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EVALUATION OF THE ORGANIC SOIL COMPRESSIBILITY FROM IN-SITU AND LABORATORY TESTS FOR ROAD APPLICATION

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Abstract. Organic soil is characterised by high compressibility and should be improved so that it can be used for construction. The use of every method of soil improvement requires knowledge of the compressibility parameters. One of these parameters is the constrained modulus. The constrained modulus can be determined using laboratory or in-situ tests. In this study, the constrained modulus of organic soil was determined using oedometer and piezocone tests (CPTU). The author analysed subsoil under an approximately 250 m section of a designed road in north-eastern Poland. The constrained modulus of organic soil sampled from four different depths was determined in oedometer tests. Piezocone tests were conducted at 18 points located every 15 m along the length of the section concerned. To determine the constrained modulus based on the cone resistance from CPTU tests, the knowledge of the α and α_M coefficients is needed. For the tested soil, the optimal range of the α coefficient from 0.4 to 0.7 was determined. The α_M coefficient ranged from 0.4 to 0.8. The value of the constrained modulus of organic soil obtained from the oedometer tests, depending on the effective stress, ranged from approximately 100 kPa to 400 kPa. The constrained modulus of the tested soil decreased with depth, which both research methods proved.

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Introduction

Construction of structures on organic soils is avoided whenever possible. However, rapid development has made construction works on organic soils increasingly inevitable. Organic soils should be improved so that they can be used for construction (Rahman et al., 2016). Many methods of soil improvement are known and used around the world (Duraisamy et al., 2007; Hartlen et al., 1996; Huat et al., 2014; Edil, 2003; Virsis et al., 2020). However, regardless of the method, knowledge of the physical and mechanical parameters of organic soil is required. Determining the parameters of organic soil may be very difficult due to its variable properties even within one deposit (Lechowicz & Szymański, 2002; Zainorabidin & Wijeyesekera, 2008) or its ability to change properties with time (Huat et al., 2005). For these reasons, organic soil should be tested in detail and its parameters should be carefully determined using various methods.

One of the organic soil types is peat. Peat is known as partially decomposed plant remains which have accumulated under water conditions for ten to thousands of years (Huat et al., 2009). It has distinctive organic odour and brown to black colour (Huat et al., 2014). The characteristics of peat soil are high water content, low shear strength and high compressibility (Bo et al., 2005; Khalid et al., 2015; Kumar & Jain, 2013; Majeed & Taha, 2012; Moon et al., 2019; Wong et al., 2008). In engineering practice, the classification of peat soil is based on the inspection of its structure and consistency. The most commonly used classification system for peat is the von Post scale consisting of 10 steps (Long, 2005). According to the von Post scale, peat can be classified depending on the degree of humification as being between completely undecomposed (H1) and completely composed (H10). Mangan (1994) reduced the von Post scale and divided peat into three types: fibrous, quasi-fibrous (semi-fibrous) and amorphous. The fibrous peat is low-humified and consists of distinct fragments of plant structure. The degree of decomposition of fibrous peat is from H1 to H4. The quasi-fibrous peat has medium degree of decomposition (H5–H7) and recognisable structure. In amorphous peat, the plant structure is no visible and the degree of decomposition ranges from H8 to H10.

Many engineering problems in the form of excessive settlement could occur either during or after the construction phase due to high compressibility of peat soil. The settlement reduction to acceptable limits is sometimes of greater significance in construction design than limitations imposed by bearing capacity (Head, 1994). This makes the compressibility of organic soils a very important issue for all researchers.

One of the most important compressibility parameters of every soil type is the constrained modulus. The constrained modulus is the most commonly used measure of soil compressibility in engineering practice. Its knowledge is required to predict the settlement or to determine coefficient of permeability (Head, 1994; Powrie, 2014).

The constrained modulus can be determined using laboratory or field tests (Młynarek et al., 2006; Senneset et al., 1989). The laboratory tests for measuring the constrained modulus are conducted in an oedometer or in a consolidometer. Oedometer and consolidometer tests are carried out in one-dimensional conditions in non-deformable ring. One-dimensional loading occurs in the soil beneath an embankment or spread foundation (Atkinson, 2007). The constrained modulus of organic soil is frequently determined using oedometers (Long & Boylan, 2013). In the field, the constrained modulus can be predicted using flat dilatometer tests (DMT) or cone penetration tests (CPTU). There are two possibilities for estimating the constrained modulus from CPTU data (Lunne et al., 1997): indirectly, based on the undrained shear strength c_u, and directly, based on the measured cone resistance q_c or on the corrected cone resistance q_t.

