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# Strength parameters of deltaic soils determined with CPTU, DMT and FVT

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ABSTRACT: This paper presents the results of soil investigation in soft, normally consolidated organic soil in the estuary of Vistula river. The analysis concerns clayey mud and peat layers interbedded with loose to medium-dense sands. Several Cone Penetration Tests with pore water measurement (CPTU), Dilatometer Tests (DMT) and Field Vane Tests (FVT) were performed on the testing site. The cone factor $N_{kt}$ was estimated using the results of FVT and peak values of undrained shear strength. The proposition of $N_{kt}$ change due to normalized Friction ratio ($F_r$) has been given. The possible value of cone factor $N_{\Delta u}$ for organic soils was also suggested. The undrained shear strength of Jazowa clayey mud and peat have been compared with DMT estimates proposed by various researchers. Finally, the structural soil sensitivity of Jazowa deltaic soils was determined on the basis of residual shear strength obtained from FVT and the measurements of sleeve friction.

## 1 INTRODUCTION

### 1.1 *Aim of this research*

The research conducted at Jazowa site is related to extensive infrastructural works on soft subsoil. The aim of the study is to establish some local correlations concerning the interpretation of in situ tests in soft organic soils. Some correlations concerning the parameters of organic soils in Central Poland based on advanced in-situ tests were elaborated by Lechowicz (1997), Młynarek (2006), Rabarijoely (2008) & Zawrzykraj (2017). The set of CPTU, DMT and FVT was performed on the trial field near the S7 highway, currently under construction. The aim of the research is to calibrate the cone factors using undrained shear strength on the basis of FVT and to compare the profiles of undrained shear strength obtained with different in-situ tests. Finally, the soil sensitivity based on CPTU and FVT is additionally examined.

### 1.2 *Testing site description*

The trial field is localized in the delta of Vistula river near Elbląg city, Poland. Alluvial soils layers as mud and peat with sandy interbeddings can be recognized up to 14–15 m depth below ground level. Below 15 m some compacted Pleistocene sands were found. Quite regular subsoil structure was detected in the trial field area with drillings and preliminary CPTU tests. According to soil classification charts and drillings the following layers can be distinguished in the subsoil:

- 0.0–0.7 m: working platform layer,
- 0.7–1.8 m: silty and sandy clays,
- 1.8–2.7 m: clayey mud,
- 2.7–4.0 m: peat,
- 4.0–7.8 m: loose to medium-dense sand,
- 7.8–14.5 m: clayey mud layer intersected with some peat and sand inclusions
- 14.5 m the roof of dense Pleistocene sand.

The soil profile is presented in Figure 1 with typical CPTU sounding results.

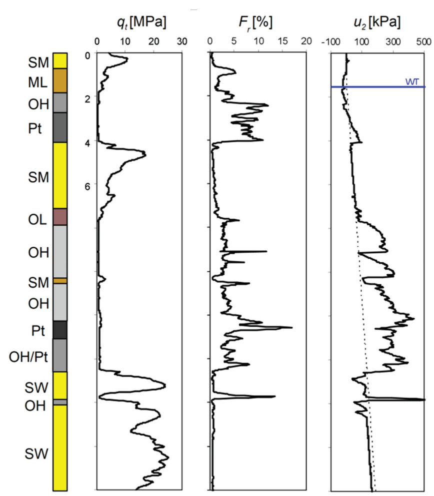


Figure 1. Typical CPTU profile for Jazowa testing site (sounding no. 4).

## 2 IN SITU TEST RESULTS

### 2.1 *CPTU and DMT soundings*

Totally 13 CPTU and 8 DMT sounding have been performed at Jazowa testing site. They were performed from the working platform in regular net with side length of 2 m. The typical results of CPTU soundings are given in Figure 1.

Typical results of DMT according to the interpretation proposed by Marchetti (2001) are given in Figure 2. One should notice that the value of lateral stress $K_{DMT}$ for deeper clayey mud layer is close to 2 which indicate normally consolidated soil deposit. The $K_{DMT}$ values for the upper peat and clayey mud layer suggest their slight preconsolidation.

