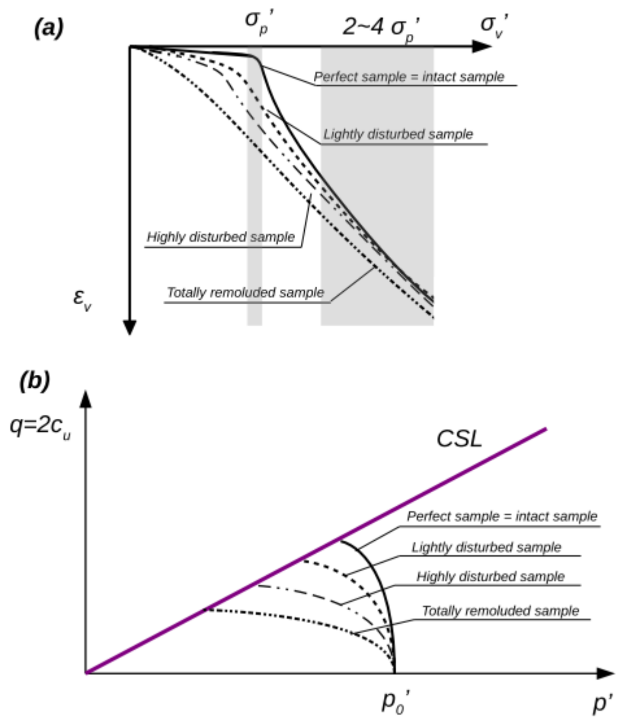

Figure 1: Schematic presentation of soft soil sample quality influence on (a) compressibility behavior and (b) undrained shear strength (Note: σ_v' = effective vertical stress; ε_v = axial strain; σ_p' = preconsolidation pressure; q = deviatoric stress according to Cambridge notation; p' = effective mean stress according to Cambridge notation; p_0' = initial mean stress; CSL = critical state line).

1.2 Soft soil compressibility parameters

Deformation properties are basic geotechnical parameters of soils. They are used in settlement calculation and the subsoil improvement with preloading and vertical drains. The most important deformation properties are related to consolidation and compressibility of soils. These include compressibility index (C_c), swelling index (C_s), and secondary compression index (C_α). In polish design practice, more popular is stress-dependent constrained (oedometric) modulus (M_0). The compressibility parameters are usually strongly influenced by sample quality (e.g., Shogaki & Kaneko, 1994). Furthermore, in the absence of direct data, compressibility parameters can be estimated using empirical equations (Kempfert & Gebreselassie, 2006). The C_c can be related to liquid limit (Bowles, 1984; Skempton & Jones, 1944; Terzaghi et al., 1996) , natural water content (Bowles, 1984; Koppula, 1981) void ratio (Bowles, 1984; Nishida, 1956), plasticity index (Kulhawy & Mayne, 1990), or more than one specific parameter (Rendon-Herrero, 1980; Wroth & Wood, 1978). The empirical relationships for C_s and C_α are less common. The C_s is related to plasticity index (Kulhawy & Mayne, 1990), natural water content or liquid limit (Scherzinger, 1991). The C_α is usually normalized with C_c and the typical C_α/C_c ratios are provided by Mersi and Godlewski (1977), Scherzinger (1991) and Klobe (1992).

1.3 Undrained shear strength (c_u)

Undrained shear strength (c_u) is basic parameter used in geotechnical design. The value of c_u is used in shallow foundation analysis, pile capacity calculation, soil improvement, and it is used for determination of piling technology. Undrained shear strength is one of the oldest and well-established parameter in any geotechnical design (Casagrande, 1932). However, it suffers many shortcomings that usually are neglected in interpretation, such as (1) strength anisotropy, (2) rate dependency, (3) sample quality, (4) disturbance during testing procedure, (5) in situ stress level, or (6) influence of soil preconsolidation (Ladd & DeGroot, 2003). Proper interpretation should take into consideration the above factors. Geotechnical industry usually assumes point value of c_u at specific depth. Such points designate distribution of c_u with depth. However, the c_u determined in the field can vary significantly, especially, in soft soils (Beesley & Vardanega, 2020). The estimation of natural variability and reliability of c_u becomes thus a crucial aspect in modern reliability-based geotechnical design.

1.4 The aims of this article

Presented research summarizes several years of soil investigation at the Vistula Marshlands undertaken in 2010s and such a comprehensive dataset allows some conclusions to be drawn in respect to soft soil behavior. After presentation of site and methodology, the topics are gathered in 7 lessons that can be delivered from soft soil investigation in the Vistula Marshlands in the last few years. First, the overall quality of samples from Vistula Marshlands is examined. The dataset includes three main soft soil types in the region and different times between sampling and testing (so-called storage time). Three sample quality criteria are investigated and the general quality of samples taken from the region with storage time influence is examined. The influence of sample quality on constrained (oedometric) moduli and compression indices is investigated. Some guidelines about natural variability and data interpretation is given as well as local correlation between physical properties and compressibility parameters. In the next part of the article, the sample quality is related with undrained shear strength obtained from unconsolidated undrained compression (UUC) triaxial test. The UUC c_u values are compared with field vane test (FVT) results. The influence of shearing rate is pointed out and differences between disturbed and perfect samples are shown. The article is closed by the practical guidelines about SHANSEP (Stress History and Normalized Soil Engineering Parameters) concept (Ladd, 1991) in estimation of undrained shear strength and its variability. The SHANSEP estimates are compared with different lab and field values.

2 Deltaic soft soils in the Vistula Marshlands

2.1 General description

Vistula Marshlands are spread over an area of 1700 km^2 located in Northern Poland, see Figure 2. Based on Vistula Marshlands geomorphology, soft soils of that region can be grouped into 4 categories: (1) silty/sandy loams, (2) organic clays, (3) organic silts, and (4) peats. All of them are of low sensitivity. The physical and index properties of each soil were evaluated statistically (Konkol & Balachowski, 2021) and the results are presented in Table 1. Silty/sandy loams are very shallow deposits (usually up to 1.5 m below ground level) and are omitted in the analysis presented in this article. Organic clays are shallow deposits, usually below the water table, and with high organic matter content (10%<LOI<30%). Organic silts are located in moderate and deep depths. They contain low-to-moderate organic content (5%<LOI<10%). Organic clays and silts sometimes contain small peat inserts. Peats were deposited at different depths, usually below the water table. The presented physical properties well covers the data in Gwizdała et al. (1983) and Stępkowska's (1986) reports.

2.2 Dataset description

The dataset used in this research covers 54 incremental loading (IL) oedometer tests performed with accordance to ASTM D2435 (2020) or PN EN ISO 17892-5 (2017). The data are divided in respect to storage time and soil type, see Table 2. The 24-h loading steps were used in IL tests regardless the end of primary consolidation was obtained or not. That loading scheme facilitates analysis and give consistent data. Furthermore, such a simple procedure is a common practice in geotechnical design industry (e.g., Ladd & DeGroot, 2003). All samples were loaded up to the vertical stress of 400 kPa. At this point the secondary compression tests have been carried out, which took from 5 to 10 days. The compression index (C_c) was determined using last 3 steps (100 kPa, 200 kPa, and 400 kPa) unless