Many correlations between the constrained modulus and cone resistance have been described in the literature (European Committee for Standardization, 2007a; Mayne, 2006, 2007; Meigh, 1987; Sanglerat, 1972; Schmertmann, 1978; Senneset et al., 1989; Robertson, 2009). However, correlations for organic soils have been rarely reported.

The prediction of consolidation parameters, such as the constrained modulus, based on the cone resistance and correlating them with the parameters determined in tests without pore pressure measurements may be difficult. However, this is the only way to develop area-specific correlations to obtain parameters with greater reliability (Lunne et al., 1997).

The research area is located in north-eastern Poland in the lake region within the river catchment area. The location is characterised by a great variety of terrain. The subsoil of the area under consideration is composed of the gravel, sand, clayey sand, silt and sandy clayey silt. The peatlands are characteristic of the considered region. Mainly peats with a thickness of about 1 m to 2 m could be found in the subsoil. In some locations, the thickness of the organic soils reaches much higher values.

The present research analysed the subsoil under an approximately 250 m section of a designed road. Peat soil with a thickness of up to 7.5 m was deposited in the considered subsoil. The constrained modulus of organic soil sampled from four different depths was determined using oedometer tests. A total of 20 samples were tested. Piezocone tests were conducted at 18 points located every 15 m along the length of the section concerned. Constrained modulus of peat soil was determined in piezocone tests, based directly on the cone resistances q_c and q_t. The objective of this study was to determine the constrained modulus of organic soil from oedometer and piezocone penetration tests. Additionally, the dependence of the constrained modulus on the depth below the soil surface was determined.

1. Materials and methods

1.1. Materials

The subsoil under one of the sections of the bypass with a total length of about 12 km was analysed. The area under consideration was about 250 m long. Peat (Pt) with a thickness of 2.1 m to 7.5 m was found in the considered subsoil. Below the organic soils, glacial sediments in a form of clayey sand (clSa), sandy silt (saSi) and silt (Si) with a very soft, soft and firm consistency were found. The ground water level was at a depth of 0.1 m to 1.5 m below the soil surface. The geotechnical cross-section of the analysed subsoil is shown in Figure 1.

The peat was sampled with thin wall cylinders with a diameter of 70 mm. The cylinders were pressed into the subsoil in a vertical direction. Samples were collected from four different depths: 1.2 m,

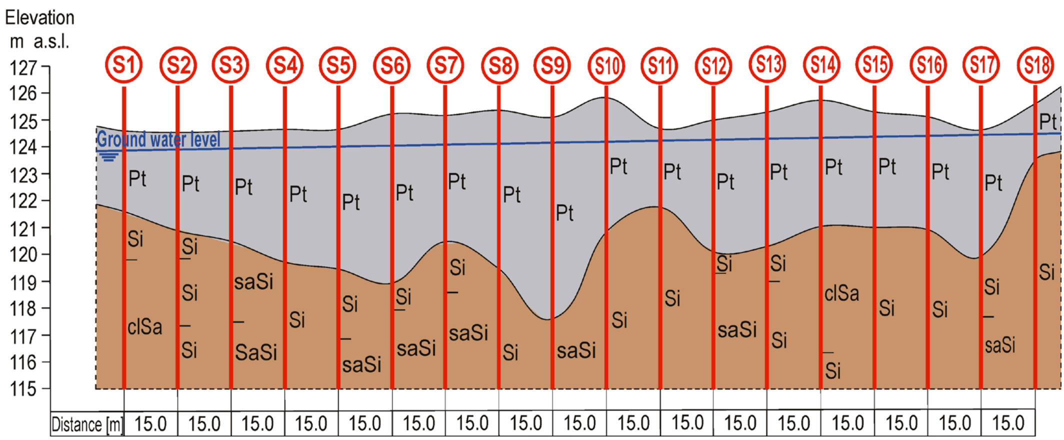

Figure 1. Geotechnical cross-section and piezocone penetration tests locations

2.2 m, 3.8 m and 5.0 m, at different distances from each other over the entire length of the analysed area. The locations of sample collection were close to the piezocone research points. The results presented are the average test results for each group of samples collected from a certain depth.