### 2.2 *Vane test results*

Two electrical FVT using 7.5*13.0 cm tapper tips were conducted as supplementary field investigation at the testing site. The profiles of measured undrained shear strength with maximum and residual values are given in Figure 3a. The FVT results have been corrected due to disturbance, anisotropy and rate effects. For clayey mud layers, correction factors have been applied taking into account plasticity index and Bjerrum relation (Terzaghi 1996). For upper mud layer, with a plasticity index (*Ip*) of 49%, a factor of 0.7 was adopted while for lower layer, with plasticity index of 27.4%, a factor of 0.9 was applied. For peat inclusions the correction factor of 0.5 has been used (Gołębiewska 1983; Landva & La Rochelle 1983, Hanzawa 1994, Long 2005). The maximum and residual profiles of undrained shear strength with applied correction factors are presented in Figure 3b.

For upper soft soil deposit generally constant value of $c_u$ can be observed and it is reasonable due to slight preconsolidation of the soil. On the other hand, for deeper mud layers nearly linear increase of undrained shear strength with depth can be seen.

## 3 CALIBRATION OF CONE FACTORS

For each CPTU sounding the subsoil was classified into thin layers typically 0.3–0.4m thick in the vicinity of vane tests. For each layer the average normalized friction ratio $F_r$ and soil type behavior index $I_c$ have been calculated.

### 3.1 $N_{kt}$ *factor*

Cone factor during undrained cone penetration is defined (Lunne 1997) as:

$$N_{kt} = \frac{(q_t - \sigma_{v0})}{c_u} \quad (1)$$

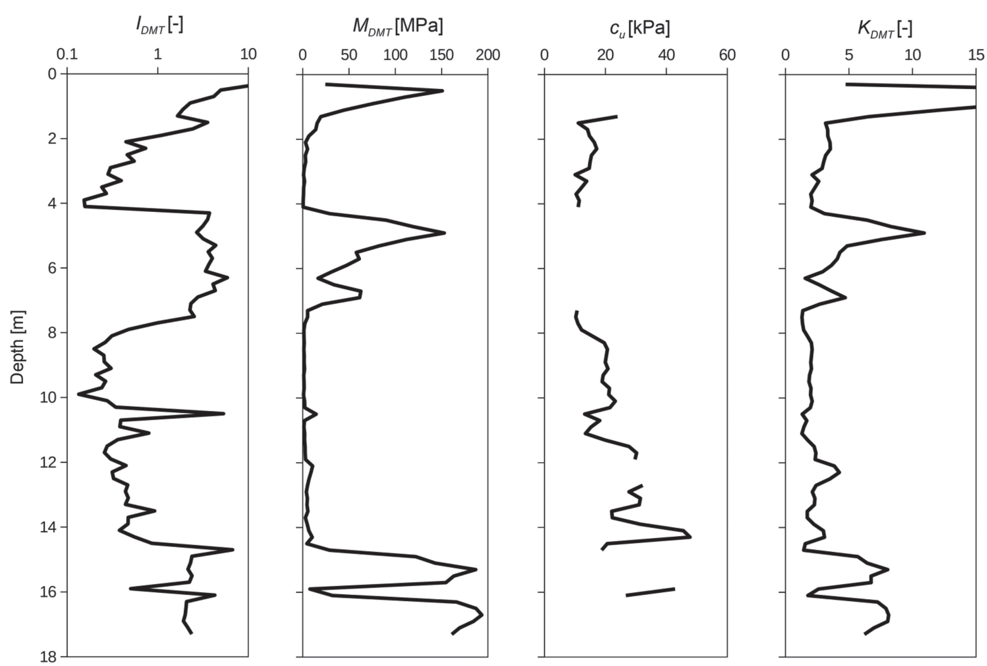


Figure 2. Typical DMT results for Jazowa trial field (sounding no.5).