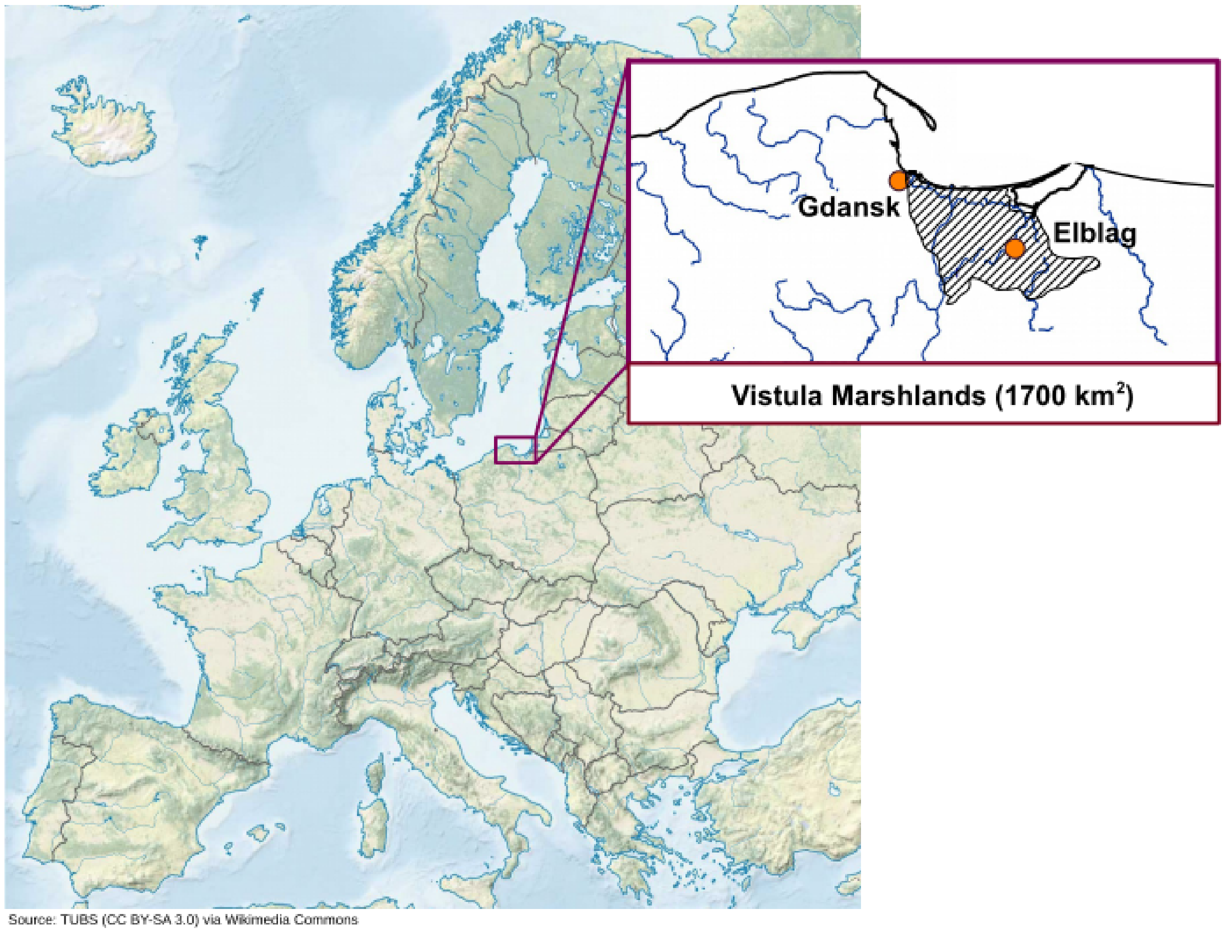

Figure 2: Vistula Marshlands, Northern Poland.

Table 1: Vistula Marshlands soft soils basic physical properties.

Physical/index properties	Soil			Standard
	Organic clay	Organic silt	Peat	
LOI	10%<LOI<30%	5%<LOI<10%	LOI>30%	ASTM D2974 or PN-ISO 10694
Fines	~50% of Cl and Si	~95% of Si	N/A	Laser diffraction method
wc	63.5±21.0	45.5±18.5	261±110.4	ASTM D2216 or PN-EN ISO 17892-1
ρ	1.58±0.16	1.74±0.18	1.17±0.27	ASTM D854 or PN-EN ISO 17892-2
G_s	2.61±0.06	2.60±0.06	2.04±0.32	ASTM D7263 or PN-EN ISO 17892-3
LL	82.5±32.1	52.0±21.0	268.9±115.7	ASTM D4318 or PN-EN ISO 17892-12
IP	50.1±25.1	29.4±13.8	159.4±87.5	ASTM D4318 or PN-EN ISO 17892-12
Casagrande's chart	Along and above A-line	Above A-line	N/A	ASTM D2487 or PN-EN ISO 14688-2

Note: LOI = loss on ignition (equivalent to organic matter content); w_c = water content; ρ = soil density; G_s = specific gravity; PL = plastic limit; LL = liquid limit; ± indicates standard deviation values

Table 2: Soil specimens used in soil sample quality evaluation.

Soil	Time of tests after sampling [number of tests]*			
	1 day	*Up to 1 week*	*2–3 weeks*	*Above 3 weeks*
Organic clay	8	7	3	4
Organic silt	6	4	4	7
Peat	6	1	4	–

*The information is gathered from the soil investigation reports.

stated otherwise. The unloading–reloading loop was performed at the following stress path 200 kPa → 25 kPa → 200 kPa.

2.3 Sampling methods

Soil specimens were usually sampled by "Shelby" tubes or different types of piston samplers. The Shelby tube is an open, stationary sampler and it is commonly used in Poland. It is a thin-walled sampler, usually approx. 500 mm long, and 75 mm in diameter with an approximately 3 mm wall. The sampler ends with a cutting edge of 30°. The piston sampler consists of a tube fitted with the piston. To obtain the soil sample, the piston is held stationary while the sample tube is driven (or jacked) down. To remove the sample from the tube, an extractor needs to be used. Extraction also can cause some disturbance to the sample, in particular in transitional soils (i.e., silts). The effect of tube sampling such as Shelby tubes on soft soil sample quality was extensively studied by Pineda et al. (2016), among others.

2.4 Sample quality designation (SQD) criteria

Tree rating criteria and relationships between them are used in quality evaluation. These criteria are pragmatic choice in design practice due to the possibility of application standard IL oedometer test data. They are: (1) change in void ratio (Lunne et al., 1997), (2) axial strain mobilized during recompression to in situ vertical stress (Terzaghi et al., 1996), and (3) ratio between recompression index and compression index (DeJong et al., 2018). Sampling and laboratory testing were performed by professional geotechnical companies from Poland according to applicable standards.

2.4.1 Volumetric strain ($\Delta\varepsilon_v$) criterion (SQD) (Terzaghi et al., 1996)

Disturbed soil specimen undergoes vertical unloading. The evaluation of strains upon recompression to in situ vertical stress was proposed by Andersen and Kolstad (1979) and Terzaghi et al. (1996). Terzaghi et al. (1996) assigned sample quality designation (SQD) rating based on vertical strains, see Table 3. This criterion is mostly dedicated to cohesive, inorganic soils.

2.4.2 Void ratio ($\Delta e/e_0$) criterion (Lunne et al., 1997)

Lunne et al. (1997) proposed $\Delta e/e_0$ criterion to evaluate sample quality. They suggest two ratings for two different ranges of OCR, see Table 3. This criterion is designated to moderate to highly sensitive clay with PI = 6÷55, OCR = 1÷4, and depth from 5 to 25 m (Lunne et al., 2006). It is also limited by the in situ void ratio. The criterion was based on samples with e_0 ranging between 0.86 and 1.23. It is also the most valid for soils plot along A-line. Careful evaluation should be taken for the assessment of sample quality for soils outside the mentioned characteristics.

2.4.3 Compression index (C_r/C_c) criterion (DeJong et al., 2018)

DeJong et al. (2018) proposed a framework to describe sample quality that uses recompression (C_r) and compression (C_c) indices, see Table 3. That criterion is more appropriate for low plasticity soils under low confining pressure. It is also less sensitive to OCRs and overburden stress.

2.4.4 Some critical insights into the quality criteria

From a practical point of view, the SQD is the easiest criteria to apply. It requires only IL oedometer test without any additional physical properties determination. The $\Delta e/e_0$ criterion requires specific gravity determination, which is crucial for organic soils due to high variability (e.g., Konkol & Balachowski, 2021; Réthási, 1988). The C_r/C_c criterion requires significant amount of vertical stress to be applied to proper estimate C_c (which is crucial for the quality of assessment). Soil sample quality based on IL oedometer tests also suffers the rate of inconsistency. The quality criteria were initially designed for CRS test (where negligible value of excess pore water pressure is produced). In IL tests, the rate of vertical displacement

Table 3: Soil specimens used in soil sample quality evaluation.

SQD (Terzaghi et al., 1966)		$\Delta e/e_0$ criteria (Lunne et al., 1997)			C_r/C_c (deJong et al., 2018)	
ε_{vol} at σ'_{vo} [%]	*SQD class*	*OCR 1-2*	*OCR 2-4*	*Rating*	*C_r/C_c*	*Rating*
<1	A	<0.04	<0.03	v. good to excellent (A)	<0.15	High
1-2	B	0.04-0.07	0.03-0.05	good to fair (B)	0.15-0.4	Moderate
2-4	C	0.07-0.14	0.05-0.1	Poor (C)	>0.4	Low
4-8	D	>0.14	>0.1	Very poor (D)	-	-
>8	E	-	-	-	-	-

can significantly vary and can include significant amount of creep (however, still relatively small-to-so-called primary consolidation). Thus, quality based on IL tests can be slightly underestimated.

2.5 Methods for undrained shear strength (c_u) evaluation

The different field, laboratory methods, and empirical approaches are considered to evaluate the c_u in Vistula Marshlands. The most widely and commonly used Polish industry methods include FVTs, electric piezocone penetration test (CPTU) estimation, and UUC triaxial test. The other methods are less often applied. For instance, the c_u estimation based on the SHANSEP method (Ladd, 1991) and oedometer tests are rarely met.

