CPT based unit weight estimation extended to soft organic soils and peat

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Cone Penetration Testing 2018

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CPT based unit weight estimation extended to soft organic soils and peat

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ABSTRACT: A reliable estimate of the saturated soil weight from CPT analysis can be useful for various purposes. An often used relation that gives a reasonable first approximation is presented by Robertson & Cabal (2010). In The Netherlands very soft and highly organic soils are omnipresent and these types of soil are absent in the aforementioned relation. In this paper a new relation is proposed that can be used to estimate the saturated soil unit weight for a wider range of soils, from sands to highly organic soils.

1 INTRODUCTION

1.1 *Problem description*

Cone penetration testing has a widespread application in The Netherlands, from code regulated pile foundation and dike design, and in recent years liquefaction triggering assessments in Groningen related to induced earthquakes.

CPT based parameter estimation is applied in a wide variety of geotechnical projects. The quantity of complementary laboratory tests in general depends on the risks involved in a project. Due to increased computer performance more and more analyses are being performed and will be automated. Since a CPT provides continuous data in a vertical soil profile, the obtained data lends itself for automated interpretation.

The use of CPTs in the design of dikes in The Netherlands has intensified with the Dijken op Veen method (Zwanenburg & Jardine, 2015). In this method a layer specific empirical cone factor (N_{kt}) is determined and applied directly to the CPTs to derive the undrained shear strength (S_u). In order to do so, laboratory test are required to determine the in-situ undrained shear strength, the undrained shear strength ratio (S), the unit weight (γ) and the pre-consolidation stress (p_c). These tests are normally performed on undisturbed samples taken from a few boreholes with an adjacent CPT. This allows for correlating the aforementioned parameters. The large natural variability associated with geotechnical soil properties is taken into account by applying the correlation to each individual CPT.

In practice it turns out that the identification of soil type and in particular the estimation of unit weight for soft organic soils and peats is often not very accurate. Most existing methods are validated for, and therefore applicable to mineral soils only. Applying these correlations will lead to an overestimation of the unit weight and consequentially and erroneous prediction of stresses and strength.

1.2 *Scope*

By combining soil properties obtained from laboratory testing with fairly constant CPT results, layer-, site- or region-specific correlations can be obtained between CPT measurement data and geotechnical properties of the soil. When automating this process for all measurement points or multiple CPTs, it is preferable to have a direct reliable relation between the measurement data and the estimated soil unit weight, so that 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 depth. For this purpose use of lookup tables (such as provided in the Dutch version of Eurocode 7) is not preferable.

1.3 *Approach*

The approach is based on matching laboratory tests results with CPT data. The CPT data is taken from the same level as the samples, where a maximum distance between borehole and CPT of 1 meter is applied. Soil investigation programs at the locations from Table 1 across the Netherlands have been used.

For the definition of the CPT Class reference is made to ISO 22476-1:2012 which is effectively in use in The Netherlands since February 2013.

In Table 2 an overview of both the number of samples and the minimum and maximum values of the observed values are presented.

Chapter 2 will further elaborate on the unit weight of organic soils as measured in the laboratory. A new correlation is presented in order to estimate the organic content based on the water content. This correlation can be useful in practice because most often the organic content or specific gratify is not determined.

Chapter 3 will elaborate on a new framework correlation for the unit weight based on the cone resistance and friction ratio, calibrated with laboratory measurements.

Table 1. Overview of CPT locations.

Location	Number of CPTs	Class
Amsterdam	42	2
Bergambacht	19	2
Delfzijl	32	2
Eemdijk	42	1
Eemshaven	52	2
Katwoude	36	1
Krimpen aan den IJssel	11	1
Leeuwarden	6	2
Rotterdam	6	2
Terneuzen	46	2
Uitdam	8	2

Table 2. Overview number of samples.

Property		Number of samples	Minimum value	Maximum value
q_t	[MPa]	300	0.10	33.05
R_f	[%]	300	0.22	10.54
u_2	[MPa]	218	–0.06	1.67
γ_{sat}	[Mg/m³]	300	10.05	21.33
γ_{dry}	[Mg/m³]	257	0.81	18.29
Water content	[%]	294	16.6	1145
Loss on ignition	[–]	78	0.0	89.5
Specific gravity	[–]	9	1.45	2.33

2 UNIT WEIGHT OF ORGANIC SOILS

2.1 *Organic clays and peats*

Large parts of The Netherlands have Holocene deposits with organic soils such as peat. The specific gravity in organic soils is affected by the organic constituents, and cannot simply be set to somewhere near 2.7 as in mineral soils. Cellulose has a specific gravity of approximately 1.6, while for lignin it is approximately 1.4. These low values reduce the compounded specific gravity of organic soils (Den Haan & Kruse, 2006). Consequently the density of organic soils is lower than mineral soils.