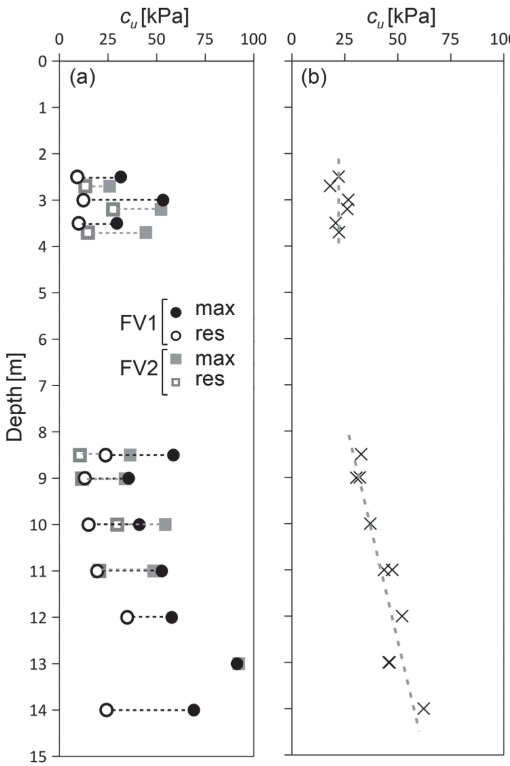


Figure 3. Uncorrected shear strength from the FVT (a) and corrected values (b).

where $N_{kt}$ = cone factor; $q_t$ = average corrected cone resistance; $\sigma_{v0}$ = total vertical stress; $c_u$ = undrained shear strength.

Here, the maximum shear strength after correction from FVT at the corresponding depth is used as a reference one. The $N_{kt}$ –$I_c$ relation obtained from sounding no.4 for given soil layers is shown in Figure 4a. It can be seen that the cone factor is generally increasing with friction ratio and $N_{kt}$ is decreasing with soil type behavior index $I_c$, see Figure 4b.

To provide the sufficient relation between $N_{kt}$ and $F_r$ and $N_{kt}$ and $I_c$ the analysis have been performed on average values obtained from all 13 CPTU tests performed at the site. The average values of $N_{kt}$ factor were calculated for each layer and the results are summarized as a function $F_r$ in Figure 5a and as a function of $I_c$ in Figure 5b.

As one can see, The $N_{kt}$—$F_r$ provides significantly better correlation with high coefficient of determination equal to 0.871. The $N_{kt}$—$F_r$ relation can be described as:

$$N_{kt} = 1.242 \times F_r + 7.803 \quad (2)$$

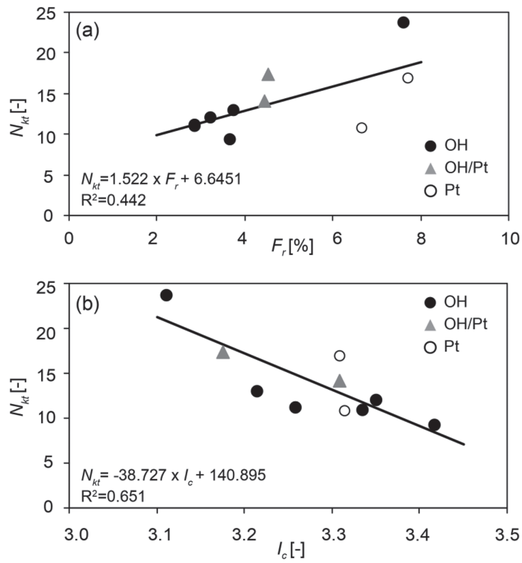


Figure 4. $N_{kt}$ *vs.* $F_r$ (a) and $N_{kt}$ *vs.* $I_c$ (b) relations.