2.5.1 Field vane tests (FVT)

The FVT tests are widely used in geotechnical investigation for almost 100 years (Chandler, 1988). FVT test consists of vane insertion into the subsoil and following rotation with the rate of 0.1°/s (6°/min). The standard vane is 130 mm in height and 65 mm in width. Classical interpretation is that undrained shear strength can be derived from FVT as:

$$c_u = \frac{0.86M}{\pi D^3} \tag{1}$$

where: M = torque and D = vane diameter. However, there are many factors that affect the undrained shear strength measured directly from FVT: (1) nonlinear stress distribution around the blade, (2) soil anisotropy, (3) vane insertion effects such as reconsolidation between insertion and rotation and blade thickness, (4) vane rotation effects, (5) rod friction, and (6) shearing in undrained conditions. The assumption of nonlinear stress distribution increases the calculated c_u by almost 10% (Chandler, 1988). Soil anisotropy, resulted from shearing mode, decreases the c_u by 5–10% (Chandler, 1988). The measured soil anisotropy resulted from soil fabric can vary between 1.14 and 1.4 (O'Kelly, 2006). The insertion effects can lower the c_u by 8%–11%, but this issue is generally the most important in sensitive soils (Roy & Leblanc, 1988). The vane is rotated with a rate of 0.1°/s, which is approx. 700%/h. As the reference strain rate is assumed to be 1%/h, the rate correction should be applied to take this effect into account (Roy & Leblanc, 1988). The most popular correction uses Chandler (1988) proposition as presented in ASTM D2573 (2015):

$$\mu_v = 1.05 - b \cdot (PI)^{0.5} \tag{2}$$

where: b = time to failure coefficient equal to 0.045, as suggested by ASTM D2573 (2015), which corresponds to time to failure equal to 10,000 min. For peat, μ_v = 0.5 is suggested (e.g, Gołębiewska, 1983). The torque measured should be reduced by estimated or measured rod friction. The insertion and shearing should be performed in undrained conditions. Roy and Leblanc (1988) suggest maximum 1 min delay between insertion and beginning of rotation. Higher delay can produce reconsolidation of the soil and thus, increase c_u by 10% in 10 min and 20% in 40 min. The rate of vane rotation equal to 0.1°/s is usually enough to preserve undrained conditions. It was shown that coefficients of consolidation (c_v) lower than 110 m2/year are required to preserve undrained shearing with vane rotation of 0.1°/s. Bearing in mind the above comments, one can notice that many factors that influence FVT measurement cancel each other, i.e., (1) and (3) can be canceled by (2) and (6). Generally, the only correction applied in standards is the one that originates from rate effects. Finally, the c_u determined from FVT is closest to the average mode of shear (or DSS shear mode).

2.5.2 Unconsolidated undrained triaxial compression (UUC)

UUC tests can exhibit many errors, which make c_u determined from UUC test very unreliable. These errors are: (1) shearing rate close to 60%/h, which increase c_u in comparison to shearing with a rate of 1%/h, (2) anisotropic effects are neglected, which leads to increased value of c_u, and (3) UUC tests are strongly affected by sample quality. These errors usually can be compensated by each other without any control (Ladd & DeGroot, 2003).

2.5.3 Direct simple shear tests

Direct simple shear tests can be used for determination of the c_u due to preserved undrained condition (ASTM D6528, 2017) in so-called constant volume tests. The errors that influence the results are (1) rate of shearing, (2) device construction, and (3) quality of the sample. (1) can be taken into account by performing several tests with different rates. (2) is usually out of control (displacement sensor location influences vertical movement of the vertical actuator during CV tests (Konstadinou et al., 2021)). (3) Quality of the sample can reduce the c_u (Karlsrud & Hernandez-Martinez, 2013; Lim et al., 2019).

2.5.4 Cone penetration tests (CPTU) estimates

CPTU estimates of c_u reflects the average shear mode. The c_u is calculated using net cone resistance and cone factor N_{kt}:

$$c_u = (q_t - \sigma_{v0})/N_{kt} \tag{3}$$

where: q_t = corrected cone resistance and σ_{v0} = total vertical stress. The problem is that cone factor is usually influenced by many factors: (1) rigidity index ($I_r = G/c_u$) which is also strain-dependent (Mayne, 2006), (2) roughness of cone and sleeve (Teh & Houlsby, 1991), (3) soil anisotropy (e.g., Baligh, 1985), and (4) rate of the cone penetration (Roy et al., 1982). These factors make estimation of the c_u hampered and designates N_{kt} to specific locations and conditions. They also enforce calibration of N_{kt} on a specific reference test (TX, DSS, or FVT) (Mayne & Peuchen, 2018). Usually, the good quality reference test on a good quality sample at the specific site is required to obtain reliable N_{kt} estimate. The N_{kt} = 14, as suggested by Robertson (2016), is usually assumed for soft, normally consolidated soils. One should bear in mind that selected N_{kt} factor have to take into account the various abovementioned factors.

2.5.5 SHANSEP estimates

SHANSEP relates the undrained shear strength with preconsolidation ratio of the soil (Ladd, 1991):

$$c_u/\sigma'_{v0} = S \cdot OCR^m \tag{4}$$

where: σ'_{v0} = in situ vertical effective stress; m = 0.88(1-C_s/C_c); C_s = swelling index; C_c = compression index; and OCR = overconsolidation ratio. Value of S depends on the shearing mode (Ladd, 1991). When one is interested in average shearing mode, S = 0.26 for organic soft soils and m approx. to 0.8 should be used (Ladd, 1991). However, SHANSEP method allows for better or worse c_u estimation, as it strongly depends on OCR. The proper determination of OCR depends on soil sample quality can vary significantly depending on interpretation method (e.g., Boone, 2010). This is a very crucial aspect in low consolidation rage, where OCR between 1 and 4 can strongly influence calculated c_u.

3 Results and Discussion

3.1 Lesson 1: Sample quality of soft soils is usually moderate or poor

The quality of the Vistula Marshlands soft soil samples according to various criteria is presented in Figure 3, and the comparison between criteria is presented in Figure 4. In terms of peats, the sample quality are usually B and C ($\Delta e/e_0$ criterion), C and D ($\Delta\varepsilon_{vol}$ at σ'_{v0} criterion), and high quality (C_r/C_c criterion). Organic clay samples are of B and C class ($\Delta e/e_0$ criterion), C and D ($\Delta\varepsilon_{vol}$ at σ'_{v0} criterion), and high (C_r/C_c criterion). Organic silt samples can be characterized by C and D class ($\Delta e/e_0$ criterion), D and E rating ($\Delta\varepsilon_{vol}$ at σ'_{v0}) and moderate to low quality (C_r/C_c criterion). The general observation is that majority of samples is at least of moderate (or fairly good) quality. This is not surprising, as Shelby tubes usually provide sample of C- and B-class quality (Di Buò et al., 2019; Lim et al., 2019), and it is almost impossible to obtain better quality of sample. Generally, the worst sample quality was obtained for organic silts. For organic clays and peats the samples were of fairly good to poor quality. Such a low quality of the samples also underestimates the preconsolidation pressure, and thus field methods are usually more accurate in determination of preconsolidation pressure and OCR (Ladd & DeGroot, 2003).

