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CPT-based unit weight estimation extended to soft organic clays and peat: An update

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ABSTRACT: Various CPT-based correlations exist for the unit weight of natural soils. One such correlation includes organic soils Lengkeek et al. (2018). This correlation is presented as a framework where the coefficients can be optimized and is based on predominantly Class 2 CPT records. This publication uses an expanded database which includes additional pairs of predominantly Class 1 CPT records selected from Holocene deposits in the Netherlands, on mineral clays, organic clays and peats. This results in a more extensive database and an improved CPT-based unit weight correlation for the whole range of soil types, which is proposed to replace the existing correlation. In addition, a specific unit weight correlation for peats is presented.

1 INTRODUCTION

1.1 *Automated processing of CPTs*

Cone penetration testing (CPT) has become increasingly popular as the preferred in-situ test method as it can be used for soil classification, estimation of geotechnical parameters and use in empirical methods. With the increase of automated processed CPT data in engineering (Brinkgreve, 2019), it is critical to have an accurate estimation of soil unit weight as this is the first and most important step in geotechnical parameter determination. This is particularly relevant for organic soils which are often not included in existing CPT-based parameter determination methods.

1.2 *Organic soils*

Organic soils are formed during the decomposition of dead organic substances i.e., remnants of plants and animals. This process takes place in different ways, mainly through bacterial activity, intensified by oxygen and temperature. Another type of sediment with a highly variable organic content are the floodplain sediments, which are deposited when streams at high water overflowed natural embankments. The peat areas and deposits of organic soils occur to a large extent in the northern parts of the world.

To date, most published research on CPT application is on mineral soils. Existing CPT-based correlations for mineral clays do not capture the behavior of soft organic clays and peats well compared to other soils. The properties of peats have been investigated and extensively published, i.e. Den Haan and Kruse (2007), (Mesri and Ajlouni, 2007). However, limited attention has been devoted to the whole range of slightly organic clay to peat, and how this relates to CPT measurements. These organic soft soils are frequently present within the Holocene deposits in the Netherlands and in other deltaic areas worldwide. Organic soft soils are characterized by a low unit weight and high compressibility. Organic soft soils can be identified by a high organic content and high CPT friction ratio. In contrast to other soft soils, the strength is not necessarily low.

1.3 *Aim of this publication*

By combining soil properties obtained from laboratory testing with CPT results, layer-, site- or region-specific correlations can be obtained between CPT measurement data and geotechnical properties of the soil. When automating the interpretation of CPTs, it is preferable to have a direct and reliable relation between the measurements and the soil unit weight. With a more reliable in-situ derived estimation of unit weight, the effect of human interference is limited to a minimum. Moreover, because many soil properties (and thus the applicable correlations) depend on the stress level, it is paramount to have an indication of the stress profile over the depth. For this purpose, the use of lookup tables such as those found in textbooks is not preferable. The aim of this publication is twofold:

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- To validate and improve the CPT-based unit weight correlation (Lengkeek et al., 2018) for the whole range of soils.
- To present additional insight in relations between index properties and CPT measurements for organic soils.

1.4 *Research approach and databases*

The 2018 database includes the sample unit weight and Class 2 CPTs (ISO22476-1, 2012) of Holocene and Pleistocene sedimentary deposits in the Netherlands. This database is used for the initial unit weight correlation and includes all soil types, however mainly mineral soils.

The 2021 database follows from soil investigations from various dike reinforcement projects across the Netherlands. This database includes classification laboratory tests and Class 1 CPTUs of mainly Holocene organic clays and peats. The CPT data is taken from the same depth as the samples, with a maximum allowable distance between borehole and CPT of 1 meter. These soil investigations are performed in the period 2010-2020.

Figure 1. Overview of 57 CPT-borehole pair locations in the Netherlands.

The Dutch Water Authorities requires that all new soil investigations be performed according to a dedicated protocol for dikes, summarized in a standardized STOWA Excel sheet (www.helpdeskwater.nl). The CPTs are standardized in GEF format. These standardized formats are very useful and efficient to set up a comprehensive database. An overview of the locations and number of CPT-borehole pairs is presented in Figure 1. The total number of undisturbed samples is 464, the number of CPT pairs is 233 of which 211 include the unit weight, 136 include organic content and 109 include specific gravity. The data of this research is available in the Delft University of Technology repository and published in Lengkeek (2022).