The basic physical properties of peat were determined. The organic content was determined using the method of loss on ignition (LOI) in accordance with the Standard PN-EN 15935:2013-02 (Polish Committee for Standardization, 2013). The method is widely used by researchers (Hoogsteen et al., 2015).

Table 1 shows the basic physical properties of the tested peat.

Table 1. Physical properties of the tested peat

Peat designation	Pt 1	Pt 2	Pt 3	Pt 4
Depth, m	1.2	2.2	3.8	5.0
Physical properties				
Unit weight, kN/m^3	11.7	12.8	11.5	12.3
Unit weight of the solid particles, kN/m^3	14.7	15.2	14.6	15.2
Water content, %	465	418	449	489
Organic content, %	90.7	84.4	92.4	84.2
Degree of humification (von Post scale)	H8	H7	H6	H6
Void ratio	8.39	5.54	7.53	5.69

It can be seen from Table 1 that the tested peat had a low unit weight (11.5–12.8 kN/m^3), high water content (up to 489 %) and a near to medium degree of decomposition. The organic content was estimated to be 84.2 % to 92.4%. The void ratio of the tested peat ranged from 5.54 to 8.39.

The tested peat is quasi-fibrous and amorphous. The structure of peat depends on the depth. The highest degree of decomposition is characteristic of organic soil at the lowest depth. It can be related to the changes in the ground water level.

1.2. Methods

Piezocone tests were performed for 18 points with numbers from S1 to S18 to the depth of about 10 m. The test points were located every 15 m along the section under consideration. Piezocone test locations are shown in Figure. 1. During the CPTU tests, the cone resistance q_c, sleeve friction f_s and water pressure u_2 were measured.

The one-dimensional constrained modulus M, also known as E_{oed} (European Committee for Standardization, 2007a), can be determined using the following equation (European Committee for Standardization, 2007a; Lunne et al., 1997; Sanglerat, 1972):

$$M = \alpha q_c, \tag{1}$$

where α is a coefficient depending on the local experience.

Mitchel and Gardner (1975) performed a detailed review of the relationship between the constrained modulus and cone resistance, and Sanglerat (1972) presented α values for different soil types with different cone resistance values. Table 2 shows α values directly for peat.

Table 2. The α values for peat (Sanglerat, 1972)

Water content of peat *w*, %	α
$50 < w < 100$	$1.5 < \alpha < 4.0$
$100 < w < 200$	$1.0 < \alpha < 1.5$
$w > 200$	$0.4 < \alpha < 1.0$

For the tested peat with water content ranging from 418 % to 489 %, it was assumed that the α ranged from 0.4 to 1.0.

The constrained modulus is typically calculated using correlations with the corrected cone resistance q_t (Mayne, 2006, 2007; Meigh, 1987; Robertson, 2009; Senneset et al.,1989; Schmertmann, 1978). The cone resistance q_t can be determined from the equation (Lunne et al., 1997; Mayne, 2007; Robertson, 1990; Senneset et al., 1989; Tschuschke & Waliński, 2005):

$$q_t = q_c + u_2(1 - a), \tag{2}$$

where q_c is the measured cone resistance, u_2 is the pore water pressure, and a is the net area ratio with a value from 0.70 to 0.85 (Robertson & Cabal, 2014); in the current study, it was assumed that $a = 0.75$.

The constrained modulus can also be calculated from the equation given below (Mayne, 2006, 2007; Meigh, 1987; Robertson, 2009; Senneset et al., 1989; Schmertmann, 1978).

$$M = \alpha_M (q_t - \sigma_{v0}), \tag{3}$$

where α_M is a coefficient depending on the local experience, and σ_{v0} is the in-situ total vertical stress.

