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 $\alpha$ and $\alpha_M$ coefficients is needed. For the tested soil, the optimal range of the $\alpha$ coefficient from 0.4 to 0.7 was determined. The $\alpha_M$ 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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Keywords: compressibility, oedometer, organic soil, peat, piezocone penetration test (CPTU), road design.

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](image-url)
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.

| 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/m³ | 11.7 | 12.8 | 11.5 | 12.3 |
| Unit weight of the solid particles, kN/m³ | 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/m³), 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):

\[ M = \alpha q_c \] (1)

where \( \alpha \) 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 \( \alpha \) values for different soil types with different cone resistance values. Table 2 shows \( \alpha \) values directly for peat.

### Table 2. The \( \alpha \) values for peat (Sanglerat, 1972)

| Water content of peat \( w \), % | \( \alpha \) |
|-------------------------------|----------------|
| \( 50 < w < 100 \)           | \( 1.5 < \alpha < 4.0 \) |
| \( 100 < w < 200 \)           | \( 1.0 < \alpha < 1.5 \) |
| \( w > 200 \)                 | \( 0.4 < \alpha < 1.0 \) |

For the tested peat with water content ranging from 418 % to 489 %, it was assumed that the \( \alpha \) 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):

\[ q_t = q_c + u_2 (1 - a), \] (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).

\[ M = \alpha_M (q_t - \sigma_v), \] (3)

where \( \alpha_M \) is a coefficient depending on the local experience, and \( \sigma_v \) is the in-situ total vertical stress.

Values of the \( \alpha_M \) coefficient presented in the literature apply mainly to clays and sands. Generally, \( \alpha_M \) varies with values from 1 to 10 (Mayne, 2006, 2007; Meigh, 1987; Senneset et al., 1989). Robertson (2009)
suggested values of $\alpha_M$ coefficients ranging from 2 to 14. For organic clays, $\alpha_M$ value from 1 to 2 may be appropriate (Mayne, 2006, 2007). An even lower value of $\alpha_M$ coefficient should be expected for peat. In the present study, it was assumed that, for peat, $\alpha_M$ 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 $\sigma_v\,'$. Table 3 shows the $\sigma_v\,'$ values for the tested peat. In Table 3, the applied stresses are marked with “+”, while the omitted stresses with “−”.

| Vertical stress $\sigma_v\,'$, 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:

$$M = \frac{\Delta \sigma_{vi}'}{\Delta \varepsilon} = \frac{\Delta \sigma_{vi}' h_i}{\Delta h_i}, \quad (4)$$

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 $\Delta h_i$ 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](image-url)
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 the peat layers 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 $\sigma_{v0}$ at each depth.

### 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           | S10            | 4.9–7.5 | 94            | 100           |
| S2             | 0.0–2.0 | 397           | 400           | 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           | 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           | 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           | 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           | 0.0–2.1       | 299     | 300           |
|                | 1.3–4.4 | 299           | 300           | 2.1–4.7       | 287     | 300           |
|                | 4.4–6.3 | 193           | 200           | 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           | 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           | 0.0–2.5       | 199     | 200           |
|                | 1.5–4.2 | 199           | 200           | 2.5–4.7       | 99      | 100           |
|                | 4.2–5.9 | 87            | 100           | 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 | $\sigma_{v0}$ 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              |
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 $\sigma_v'$ 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](image-url)
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 \( \sigma_{\text{vin}}' \) 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 \( \sigma_{\text{vin}}' \) stress was determined using functions from Figure 5. Table 6 shows the results of calculations.

![Figure 5. The constrained modulus of peat in relation to effective stress](image)

| Peat designation | Depth, m | \( \sigma_{\text{vin}}' \), 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 $\alpha$ and $\alpha_M$ 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 $\alpha$ 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 $\alpha_M$ coefficient is from 0.4 to 0.8. The constrained modulus results from the oedometer and piezocone tests had comparable values.

![Figure 6](image)

**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 $q_t$. 

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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 $\alpha$ and $\alpha_M$ coefficients which should be obtained on the basis of local experience.

2. In the current study, the $\alpha$ and $\alpha_M$ coefficients adopted from the literature gave satisfactory results.

3. For the tested peat, the optimal range of the $\alpha$ coefficient was from 0.4 to 0.7. The $\alpha_M$ 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, αₘ – coefficients dependent on the local experience;
ε – vertical strain;
σᵥ’ – effective vertical stress, kPa;
σᵥ₀ – in-situ total vertical stress, kPa;
a – net area ratio;
cᵤ – undrained shear strength, kPa;
fₛ – sleeve friction, kPa;
hᵢ – height of the sample, mm;
M, Eₒₑᵈ – constrained modulus, kPa;
u₂ – pore water pressure, kPa;
qₐ – measured cone resistance, kPa, MPa;
qₜ – corrected cone resistance, kPa, MPa;
w – water content, %;
CPTU – piezocone penetration test;
DMT – dilatometer test.