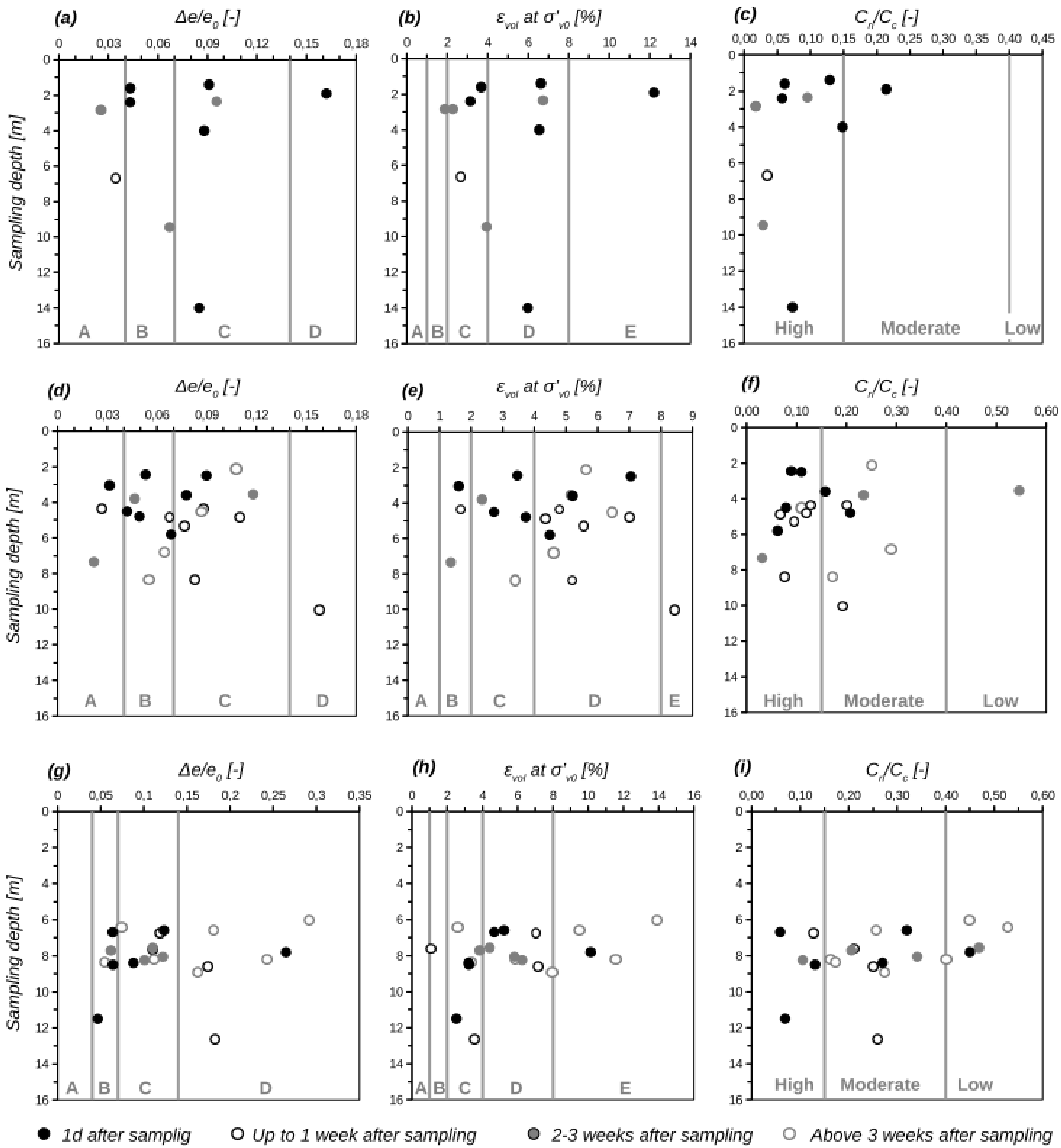

Figure 3: Soil sample quality according to different rating systems for peats (a,b,c), organic clay (d,e,f), and organic silt (g,h,i).

The compatibility between criteria is questionable. The best agreement between $\Delta e/e_0$ and C_r/C_c is obtained for organic silt. The same observation can be made between $\Delta e/e_0$ and $\Delta\varepsilon_{vol}$ at σ'_{v0} criteria for peats and organic clays. The $\Delta e/e_0$ and C_r/C_c ratings are not compatible. The comparison between $\Delta e/e_0$ and $\Delta\varepsilon_{vol}$ at σ'_{v0} criteria shows one class lower quality for $\Delta\varepsilon_{vol}$ at σ'_{v0} criterion than $\Delta e/e_0$. This sparks a question as to what quality criterion one should apply. The $\Delta e/e_0$ works well for soft clay-like materials (Lunne et al., 1997), $\Delta\varepsilon_{vol}$ at σ'_{v0} and C_r/C_c are more general, but their application to peats is strongly questionable (due to significant amount of water leakage during sampling and usually high swelling after resubmerging in water), but it is used (e.g., Mesri & Feng, 2019). The other problem with C_r/C_c criterion in soft soils is its incompatibility with other criteria, which

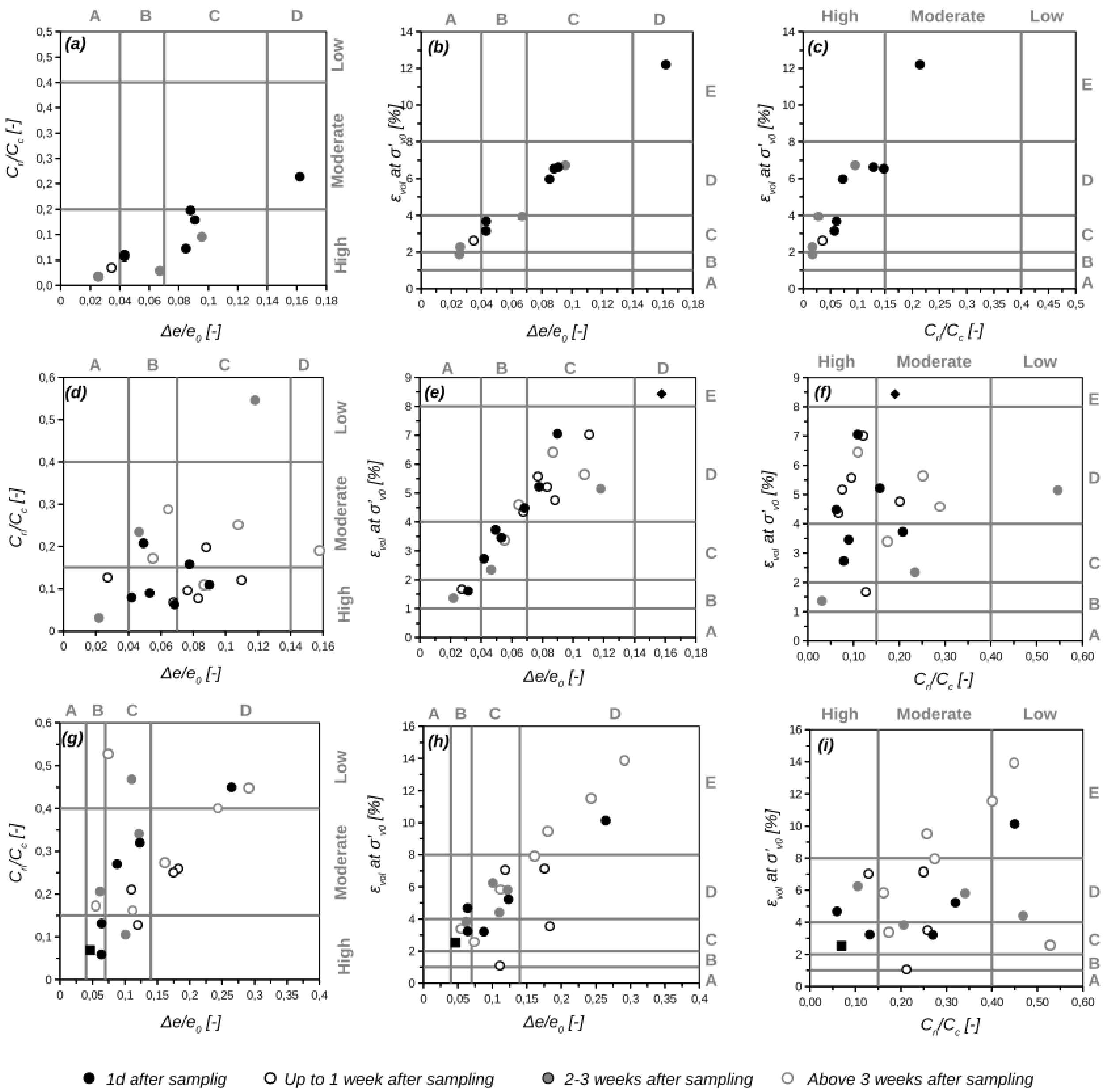

Figure 4: Relationships between different SQD criteria for peats (a,b,c), organic clay (d,e,f), and organic silt (g,h,i).

is quite opposite to the standard soils tested by DeJong et al. (2018).

3.2 Lesson 2: Storage time does not significantly influence quality of samples

Storage time does not significantly influence the soil sample quality, see Figure 2. The major disturbances are made due to direct sampling procedure. This is quite typical for low sensitive soft clays (Amundsen & Thakur, 2019; Lim et al., 2019) and can be an advantage. Typical engineering practice suggests to reduce the time period between sampling and lab testing (Amundsen & Thakur, 2019). However, if a significant loss of quality is unstoppable during sampling, the storage time becomes a factor of less importance.