Values of the α_M coefficient presented in the literature apply mainly to clays and sands. Generally, α_M varies with values from 1 to 10 (Mayne, 2006, 2007; Meigh, 1987; Senneset et al., 1989). Robertson (2009) suggested values of α_M coefficients ranging from 2 to 14. For organic clays, α_M value from 1 to 2 may be appropriate (Mayne, 2006, 2007). An even lower value of α_M coefficient should be expected for peat. In the present study, it was assumed that, for peat, α_M value from 0.4 to 1.0 would be appropriate.

Oedometer tests were performed using a set of oedometers with automatic registration of displacement sensor readings presented in Figure. 2.

Tests were carried out on peat samples with an initial height of 20 mm and a diameter of 63.5 mm. The peat samples were tested in accordance with the European Standard EN ISO 17892-5:2017 (European Committee for Standardization, 2017b) at different vertical stresses σ_v'. Table 3 shows the σ_v' values for the tested peat. In Table 3, the applied stresses are marked with "+", while the omitted stresses with "–".

Table 3. The σ_v' values for the tested peat

Vertical stress σ_v', kPa	Peat designation			
	Pt 1	Pt 2	Pt 3	Pt 4
15	+	+	+	+
32	+	+	+	+
64	+	+	+	+
96	–	–	–	+
128	+	+	–	–

Due to the high compressibility of samples and the technical capabilities of oedometers, the maximum vertical stresses for peat Pt 3 and Pt 4 were equal, respectively, 64 kPa and 96 kPa.

Figure 2. Set of oedometers

From the oedometer tests, the constrained modulus of soil was determined by measuring the sample height changes under the applied stress. The constrained modulus can therefore be calculated using the formula:

$$M = \frac{\Delta\sigma_{vi}'}{\Delta\varepsilon} = \frac{\Delta\sigma_{vi}' h_i}{\Delta h_i}, \tag{4}$$

where $\Delta\sigma_{vi}'$ is the effective vertical stress increment, $\Delta\varepsilon$ is a strain, h_i is the initial height of the sample, and Δh_i is the change in the height of the sample due to the stress change.

2. Results and discussion

2.1. Piezocone tests

Similar dependencies of the parameters q_c, f_s and u_2 on the depth were obtained in all 18 research points. The sample CPTU test results in point S5 are shown in Figure 3. Figure 3 also shows the calculated averaged values of cone resistance q_{cav}, sleeve friction f_{sav} and water pressure u_{2av} for each separated soil layer.

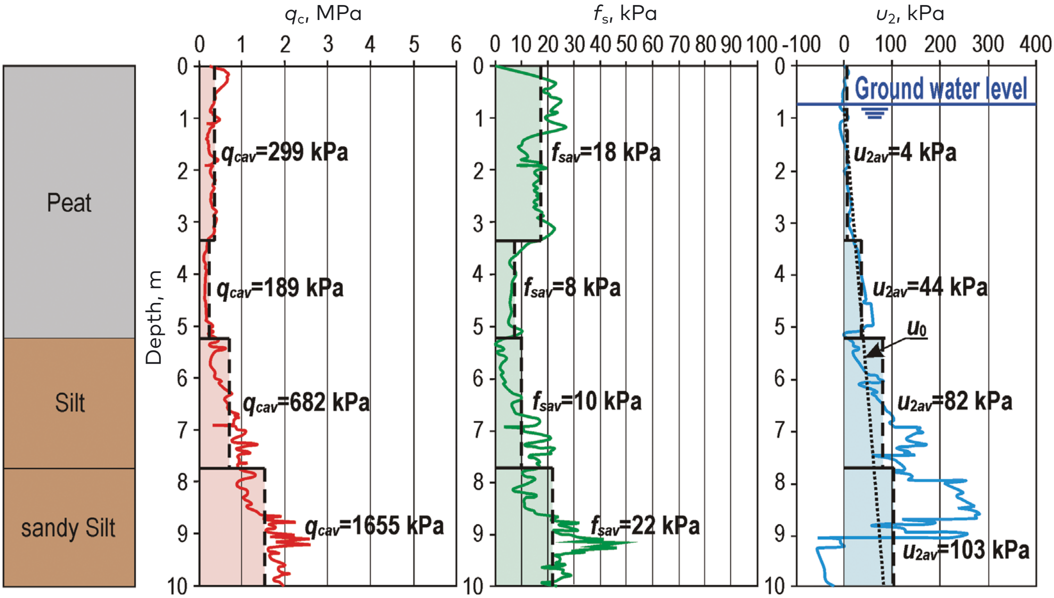

Figure 3. CPTU test results in research point S5

Table 4. Averaged values of cone resistances q_{cav} and q_{tav} in the peat layers