2 UNIT WEIGHT CORRELATION

2.1 *Soil type categories*

The selected classification method for organic fine-grained soils is based on the FHWA system. Sand (coarse grained soils) are classified based on the sample identification description. The FHWA classification system, based on organic content measured by the Loss on ignition (N), consists of the following soil categories:

- mineral fine-grained soils: N≤3%.
- mineral fine-grained soils with organic matter: 3<N≤15%.
- organic fine-grained soils: 15<N≤30%.
- peats: N>30%.

The classification results for the 2021 database with organic soils are presented in Table 1. The names of the soil categories in the graphs are shortened for practical reasons. For samples where the organic content is unknown, the classification is based on the unit weight; Peat: $\gamma_{sat} \leq 12$, Organic clay: $12 < \gamma_{sat} \leq 14$, Clay with organic matter: $14 < \gamma_{sat} \leq 17$, Clay, mineral: $\gamma_{sat} > 17$, all in kN/m³.

Table 1. Classification results for organic soil types: average organic content, range of unit weight and specific gravity per soil type in the 2021 database.

Results:	N_{mean}	γ_{sat}	G_s
Soil type	(%)	(kN/m³)	(-)
Peat	79	10.1 - 13.1	1.4 - 2.0
Organic Clay	22	11.6 - 14.0	1.9 - 2.4
Clay (org.matter)	8	12.4 - 19.2	2.3 - 2.7
Clay (mineral)	2	15.6 - 20.0	2.6 - 2.7

2.2 *Updated CPT-based unit weight correlation*

The updated CPT-based unit weight correlation is based on the combined database. The 2018 database mainly consists of mineral soils whereas the 2021 database mainly consists of organic soils. The combined database allows for a validation and improvement of the correlation for unit weight. The CPT-based unit weight correlation of Lengkeek et al. (2018) is shown in Equation (1). The correlation is based on the corrected cone resistance q_t and friction ratio R_f, which are both normalized by a reference value. The reference unit weight, here 19.5 kN/m³, is the value when q_t equals $q_{t,ref}$. The updated variables based on the combined database of 427 pairs are presented in Table 2.

$$\gamma_{sat} = \gamma_{sat,ref} - \beta \cdot \frac{\log\left(\frac{q_{t,ref}}{q_t}\right)}{\log\left(\frac{R_{f,ref}}{R_f}\right)} \tag{1}$$

Herein:

$\gamma_{sat,ref}$ is the reference unit weight at which the cone resistance is constant regardless of R_f.

$q_{t,ref}$ is the reference cone resistance at which the unit weight is constant regardless of friction ratio.

$R_{f,ref}$ is the reference friction ratio at which the apex of all lines of equal unit weight is located.

β is the fit factor, which is a measure for the inclination of the equal unit weight contours.

Table 2. Updated parameters for unit weight correlation.

Parameter	Value	Unit
$\gamma_{sat,ref}$	19.5	kN/m^3
$q_{t,ref}$	9.0	MPa
$R_{f,ref}$	20	%
β	2.87	

Figure 2 presents all measured data per soil type combined with the lines of equal unit weight [10, 21] kN/m³. The results are plotted on the SBT template of Robertson (2010). From this figure it can be concluded that the lines of equal unit weight are well aligned with the orientation of SBT zone boundaries. Coarse grained soils, SBT=5 and higher correspond to a unit weight of 18 to 21 kN/m³. The variation in unit weight for fine soils is much larger.

Figure 3 shows the measured unit weight versus the predicted unit weight using the improved correlation. The points are subdivided in the database categories [Peat; Organic Clay; Clay with organic matter; Mineral Clay; Sand]. These database categories are based on the laboratory classification. From this graph it can be seen that the trend follows the 1:1 line very well. The scatter is larger for lower unit weights and organic soils; however, for peats the results are close to 10 kN/m^3, which is also the minimum value as applied.

Figure 4 presents an example of a CPT with clay, peat and sand layers, including the unit weight according to Equation 1. The unit weight from the laboratory tests are respectively 12.6 to 15.0 kN/m³ in the upper 2m clay, 10.3 kN/m³ for the peat layer and 19.5 kN/m³ for the underlain sand layer.

The performance of the improved correlation can be expressed in statistical parameters such as the coefficient of determination (R²) and the standard deviation on regression (S_y) and the slope of the trendline through the origin [x=measured, y=predicted]. The comparison with other existing correlations Mayne (2014), (Robertson and Cabal, 2010, Lengkeek et al., 2018) is presented in Table 3. The R² and S_y comply to Ordinary Least Squares (OLS) regression with free intercept. The slope complies to regression through the origin and is a measure for the bias of the trend in Figure 3. From this comparison it can be concluded that the new correlation performs better for all statistical parameters. The 2018 correlation results in slightly different values which validates the use it.