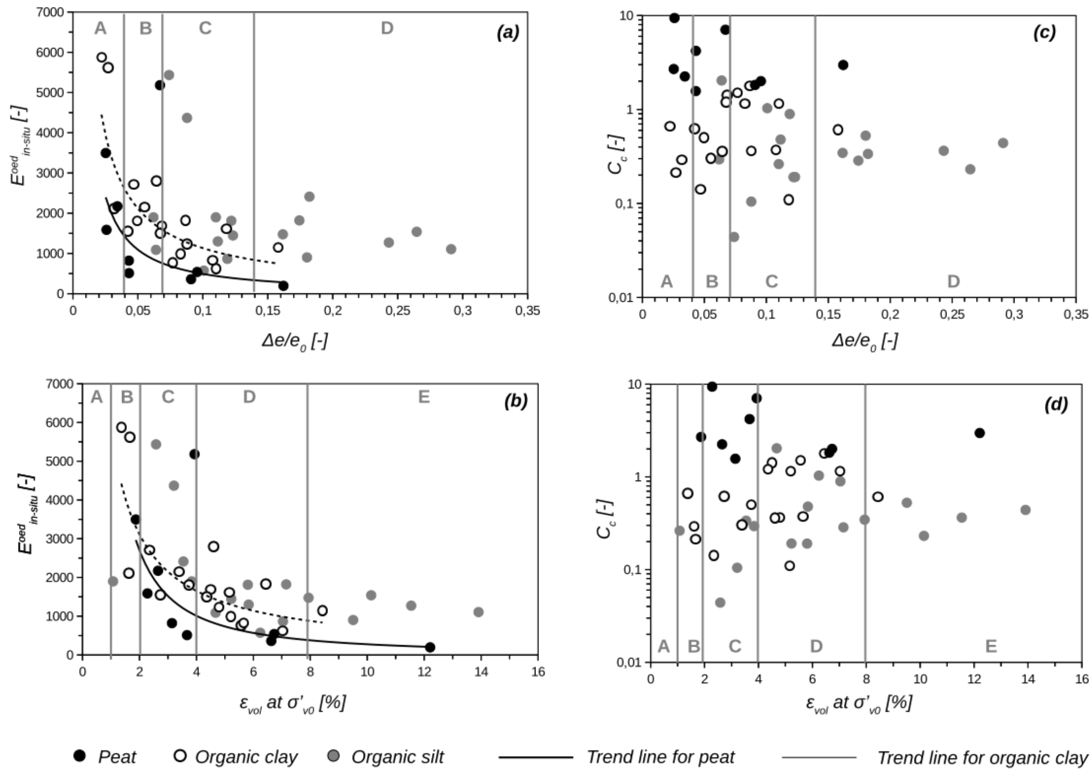

Figure 5: Influence of sample quality on oedometric modulus and compression index.

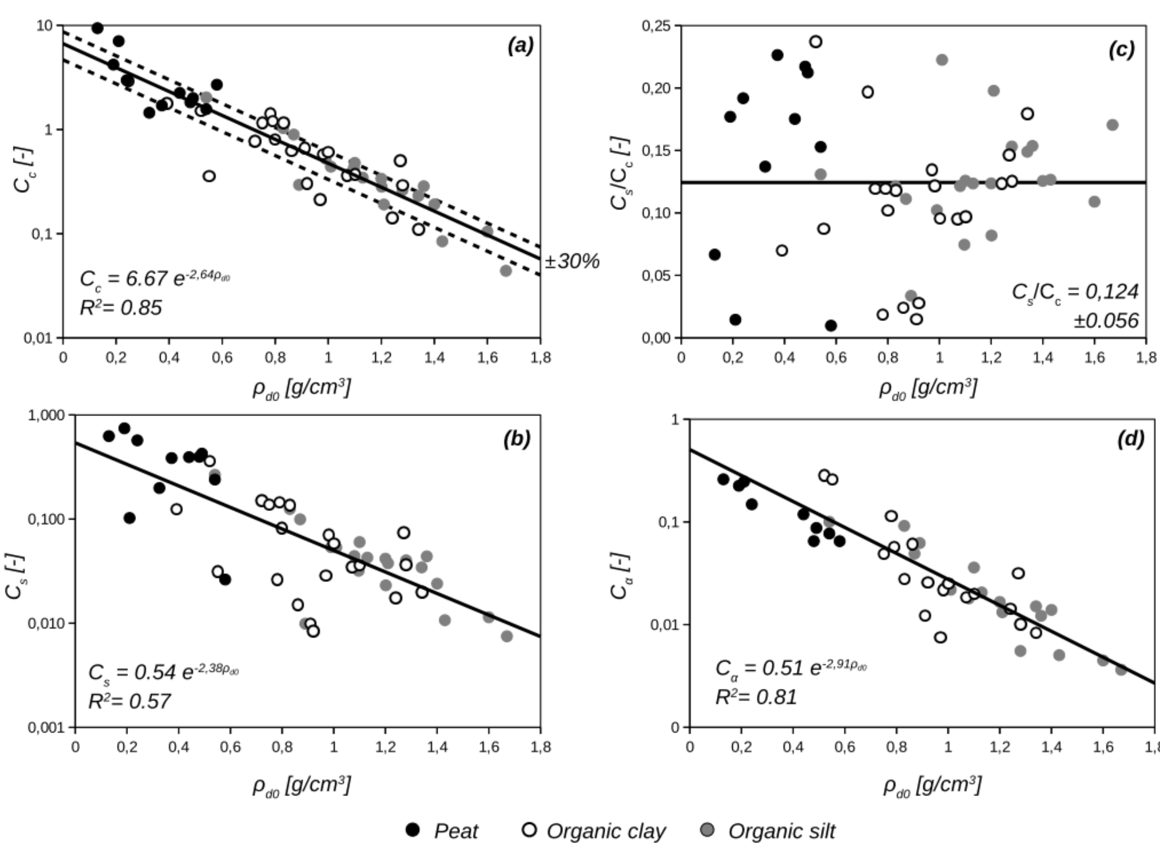

Figure 6: Local relations of (a) C_c, (b) C_s, (c) C_s/C_c and (d) C_α with ρ_{d0}

3.3 Lesson 3: Soil Sample quality influences constrained modulus but has limited influence on compressibility, swelling and creep indices

Figures 5a and 5b present the general picture of sample quality influence on oedometric (constrained) modulus for in situ stress level. For peats and organic clay there is clear trend that oedometric modulus decreases with sample quality. The highest values are for A-class samples ($\Delta e/e_0$ criterion) or A- and B-class samples ($\Delta\varepsilon_{vol}$ at σ'_{v0} criterion). For typical quality of samples (moderate and poor) the differences are negligible. For organic silt the results are extremely scattered with no clear trend. Thus, these soils are the hardest to possess in quality accepted for testing. Figures 5c and 5d present sample quality indices versus compression index (C_c). No clear trend is observed. This suggest that natural variability is a main factor that governs the sample behavior. The relation between C_s and C_α with sample quality criteria also does not show any significant trend. Consequently, a conclusion can be drawn, that C_c, C_s, and C_α are rather independent from sample quality in typical sampling procedure using tube samplers.

3.4 Lesson 4: Local relationships between deformation indices and initial bulk densities

Konkol et al. (2019) presented the preliminary relationship between C_c and initial dry bulk density (ρ_{d0}). Relationships with other parameters were not satisfactory. The concept of such relationship has strong practical advantage. Dry bulk density can be calculated directly with initial water content (w_c) and soil density (ρ), which are commonly determined for soft soils in any geotechnical investigation. Here, this concept was extended to swelling (C_s) and secondary compression (C_α) indices, see Figure 6. The best agreement is obtained for compression index while the worst for swelling index. The highest data scatter is observed for organic clay. The reason of such phenomenon can be related to small peat inserts in organic clay samples. Those small inserts does not change the bulk density of the whole sample directly, but can influence swelling and secondary compression. One should notice, that C_c–ρ_{d0} relationship can however suffer from a few drawbacks:

1. Sample quality. The value of C_c can be related to soil sample quality (e.g., Shogaki & Kaneko, 1994). In the research of Shogaki and Kaneko (1994), there was 30% difference in C_c values between samples quality of A class and D class. The differences in C_c from high and low quality samples are also negligible for C_c determined at high level of consolidation stress (higher than two or three times the preconsolidation stress) (e.g., Holtz et al., 1986; Tanaka, 2000). Bearing that in mind, natural variability seems to be much more influencing factor (see Lesson 3) as long as C_c is determined for higher stress levels.
2. ρ_{d0}, w_c, and ρ are also sensitive to sample quality. It was shown that ρ_{d0} variability for soft soils from the region can be about 25% (Konkol & Balachowski, 2021), being however one of the lowest among all considered physical and index parameters.
3. Combing the above two points leads to the conclusion that some scatter in C_c based on ρ_{d0} is unavoidable.
4. The correlations with ρ_{d0} have no physical meaning (Nagaraj & Srinivasa Murthy, 1986) and is similar to universal compression equation by Rendon-Herrero (1980). Thus, it is only a practical guideline.

3.5 Lesson 5: Knowledge of soft soil variability is critical for proper interpretation of soil compressibility parameters for disturbed samples

Some concerns related to natural soil variability were raised in previous sections. This topic will be now put forward. In order to exclude the influence of sample disturbance and to clarify the overall picture of the sample behavior in one-dimensional compression, the example based on 9 samples of D-class will be shown. All specimens were sampled in the same location and obtained from 4 different borings. More details are provided in Table 4. As one can see, samples No. 1 and No. 2 are from the same tube, separated by only few centimeters. Samples No. 3 and No. 4 are from the same depth but different borings (separated by about 10 m), samples No. 5 to No. 9 are from two neighboring borings. Samples No. 6 and No. 7 have very large water content in comparison to other samples. During lab testing, the soil in tubes was very varied in terms of plasticity (very plastic and close to liquid). The reason of natural variability or disturbance produced during sampling remains unclear. To summarize, even of uncertain status of samples No. 6 and No. 7, it can be said that organic silt has water content between 40% and 60%, soil density between 1.4 and 1.8, and specific gravity between 2.52 and 2.58. These values are in the range of typical parameters reported in Table 1.