Research point	Depth, m	q_{cav}, kPa	q_{tav}, kPa	Research point	Depth, m	q_{cav}, kPa	q_{tav}, kPa
S1	0.0–1.8	397	400	S9	0.0–4.9	199	200
	1.8–3.0	194	200		4.9–7.5	94	100
S2	0.0–2.0	397	400	S10	0.0–3.7	299	300
	2.0–3.7	89	100		3.7–5.0	193	200
S3	0.0–3.2	293	300	S11	0.0–2.0	199	200
	3.2–4.1	185	200		2.0–3.0	193	200
S4	0.0–4.1	193	200	S12	0.0–2.8	199	200
	4.1–5.0	283	300		2.8–4.9	93	100
S5	0.0–3.3	299	300	S13	0.0–3.2	294	300
	3.3–5.2	189	200		3.2–5.0	86	100
S6	0.0–1.3	599	600	S14	0.0–2.1	299	300
	1.3–4.4	299	300		2.1–4.7	287	300
	4.4–6.3	193	200	S15	0.0–3.0	294	300
S7	0.0–1.2	599	600		3.0–4.3	87	100
	1.2–3.3	299	300	S16	0.0–3.0	197	200
	3.3–4.7	187	200		3.0–4.2	89	100
S8	0.0–1.5	499	500	S17	0.0–2.5	199	200
	1.5–4.2	199	200		2.5–4.7	99	100
	4.2–5.9	87	100	S18	0.0–2.1	396	400

Table 5. Cone resistances and the total stresses at considered depths

Depth, m	q_{cav}, kPa	q_{tav}, kPa	σ_{v0}, kPa
1.2	325	328	14.0
2.2	237	241	26.3
3.8	170	179	45.7
5.0	161	171	60.0

Only peat layers will be considered further in the study. Thus, Table 4 shows the averaged values of the cone resistances q_{cav} and q_{tav} in research points from S1 to S18 for peat layers only. The cone resistances q_{tav} were calculated using Formula (2) for the values of cone resistance q_{cav} and water pressure u_{2av} averaged within a separate layer.

The averaged values of cone resistances at the considered depths, 1.2 m, 2.2 m, 3.8 m and 5.0 m, are presented in Table 5. Additionally, Table 5 shows the total vertical stress values σ_{v0} at each depth.

In Table 5, the cone resistances for the tested peat decreased with depth. The corrected cone resistances q_t in peat layers presented in the literature are similar to those obtained in the current study and generally range from about 100 kPa to 500 kPa (Carlsten, 2000; Den Chann, 1997; Edil, 2001; Long, 2005; Long & Boylan, 2012; Mitachi, 1998).

2.2. Oedometer tests

Figure 4 shows the consolidation curves as a result of the oedometer tests.

The vertical strain of peat Pt 4 from the depth 5.0 m was the highest of all tested peats. This corresponds to the CPTU tests results because the higher soil compressibility corresponds to a lower value of the cone resistance.

The constrained modulus of peat calculated from Formula (4) in relation to the effective stress σ_v' is shown in Figure 5.

The constrained modulus directly depends on the effective stress. The effective stresses of 15 kPa and lower are closest to the in-situ conditions. It can be seen in Figure 5 that for this range of effective stress, peat Pt 4 had the lowest constrained modulus, while peat Pt 2 had the highest.