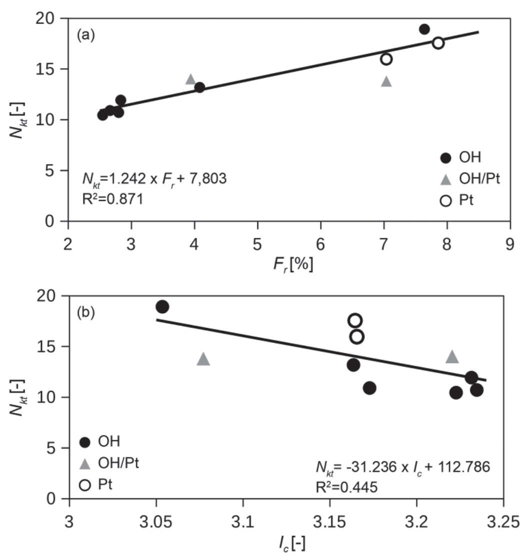


Figure 5. $N_{kt}$—$F_r$ (a) and $N_{kt}$—$I_c$ (b) relations based on averaged 13 CPTU soundings.

where: $N_{kt}$ = cone factor; $F_r$ = normalized friction ratio.

### 3.2 $N_{\Delta u}$ *factor*

Cone factor can be also calculated on the basis of excess pore water pressure defined as:

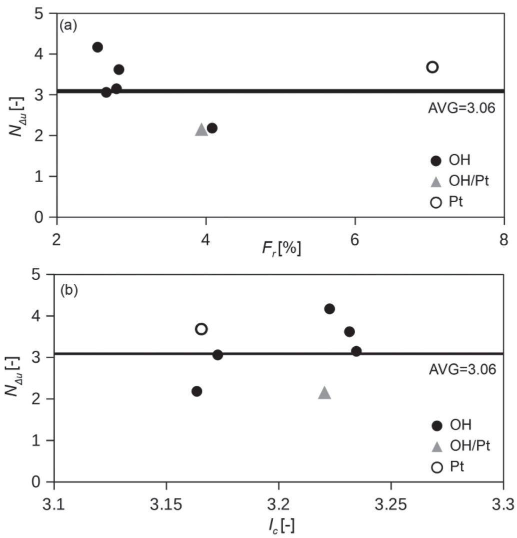


Figure 6. $N_{\Delta u}$—$F_r$ (a) and $N_{\Delta u}$—$I_c$ (b) relations based on averaged 13 CPTU soundings.

$$N_{\Delta u} = \frac{(u_2 - u_0)}{c_u} \tag{3}$$

where $N_{\Delta u}$ = cone factor; $u_2$ = average pore water pressure registered on shoulder filter element during penetration; $u_0$ = hydrostatic pore water pressure; $c_u$ = undrained shear strength of soil.

The field measurements of $u_2$ are characterized by high scatter of data and negative registered pressure up to 3,5 m, see Figure 1 for instance. Consequently, the analysis have been performed only for the deeper clayey mud layer. As in the case of $N_{kt}$ factor, the results are compiled for all profiles and the average values form the measurement have been used. The corrected maximum shear strength from FVT at the corresponding depth is used as a reference value.

The relationship between $N_{\Delta u}$ and $F_r$ is shown in Figure 6a and between $N_{\Delta u}$ and $I_c$ in Figure 6b. As can be seen, considerably higher scatter of cone factor $N_{\Delta u}$ was found due to irregularities in the registered pore water pressure $u_2$. In both relationships the $N_{\Delta u}$ is ranging between approximately 2.16 and 4.17 with average value of 3.06.

### 3.3 *Undrained shear strength*

Undrained shear strength $c_u$ for clayey mud obtained from FVT is compared with CPTU assessment with $N_{kt}$ after Equation 2 in Figure 7a. The additional estimations of $c_u$ used in the comparison are based on DMT and Unconsolidated Undrained