The organic content is unfortunately not always measured in practice. A collection of measurements from various soil investigation programs across the Netherlands is presented in Figure 1. Herein the measured loss on ignition (closely related to the organic content) is plotted measured saturated water content. Equation 1 presents the best fit to the data and is a slight adjustment to the correlation presented by Mitchell & Soga (2005).

$$N = 0 < \frac{(W - 18.3)}{6.35} < 90 \quad (1)$$

In which:
N is the loss on ignition [%]
W is the saturated water content [%]

Equation 1 can be used in case the field classification indicates organic soils and no measurements of organic content has been performed. Once the loss on ignition is known the specific gravity (ρ_s) of the solids can be determined. In Figure 2 the measurement loss on ignition is plotted against the

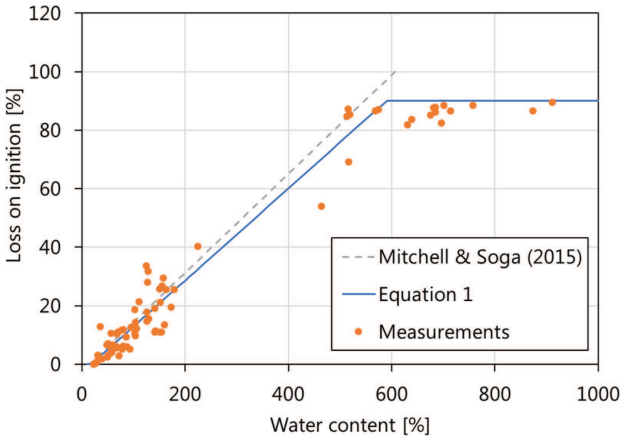

Figure 1. Measurements versus correlation Mitchell & Soga.

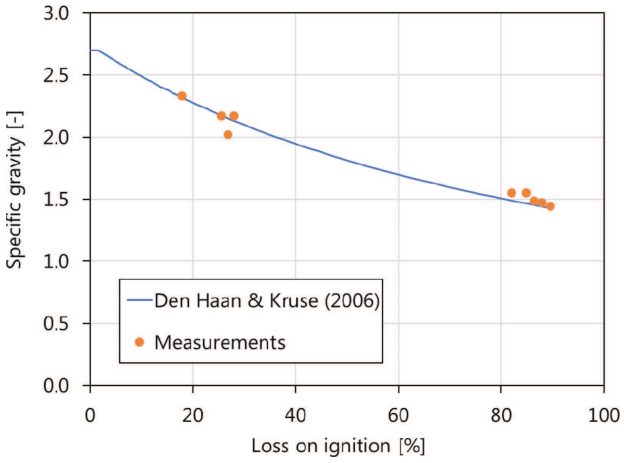

Figure 2. Measurements versus correlation Den Haan & Kruse.

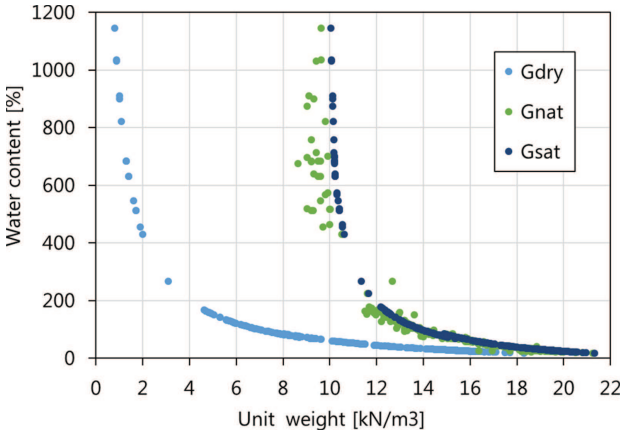

Figure 3. Measured unit weights.

specific gravity together with Equation 2 as presented in Den Haan & Kruse (2006).

$$\frac{1}{\rho_s} = \frac{N}{1.354} + \frac{(1-N)}{2.746} \tag{2}$$

The data fits very well with the existing equation and data of Den Haan & Kruse (2006). This is probably the reason why this test is not often performed in practice. The specific gravity is required to calculate the correct densities and other classification parameters, in particular the void ratio. In Figure 3 the measured dry and natural unit weights are presented together with the calculated saturated unit weight. From Figure 1 to Figure 3 it can be observed that there is practically an absence of data on organic clays and peats with a saturated unit weight between 11.0–12.0 kN/m^3, dry unit weights between 2.0–4.5 kN/m^3, water content between 200–400%, loss on ignition between 30–70% and specific gravity between 1.6–2.0 [-]. Apparently these soils are less present in the Holocene deposits in The Netherlands.