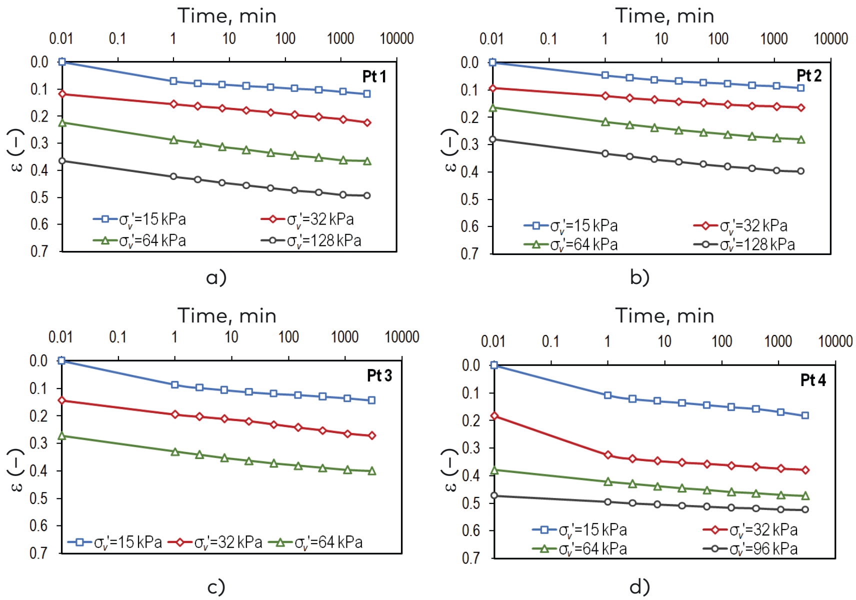

Figure 4. Strain versus time curves for the tested peat: a) Pt 1; b) Pt 2; c) Pt 3; d) Pt 4

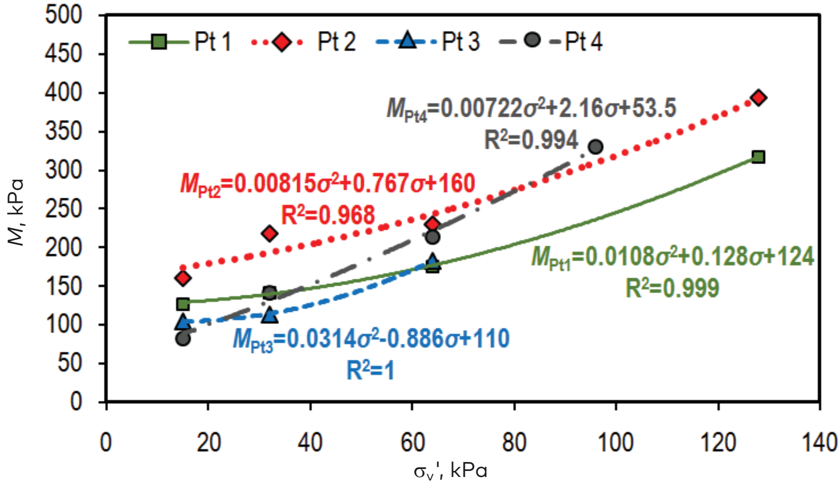

Figure 5. The constrained modulus of peat in relation to effective stress

The constrained modulus of peat obtained from the oedometer tests ranged, depending on the effective stress, from approximately 100 kPa to 400 kPa and was very close to the values presented in the literature (Gabryś & Szymański, 2010; Wierzbicki et al., 2015).

2.3. Comparison of research methods

To compare the constrained modulus obtained from the oedometer and piezocone penetration tests, effective stress at in-situ conditions the σ_{vin}' was determined. The calculations considered the average ground water level, which was equal to 0.7 m, and the buoyant unit weight of peat. Due to the very high values of the coefficient of determination R^2 describing the correlation between the constrained modulus and effective stress, the modulus at σ_{vin}' stress was determined using functions from Figure 5. Table 6 shows the results of calculations.

Table 6. The effective stress and constrained modulus at in-situ conditions

Peat designation	Depth, m	σ_{vin}', kPa	*M*, kPa
Pt 1	1.2	8.87	126
Pt 2	2.2	9.44	168
Pt 3	3.8	10.5	104
Pt 4	5.0	11.3	79

The constrained modulus from piezocone penetration tests was calculated using the values shown in Table 5 for α and α_M coefficients ranging from 0.4 to 1.0.

Figure 6 presents the final values of the constrained modulus depending on the research method and depth.

In Figure 6, the constrained modulus determined from the piezocone penetration tests decreased with depth. The constrained modulus is strictly related to the cone resistances q_c and q_t that also decrease with depth. The constrained modulus from the oedometer tests with the highest value was at a depth of 2.2 m, and the lowest was at a depth of 5.0 m.