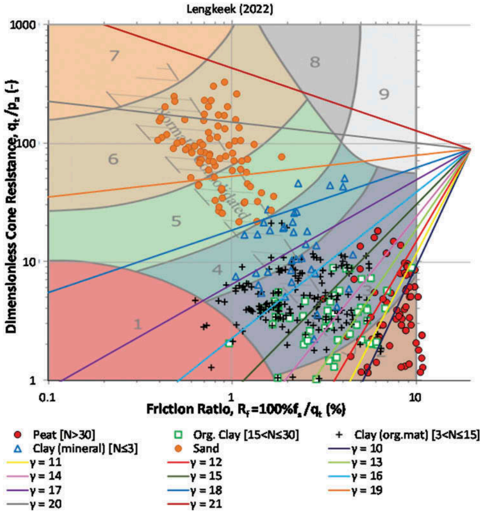

Figure 2. Unit weight measurements and lines of equal unit weight of the improved correlation, presented on top of Robertson (2010) SBT template.

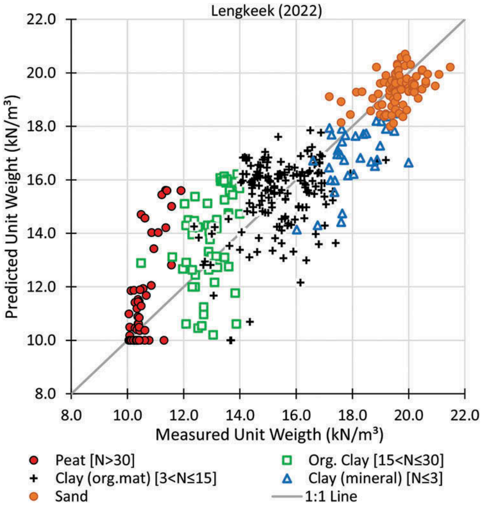

Figure 3. Measured versus predicted unit weight based on the improved correlation.

Table 3. Comparison of statistical results of multiple correlations for the whole range of soils.

Method	R^2	S_y	OLS slope [y:x]	slope through origin [y:x]
Improved correlation Lengkeek (2022)	0.80	1.32	0.84	1.00
Lengkeek (2018)	0.79	1.33	0.80	1.00
Robertson & Cabal (2010)	0.25	1.46	0.26	1.06
Mayne (2014)	0.12	1.68	0.20	1.03

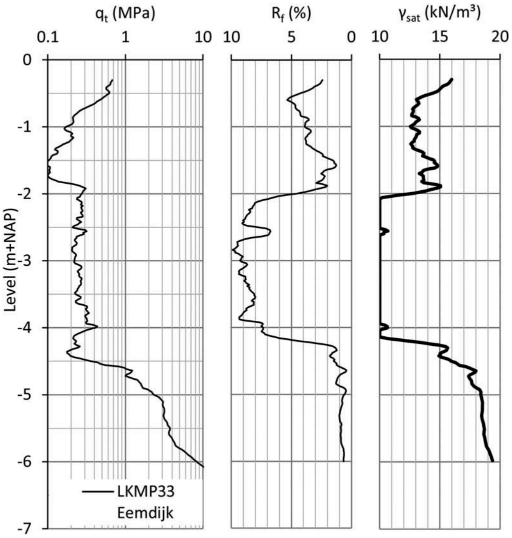

Figure 4. CPT results and unit weight according to equation 1 for a CPT from Eemdijk, the Netherlands.

3 CPT-BASED CORRELATIONS FOR ORGANIC SOILS

3.1 *Introduction*

The pairwise established database of classification test results and CPT measurements allows for comparison of properties of organic soils and additional insight in relations. In this section three graphs with organic content and index properties are presented as well as three graphs with CPT-based correlations.

For each graph the results and the confidence intervals are plotted in the graphs and the statistical parameters are shown in the title. The subcategories are indicated in the legend. The regression is applied to all samples as one group and not per soil type. Correlations for each soil category would result in a lower coefficient of determination and limit any reliable correlation to an average value and standard deviation per soil type.

3.2 *Correlations with organic content*

Figure 5 presents the organic content versus the water content and was first published by Mitchell and Soga (2005). This correlation provides a first estimate of the organic content for any soil which is expected to be organic. The data shows an increase of organic content with water content up to N=90 which is considered as a physical upper bound. The bi-linear fit performs better than the correlation by Mitchell and Soga (2005), which is based on less data.

Figure 6 presents the specific gravity versus the organic content. The results confirm the empirical relation as published by Den Haan and Kruse (2007). Once the organic content is known, the specific gravity and ultimately the unit weight can be estimated.