Table 4: Natural variability of the organic silt samples for oedometric tests.

Sample no	*Boring no*	*Sample depth [m]*	*Test method*	w_c [%]	ρ [g/cm³]	G_s [-]	*Notes*
1	O3	10.5-11	24h IL	50.6	1.46	2.58	Sample few cm to no.2
2	O3	10.5-11	24h IL	59.9	1.29	2.58	Sample few cm to no.1
3	O1	9.5-10	24h IL	51.4	1.57	2.57	O1 borehole is at distance of 10 m from O2
4	O2	9.5-10	24h IL	42.9	1.71	2.54	O2 borehole is at distance of 10 m from O1
5	O3	9.3-9.8	24h IL	48.0	1.80	2.58	
6	O3	10-10.5	24h IL	91.0	1.39	2.46	Very variable water content and plasticity of soil in the tube
7	O4	10-10.5	24h IL	103.5	1.37	2.26	Very variable water content and plasticity of soil in the tube
8	O4	10.5-11	24h IL	55.8	1.53	2.52	-
9	O2	9.5-10	CRS*	41.2	1.68	2.57	-

Note: w_c = water content; ρ = soil density; G_s = specific gravity; IL = incremental loading oedometer test

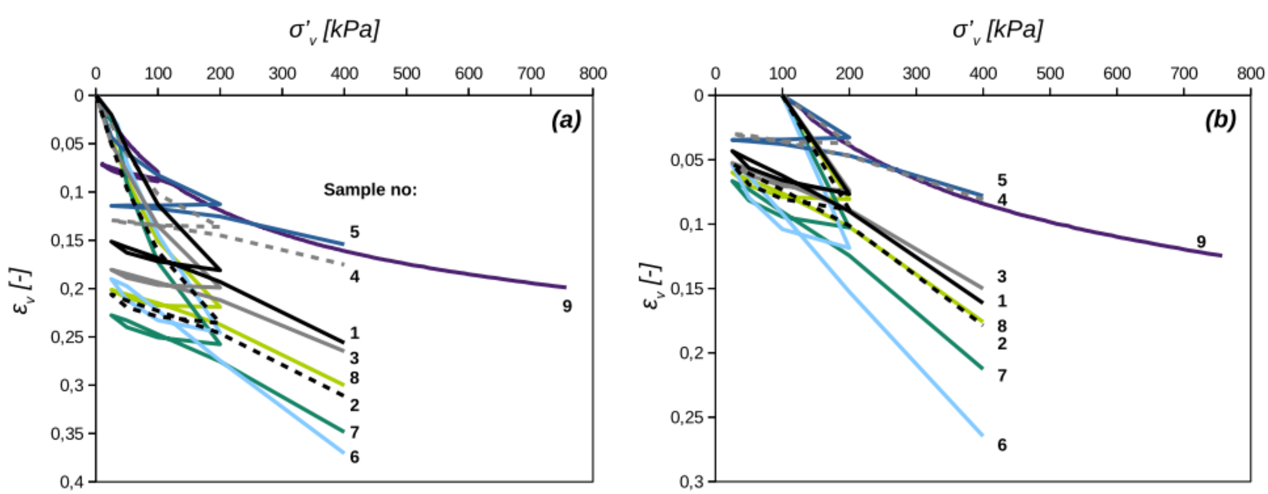

Figure 7: (a) Raw oedometer results (lab selected seating stress level is the reference one; usually approx. 5 kPa) and (b) "corrected" plots due to soil sample disturbance (in situ stress level is the reference one, here 100 kPa).

The raw oedometer results are presented in Fig 7a. As one can see, the analysis of these curves can be quite difficult. To facilitate the interpretation and to exclude the significant portion of the sample disturbance due to sampling, the oedometer results were drawn in respect to starting point for vertical stress of 100 kPa, which is an equivalent to in situ vertical stress at the site. The results are summarized in Figure 7b. Such a different presentation clarifies the interpretation and shows some trends. Compression curves can be divided into 2 groups. The first group contains samples No. 1, 2, 3 6, 7, and 8. The second one contains the rest of the samples. It is significant that samples No. 3 (O1) and No. 4 (O2) differ so much, but were poses from the same formation, separated by a distance of 10 m. This indicates that the inherent variability can be predominant for these deposits. Furthermore, such a variability was observed in the laboratory, where in the same tube soil varies in terms of plasticity, and the selection of "representative" sample was very difficult. In this research, all soil from tube was extruded and investigated just after sampling. In typical lab tests, such a procedure is unordinary, which can increase the uncertainty of sample selection and test outcomes.

Tables 5 and 6 show the variation in oedometric moduli and compression coefficient depending on the reference level (lab-selected seating stress level or in situ stress

Table 5: Variability of constrained modulus and compression index for first group of soils (samples No. 1, 2, 3, 6, 7, and 8).

Sample no	E^{oed} [kPa]	E^{oed}_{corr} [kPa]	$C_c^{\ 100\text{-}200kPa}$ [-]	$C_c^{\ 200\text{-}400kPa}$ [-]	ρ_{d0} [g/cm³]	$C_c^{\ eq.(5)}$ [-]	*RE* [%]
1	1468	1304	0.601	0.557	0.973	0.511	14.9
2	1342	1125	0.788	0.687	0.811	0.783	0.5
3	1565	1351	0.525	0.434	1.037	0.432	17.7
6	983	843	1.141	1.077	0.728	0.976	14.4
7	1175	973	0.951	0.816	0.673	1.127	18.6
8	1462	1240	0.583	0.536	0.982	0.499	14.4
AVG	1332	1140	0.764	0.684	-	-	-
SD	198	181	0.221	0.213	-	-	-
COV	0.14	0.16	0.29	0.31	-	-	-

Note: E^{oed} = oedometric (constrained) modulus; E^{oed}_{corr} = oedometric (constrained) modulus corrected due to sample disturbance; C_c = compression index, number in brackets indicated stress range; ρ_{d0} = initial dry bulk density; RE = relative error; AVG = average; SD = standard deviation; COV = coefficient of variation.

Table 6: Variability of constrained modulus and compression index for second group of soils (samples No. 4, 5, and 9).

Sample no.	E^{oed} [kPa]	E^{oed}_{corr} [kPa]	$C_c^{\ 100\text{-}200kPa}$ [-]	$C_c^{\ 200\text{-}400kPa}$ [-]	ρ_{d0} [g/cm³]	$C_c^{\ eq.(5)}$ [-]	*RE* [%]
4	2949	2679	0.239	0.215	1.196	0.283	18.4
5	3311	3058	0.213	0.203	1.216	0.269	26.3
9	3125	2905	0.243	0.291	1.189	0.288	18.6
AVG	3128	2881	0.232	0.236	-	-	-
SD	147	155	0.013	0.039	-	-	-
COV	0.05	0.05	0.06	0.16	-	-	-

Note: E^{oed} = oedometric (constrained) modulus; E^{oed}_{corr} = oedometric (constrained) modulus corrected due to sample disturbance; C_c = compression index, number in brackets indicated stress range; ρd0 = initial dry bulk density; RE = relative error; AVG = average; SD = standard deviation; COV = coefficient of variation.

level). The differences are small in terms of constrained moduli and none in terms of compression index (it is theoretical consequence of definition of C_c, where $C_c = \Delta e/\Delta\log\sigma_v$'). The most interesting feature of Tables 5 and 6 is average value of C_c and E^{oed} and their variability. For first group of soils $C_c = 0.701 \pm 0.209$ and $E^{oed} = 1332 \pm 198$ kPa, while for second group, the $C_c = 0.236 \pm 0.039$ and $E^{oed} = 3128 \pm 147$ kPa. One can also find very good performance of local relationship for C_c (see Figure 6a):

$$C_c = 6.67e^{-2.64\rho_{d0}} \tag{5}$$

The error between calculated and measured value is in the range of natural variability of C_c.

3.6 Lesson 6: FVT tests can be as good as lab tests on perfect samples

Sample quality influences undrained shear strength (e.g., Karlsrud & Hernandez-Martinez, 2013; Lim et al., 2019). The influence of sample quality on UUC c_u is shown in Figure 8. The c_u seems to be more influenced by inherent variability than sample quality, see Figure 8a, where all data from the Vistula Marshlands is gathered. Figure 8b shows the results of FVT tests. The FVT values (already corrected due to rate effects, see eq. (2)) are usually higher than the UUC values. Such a conclusion can be drawn both from the general picture for Vistula Marshlands (Figures 8a and 8b) and for specific location in Vistula Marshlands (Jazowa testing site, see Figure 8c). The reasons can

Table 7: Jazowa testing site—different c_u estimates.