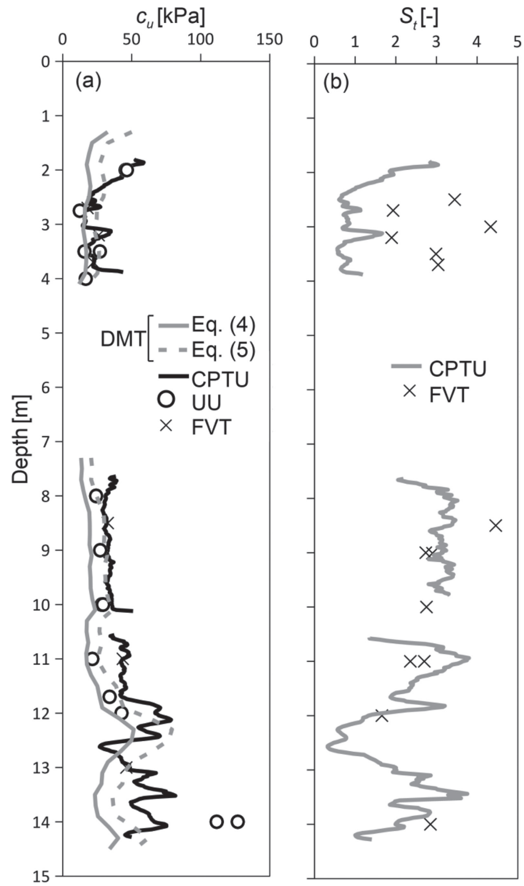


Figure 7. Undrained shear strength of Jazowa soft soil deposits estimated with different methods (a) and soil sensitivity assessed from CPTU and FVT (b).

(UU) triaxial compression tests. Two DMT estimates are based on Marchetti (2001) proposition:

$$\frac{c_u}{\sigma'_{v0}} = 0.22 \times (0.5 \times K_{DMT})^{1.25} \tag{4}$$

where $c_u$ = undrained shear strength; $\sigma'_{v0}$ = effective vertical stress; $K_{DMT}$ = horizontal stress index, and Lechowicz (1997) equation:

$$\frac{c_u}{\sigma'_{v0}} = S \times (0.45 \times K_{DMT})^{1.20} \tag{5}$$

where $c_u$ = undrained shear strength; $\sigma'_{v0}$ = effective vertical stress; $S$ = normalized undrained shear strength for normally consolidated state equal to 0.4 for organic soils (Lechowicz 1997); $K_{DMT}$ = horizontal stress index.

In DMT-based estimates of $c_u$ the average distribution of $K_{DMT}$ is used. As one can see, the back-calculated CPTU estimation fits well into the FVT results and UU results. Lechowicz proposition also corresponds to the other results. On the other hand the Marchetti (2001) formula underestimates the $c_u$ in the considered soft soils.

## 4 SOIL SENSITIVITY

The last analyzed aspect of strength parameters is related to the soil sensitivity which was estimated using two approaches. In the first one the results of FVT with the maximum and residual value of shear strength have been applied. The second approach uses the undrained shear strength estimated from the cone factor $N_{kt}$ calibrated in the present study and the sleeve friction.

The residual shear strength is assumed as a averaged sleeve friction value in a given layer from all conducted CPTU tests. The comparison is presented in Figure 7b. One can notice that for deeper soft soil deposits the sensitivity obtained from CPTU correlation fits well the trend outlined by FVT tests. However the results for upper mud and peat layer are quite dispersed and the soil sensitivity obtained with CPTU is underestimated.

## 5 CONCLUSIONS

Distinct relationship between the $N_{kt}$ and $F_r$ ($I_c$) parameters for organic soils in the delta of Vistula river was found in the present study. In this particular case, the $N_{kt}$ factor is more suitable for calculating the undrained shear strength than $N_{\Delta u}$. In case of the $N_{\Delta u}$ factor, no specific correlation between the parameters $N_{\Delta u}$ and $F_r$ ($I_c$) was determined. Particular measurement points are quite dispersed and the determination of any relation between them is practically impossible, so the constant value of $N_{\Delta u} = 3.06$ was proposed. For this reason, the $N_{kt}$ factor was used for further calculations.

In this research site, the Lechowicz (1997) DMT formula was able to correctly estimate undrained shear strength. The undrained shear strength profile from CPT test, shown in Fig. 7a, was prepared relying on the $N_{kt}$ factor given by Equation 2. It can be noticed that they correspond to values obtained from the vane test and are similar to the triaxial UU compression test results. Similar situation is in case of the soil sensitivity. The profile obtained from CPT is close to the values outlined from FVT and the sensibility of clayey muds and peats in deeper layers is rather low and generally does not exceed 4.

## ACKNOWLEDGEMENTS

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