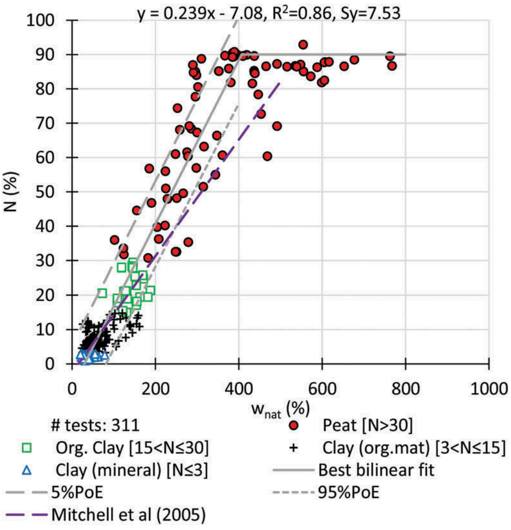

Figure 5. Organic content versus natural water content, for organic to mineral soils. Best bi-linear fit: $N = \min[90\%, 0.239\,w_{nat} - 7.08]$ with standard deviation Sy=7.53.

Figure 7 presents the unit weight versus the organic content. This figure is the basis for the secondary criteria for classification of organic soils based on the unit weight. The variation is more than that for the specific gravity correlation as the unit weight is not just a unique soil property but also a state parameter depending on the preloading and stress level.

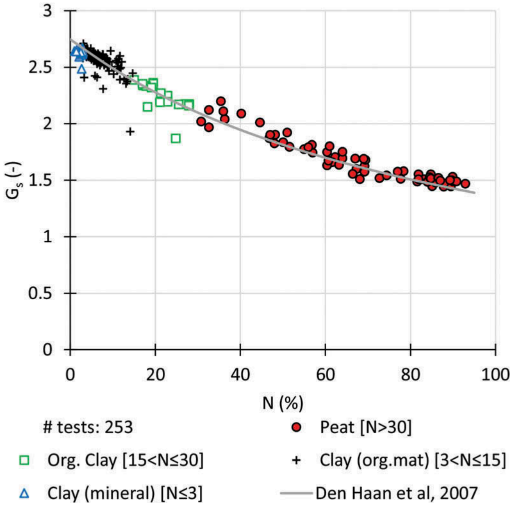

Figure 6. Specific gravity versus organic content, for organic to mineral soils. The standard error on regression (Sy) is 0.082 and coefficient of determination (R^2) is 0.97.

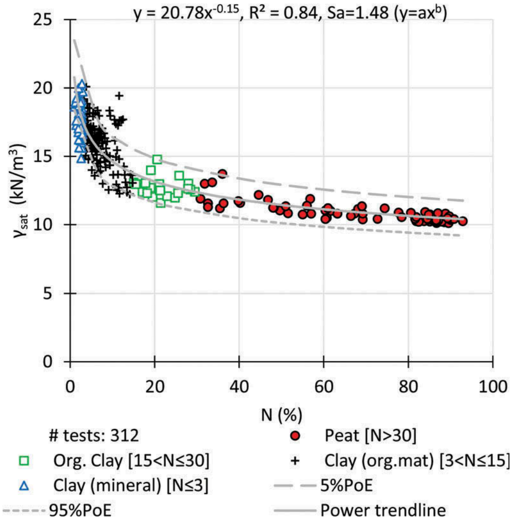

Figure 7. Saturated unit weight versus organic content, for organic to mineral soils. The best power function fit is: $\gamma_{sat} = 20.8N^{-0.153}$ with standard deviation Sa=1.48 (for $y=a \cdot x^b$).

3.3 *CPT-based correlations*

Figure 8 presents the unit weight of soils that are classified as peat and the correlation is shown in Equation (2). This figure illustrates a linear relation where the range is [10, 12] kN/m³, the R² is moderate and the S_y=0.265 kN/m³. This correlation is only applicable with prior knowledge of the soil type and cannot be used for organic clays. The accuracy is however better than Equation (1).

$$\gamma_{sat;peat} = 0.000685 \cdot q_t + 10.1 \qquad (2)$$

Where $\gamma_{sat,peat}$ is the saturated unit weight of peat in (kN/m^3) and q_t is the corrected cone resistance in (kN/m^2).

Figure 9 presents the specific gravity versus the friction ratio. Figure 10 presents the organic content versus the friction ratio. Both correlations confirm that the unique soil properties are reasonably correlated with the friction ratio with a high R². However, the large variation S_y makes these correlations less useful in practice.