Sample no	Type ($\Delta e/e_0$)	Sampling/Testing depth [m]	Soil type	Test method	c_u [kPa]	Rate	c_u normalized to 1%/h [(1)] [kPa]
1	In situ (B)	8	orSi	UUC	24.2	70%/h	18.9
2	In situ (B)	9	orSi	UUC	27.3	70%/h	21.3
3	In situ (B)	10	orSi	UUC	28.2	70%/h	22.1
4	In situ (B)	10	orSi	UUC	29.3	70%/h	22.9
5	In situ (N/A)	8.5	orSi	FVT	30.7[(2)]	0.1°/s (700%/h)	30.7[(2)]
6	In situ (N/A)	9	orSi	FVT	30.1[(2)]	0.1°/s (700%/h)	30.1[(2)]
7	In situ (N/A)	9	orSi	FVT	28.5[(2)]	0.1°/s (700%/h)	28.5[(2)]
8	In situ (N/A)	10	orSi	FVT	33.5[(2)]	0.1°/s (700%/h)	33.5[(2)]
9	Reconstituted (A)	9	orSi	CK_0UC	32.7	1%/h	32.7
10	Reconstituted (A)	9	orSi	CK_0UC	29.3	1%/h	29.3
11	Reconstituted (A)	9	orSi	DSS	27.2	20%/h	22.8
12	Reconstituted (A)	9	orSi	DSS	29.3	20%/h	24.5

Note: (1) Rate dependency of organic silt was observed in lab and field tests. These tests indicates that c_u increases of about 15% in one log cycle due to strain rate increase; (2) FVT tests were already corrected due to rate effects according to equation (2).

be related to the limitations of UUC tests mentioned in Section 2.6.2. Consequently, the UUC tests are not the best choice for soft soil testing in general, and the accurate value of c_u can be a pure luck. On the other hand, the UUC c_u values are always lower than FVT, which provide very conservative estimation.

More precise influence of sample disturbance on c_u is presented in Table 7 where the different type of tests are summarized for Jazowa testing site. To achieve meaningful comparison, the c_u is normalized to rate equal to 1%/h. The rate dependency of organic silt was observed in lab and field tests. These tests indicates that c_u increases of about 15% in one log cycle of strain rate. The FVT tests are within good agreement with CK_0UC triaxial tests on reconstituted A-class samples. The DSS values are slightly lower than those in CK_0UC, which indicates undrained shear stress anisotropy (Jamiolkowski et al., 1985). The UUC tests are underestimated over 30% (when the rate correction is applied). However, uncorrected values are in good agreement with CK_0UC and FVT. That supports Ladd and DeGroot's (2003) argument that UUC test results depend mostly on pure luck. In this example, the UUC tests were conducted on B-class samples. Samples of lower class may return much lower c_u.

3.7 Lesson 7: SHANSEP estimates can satisfactorily describe uncertainties of undrained shear strength

3.7.1 General remarks

Owing to natural uncertainties of c_u, sample disturbance, and sometimes pure performance of UUC triaxial tests, the SHANSEP method can be a good tool for estimation of c_u in soft soils. In this section, three examples of application of SHANSEP method for soft soils will be shown. The analysis covers all possible c_u estimates with a range of uncertainty (included are TX results, CPTU estimates, and FVT values).

3.7.2 Organic silt (location No. 1—Jazowa testing site)

This is the best investigated site. The c_u estimates covers CPTU (15 tests in grid of 2 x 2 m), FVTs, UUC triaxial tests on in situ, B-class samples ($\Delta e/e_0$ criterion) as well as CK_0UC, CK_0UE, DSS tests on reconstituted samples, and SHANSEP estimates. The CPTU estimates were determined with equation (3). A small variation in N_{kt} = 14.5±1.5 and vertical stress (COV = 5%) was used. FVT values are corrected due to rate effects (Eq. (2)). UUC c_u will be shown as corrected and uncorrected values due to rate effects. The results of CK_0UC, CK_0UE, and DSS are for rate of shearing equal to

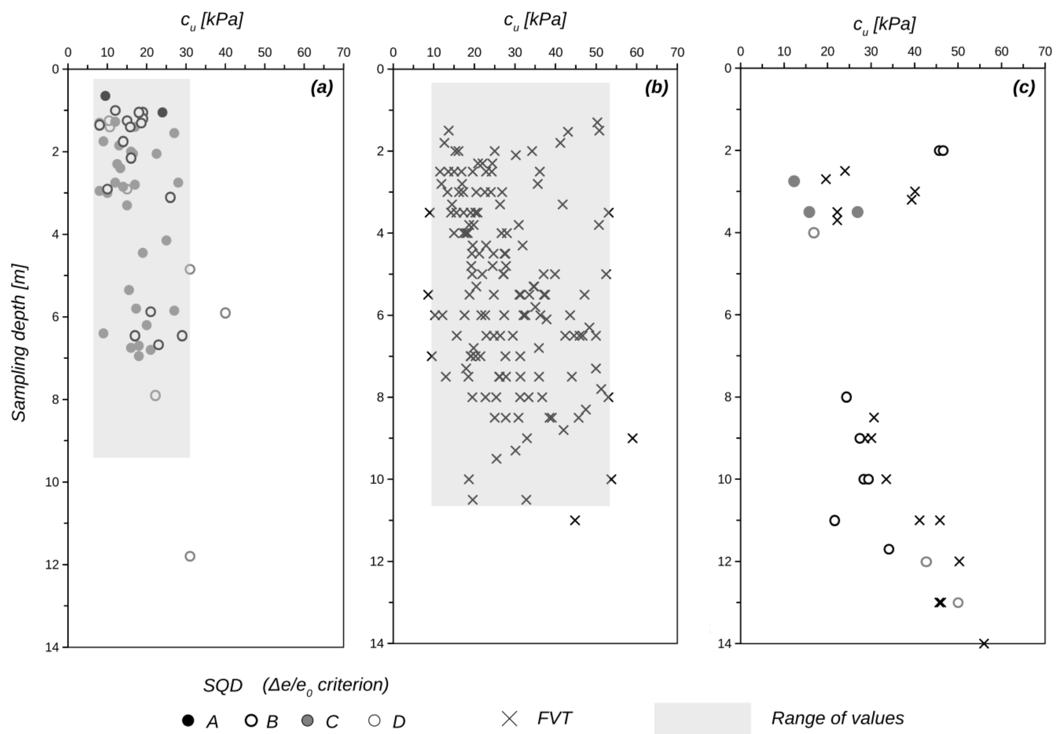

Figure 8: General picture of undrained shear strength of soft soil in Vistula Marshlands: (a) UUC test results, (b) FVT tests, and (c) specific location values (Jazowa testing site).

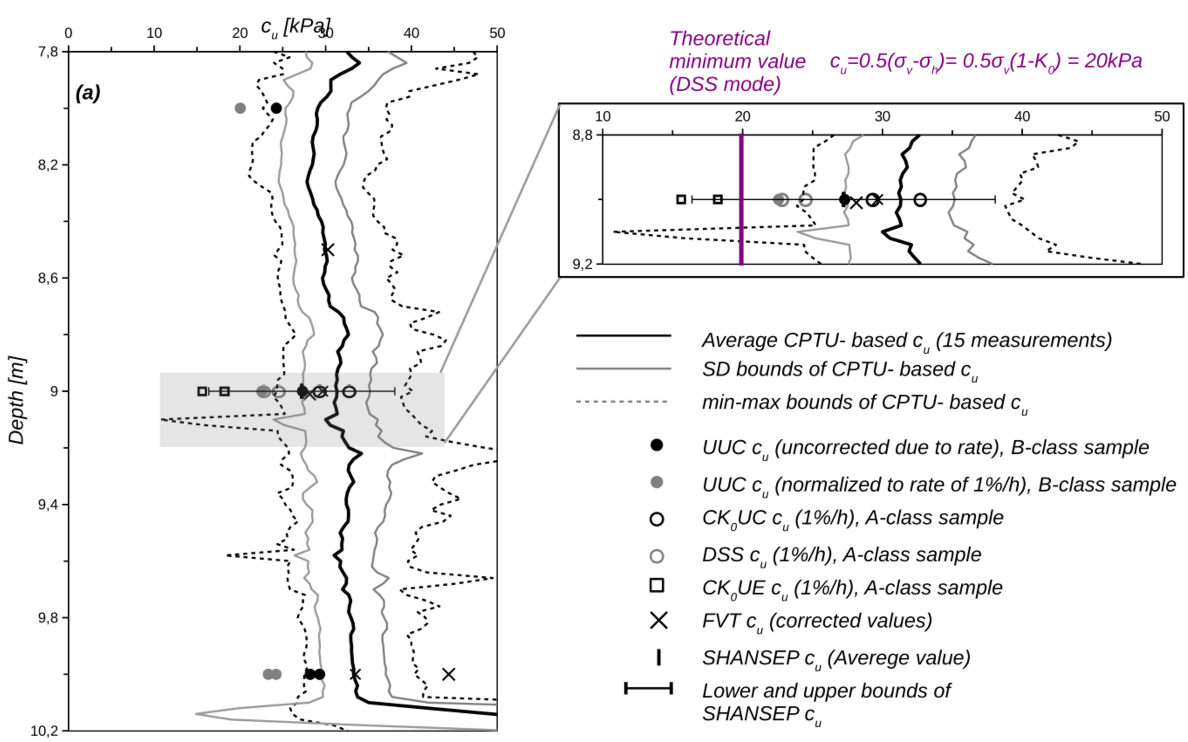

Figure 9: Different estimates of c_u for Jazowa site.