In general, as shown in Figure 6, the values of the α coefficient presented in the literature for peat are correct. However, the constrained modulus results from the oedometer tests are compared better with the upper limit of $0.7q_c$. The optimal range of the α_M coefficient is from 0.4 to 0.8. The constrained modulus results from the oedometer and piezocone tests had comparable values.

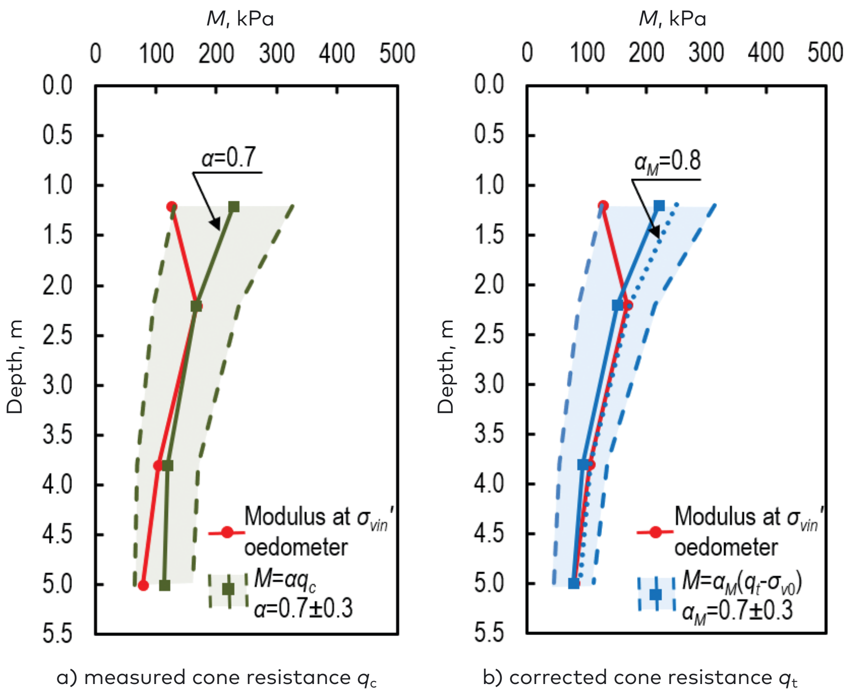

Figure 6. The constrained modulus of peat from the oedometer and CPTU tests determined on the basis of the measured cone resistance q_c and corrected cone resistance q_t

Conclusions

The following general conclusions may be formulated from the performed analysis.

1. The constrained modulus of peat was determined on the basis of the measured cone resistance q_c and corrected cone resistance q_t. The value of the constrained modulus depended on the α and α_M coefficients which should be obtained on the basis of local experience.
2. In the current study, the α and α_M coefficients adopted from the literature gave satisfactory results.
3. For the tested peat, the optimal range of the α coefficient was from 0.4 to 0.7. The α_M coefficient ranged from 0.4 to 0.8.
4. The constrained modulus of peat obtained from the oedometer tests, depending on the effective stress, ranged from approximately 100 kPa to 400 kPa and was close to the values presented in the literature.
5. The constrained modulus of the tested peat decreased with depth, which both research methods proved.
6. Piezocone penetration tests are an effective method of obtaining accurate values of the constrained modulus. However, comparing the results with another research method is recommended, particularly for peat.
7. In the author's opinion, the laboratory tests give more reliable results, provided that the samples have been properly collected, transported and stored. However, the analysis performed showed that the constrained modulus could also be predicted from the results of field tests.

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Notations

α, α_M – coefficients dependent on the local experience;
ε – vertical strain;
σ_v' – effective vertical stress, kPa;
σ_{v0} – in-situ total vertical stress, kPa;
a – net area ratio;
c_u – undrained shear strength, kPa;
f_s – sleeve friction, kPa;
h_i – height of the sample, mm;
M, E_{oed} – constrained modulus, kPa;
u_2 – pore water pressure, kPa;
q_c – measured cone resistance, kPa, MPa;
q_t – corrected cone resistance, kPa, MPa;
w – water content, %;
CPTU – piezocone penetration test;
DMT – dilatometer test.