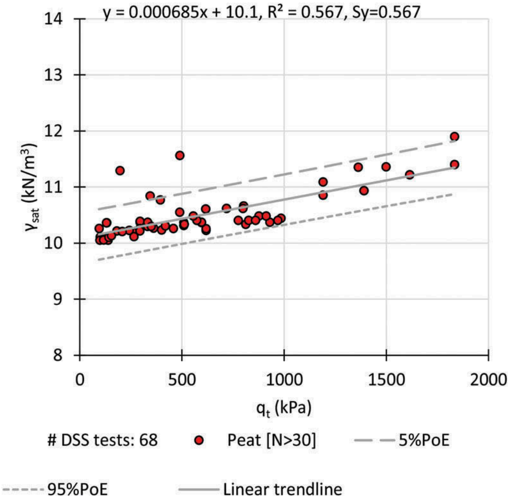

Figure 8. Saturated unit weight versus CPT corrected cone resistance, for soils classified as peat.

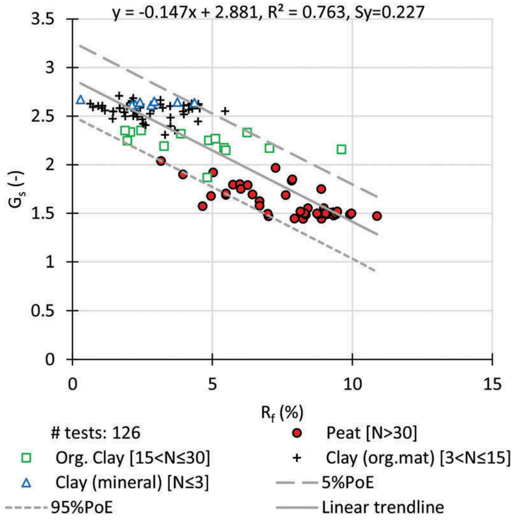

Figure 9. Specific gravity versus CPT friction ratio, for organic to mineral soils. The subcategories are indicated in the legend. The best linear fit is: $G_s = -0.147R_f + 2.88$ with standard deviation Sy=0.227.

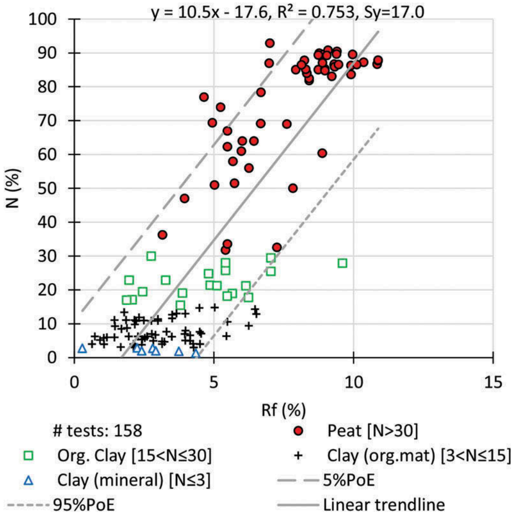

Figure 10. Organic content versus CPT friction ratio, for organic to mineral soils. The subcategories are indicated in the legend. The best linear fit is: $N = 10.5R_f - 17.6$with standard deviation Sy=17.0.

4 CONCLUSIONS AND RECOMMENDATIONS

The pairwise established database of classification test results and CPT measurements provides valuable insight into the properties of organic soils as well as new and updated correlations.

The existing unit weight correlation is validated and improved by the extension of the 2018 database with organic soils resulting in 427 pairs. The statistical parameters of the improved CPT-based unit weight correlation are compared with existing correlations and show better performance. The advantage of the improved correlation shown in equation 1 is that it can be applied for organic soils and mineral sedimentary soils. This is useful for SBT classifications which include stress correction. Specifically, for soils which are classified as peat, equation 2 can be used with even higher accuracy.

The 2021 database confirms existing relations between the organic content and other index parameters. Furthermore, the organic content and specific gravity can be correlated to the CPT friction ratio. Both correlations confirm that the unique soil properties are reasonably correlated with the friction ratio.

The correlations allow for establishing prior estimates where no laboratory tests are available. The disadvantage of this approach is that it increases inherent variation along the trend and the possibility that site specific units are biased to the trendline. The confidence interval and standard deviation are provided to account for such bias. For final estimates of soil parameters, it is recommended to combine these correlations with sampling and testing of site-specific geological units.

In general, it is highly recommended to perform CPTs adjacent to boreholes, select pairs of high-quality laboratory tests according to a standardized protocol (STOWA). This will allow for new or improved correlations which will improve prior estimates.

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