Table 8: Organic clay—different estimates of c_u (location No. 2).

Sample no.	Type ($\Delta e/e_0$)	Sampling/Testing depth [m]	Soil type	Test method	c_u [kPa]	Rate
1	In situ (D)*	2-3	orCl	CK_0UC	17.0	1%/h
2	In situ (D)*	2-3	orCl	CK_0UC	23.4	1%/h
3	In situ (D)*	2-3	orCl	CK_0UE	15.2	1%/h
4	N/A	2-3	orCl	SHANSEP	18.2±9.5	N/A

* In K_0 (or anisotropic) consolidation triaxial tests, the influence of sample disturbance is marginal due to sample restoration to in situ conditions.

Table 9: Organic clay—different estimates of c_u (location No. 3).

Sample no.	Type (SQD)	Sampling/Testing depth [m]	Soil type	Test method	c_u [kPa]	Rate
1	In situ (D)	9-10	orSi	CK_0UC	26.4	1%/h
2	In situ (D)	9-10	orSi	CK_0UC	32.7	1%/h
4	N/A	9-10	orSi	SHANSEP	25±5.2	N/A

* In K_0 (or anisotropic) consolidation triaxial tests, the influence of sample disturbance is marginal due to sample restoration to in situ conditions.

1%/h. The SHANSEP estimate used S = 0.25±0.05, OCR = 1.5±0.5 (based on oedometer B-class estimate) and m = 0.8. Slight uncertainty in vertical stress (COV = 5%) was used. Application of variability will indicate the upper bound (CK_0UC mode) and the lower bound (CK_0UE mode). Results are shown in Figure 9. The average SHANSEP estimates fits in FVT results and in the lower bound of CPTU estimate. The upper SHANSEP value exceed CK_0UC tests and is close to maximum values from CPTU estimate. The lower bound of SHANSEP seems to be significantly underestimated, but one should keep in mind that theoretical lower value of c_u (DSS mode) for 9 m depth is 20 kPa. For triaxial extension mode it is lower (see Figure 9), so the lower SHANSEP estimate is probable. Example presented above shows the problem in interpretation of c_u in soft soils. Average SHANSEP value seems to provide very reliable estimate of c_u for average mode of shear. However, the variation in c_u can reach 50%. This is the outcome from SHANSEP estimate and 15 CPTU tests. Lab tests on reconstituted samples (A-class) gives more accurate results, but this kind of samples are impossible to possess by traditional sampling methods.

3.7.3 Organic clay (location No. 2—Gdansk testing site)

For this site, CK_0UC and CK_0UE (shearing rate 1%/h) were made on in situ D-class samples. One should keep in mind that K_0 consolidation allows to bring the sample to the state close to in situ conditions, so for K_0 (or anisotropic) consolidation triaxial tests, the sample quality becomes marginal problem. The SHANSEP estimates uses S = 0.25±0.05, m = 0.8 (Ladd, 1991), and OCR = 2.0±0.5 (based on oedometer D-class estimate). Slight uncertainty in vertical stress (COV = 5%) was also used. Results are summarized in Table 8. SHANSEP estimate fits quite well to lab tests, although the SD is quite high. The variability can be induced by many, previously mentioned factors.

3.7.4 Organic silt (location No. 3—Gdansk testing site)

For that soil, only CK_0UC (shearing rate 1%/h) were made on in situ D-class samples. The K_0 consolidation significantly reduced the influence of sample disturbance, as was mentioned earlier. The SHANSEP estimates uses S = 0.25±0.05, OCR = 1.0±0.0 (based on oedometer D-class estimate), and m = 0.8. Slight uncertainty in vertical stress (SD = 5%) was also used. Results are summarized in Table 9. As one can see, the average SHANSEP value seems to be close to average mode (as it should be) and upper bound fits well the lab tests (triaxial compression mode). The moderate variability allows to estimate lower and upper bound of value.

4 Conclusions

This article presents the evaluation of the quality of soft soil samples from the Vistula Marshlands and its influence on compressibility parameters and undrained shear strength. Some aspects of natural (inherent) variability of the Vistula Marshlands soft soils were also recognized. The seven lessons were introduced to explain the difficulties in interpretation of soft soil parameters. Bearing in mind all the above notes based on the quality of the samples, testing methods and procedures, and inherent variability of soft soils, the following final conclusions can be drawn:

1. There is no significant influence of storage time on sample quality in terms of test performed up to 4 weeks after sampling. Slight influence can be only noticed for organic silts.
2. The better sample quality is obtained for organic clay than organic silt. Organic clays are usually of fairly good to poor quality while organic silts samples are poor to very poor. The quality of peats is usually high and moderate, but this is induced by sample swelling under low confining pressure, which was often reported in oedometer test data.
3. The $\Delta e/e_0$ and $\Delta\varepsilon_{vol}$ at σ'_{v0} (SQD) ratings show the most consistent results in terms of influence of sample quality on constrained modulus. C_r/C_c are characterized by significant and large scatter and is not compatible with $\Delta e/e_0$ and SQD. Thus, C_r/C_c criterion for soft soils should be avoided.
4. There is no significant influence of sample quality on C_c, C_s, and C_α. The reason is that C_c determination was usually based on samples subjected to high consolidation stress (2–4 times higher than preconsolidation pressure).
5. C_c, C_s, and C_α shows relationship with initial dry bulk density. The local empirical correlation were established.
6. Regardless of testing method, the c_u in the Vistula Marshlands soft soils can vary between 20% and 50% depending on the deposit depth and soil type.
7. The Vistula Marshlands soft soils are rate dependent and their rate-dependency should be taken into account in geotechnical design or data analysis.
8. The UUC test is not recommended for soft soil deposits, due to high variability that originates from testing method, which provides usually underestimation of c_u.
9. The most accurate estimation of c_u can be obtained from FVT test. The rate correction depending on IP returns very reliable results. The FVT c_u also depends only on one factor (IP). The determination of IP can be conducted on remolded sample and if there is a lack of IP for a specific site, the literature or dataset values can be used as a guide. For instance, typical values of IP for the Vistula Marshlands soft soils are provided in Stępkowska's (1986) report and Konkol and Bałachowski (2021) article.
10. The CPTU estimates also gives relatively accurate c_u. However, the application of uncertainty of unit weight, water table variations, and variability of N_{kt} value, can significantly change the interpretation. The N_{kt} factor should not be calibrated on UUC tests. The N_{kt} = 14.5±1.5 seems to be a good choice for the Vistula Marshlands soft soils.
11. The SHANSEP approach can be considered as an additional estimate of c_u next to the CPTU and FVT. SHANSEP estimation proves its applicability to soft soil and allows to establish in relatively easy way lower and upper bounds of c_u. This can be important in risk management and probability analysis involving soft soils.
12. Qualitative comparison of current (this article and Konkol and Bałachowski (2021)) and old database (Gwizdała et al., 1983; Stępkowska, 1986) shows as many similarities as differences. The best agreements are in terms of physical properties and index properties. The constrained moduli reported in old dataset are usually lower than in this research and usually did not exceed 2 MPa (typical value is 1 MPa). That suggests high soil disturbance during sampling in the past. The lab-based c_u in old dataset is very low and usually does not exceed 20 kPa (with the average value of 15 kPa) regardless of sampling depth. The best agreement with old and current datasets are the results of FVT, which are quite consistent.

Presented research continues data storage of geotechnical investigation of the Vistula Marshlands soft soil started in 1970s and 1980s (Gwizdała et al., 1983; Stępkowska, 1986). Such a wide presentation of the data from the Vistula Marshlands in terms of physical properties, index properties, compressibility parameters, and undrained shear strength can be used as a reference to design strategy of geotechnical investigation of the soft soils in the region. It also allows to assess the variability of parameters, both from natural variability as well as those from sample disturbance.

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