3 PROPOSAL NEW FRAMEWORK AND UNIT WEIGHT CORRELATION

3.1 *Existing methods*

Estimating the soil unit weight from CPT measurement data is required to determine the total and effective stresses in a soil profile. As such this step is at the basis of further CPT data interpretation and evaluation as for many relations correcting for the in-situ (effective) stress level is required.

One way to determine unit weights and an initial stress profile is by using look-up tables. After having identified a certain soil type from the raw measurement data, e.g. Douglas & Olsen (1981) and Robertson et al. (1986), a discrete unit weight value can be assigned to each soil type after which the total and effective vertical stresses can be computed. Using a continuous rather than a discrete function is however preferable because also intermediate states and densities can be accounted for.

Robertson & Cabal (2010) proposed a continuous function where the saturated unit weight is a function of the cone tip resistance q_t and the friction ratio R_f. The downside of their formulation is that it is only derived for clays and sands that have saturated unit weights of 15 kN/m^3 and higher. As can be observed from the dotted curves in Figure 4, the estimated unit weight increases with increasing friction ratio for all soil types. For soft clays and organic soils typically the opposite is observed, namely that the saturated unit weight is expected to decrease as the friction ratio increases as a consequence of the increase of the organic content in the soil.

Mayne et al. (2010) used a regression analysis on a wider array of soil types including soft clays and silts with a minimum considered γ_{sat} of about 12 kN/m^3. Their regression analysis resulted in the formulation presented by Equation 3.

$$\gamma_{sat} = 1.95 \cdot \gamma_w \cdot \left(\frac{\sigma'_{vo}}{\sigma_{atm}}\right)^{0.06} \cdot \left(\frac{f_s}{\sigma_{atm}}\right)^{0.06} \tag{3}$$

Although this relation captures the range of interest better, an iteration or first estimate of the vertical effective stress is required which is surmountable, but undesirable nonetheless. The same holds for relations that depend on the shear wave velocity, unless SCPT measurement data is available. As the latter is most often not the case, the application range of such relations is less desirable.

Mayne (2014) furthermore suggests a relation that is solely dependent on the sleeve friction f_s which gives reasonable results to the soft clay domain. When organic soils are considered the relation seems clearly off. By considering the graphical interpretation of f_s relation introduced

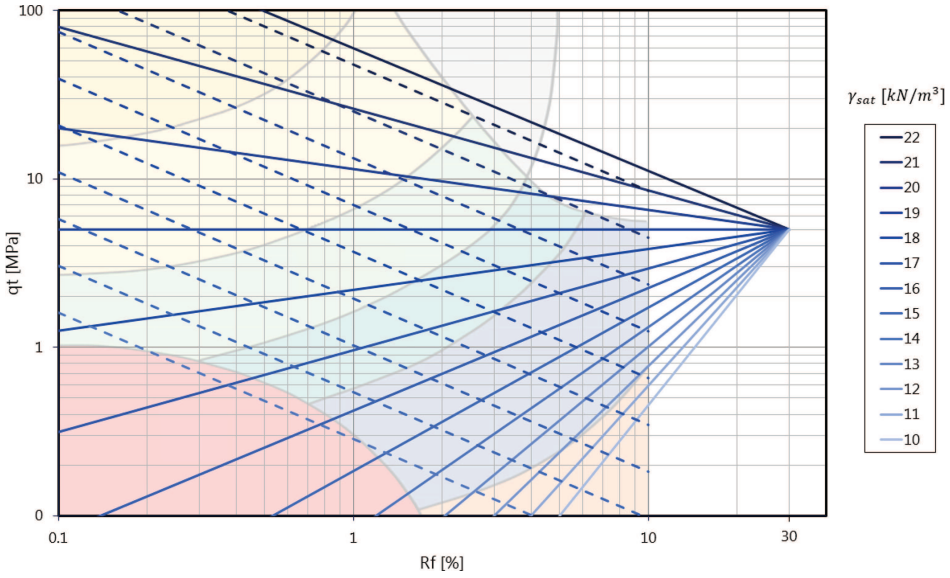

Figure 4. Graphical representation of the framework by Robertson & Cabal (dotted) and the proposed framework (continuous).

by Mayne (2014) it can be seen clearly that organic peats do not fall within the desired range.

3.2 *Formulation*

A new formulation is proposed to estimate the soil unit weight from CPT measurement data, having the following expedient properties:

- The saturated unit weight is a continuous function of the standard CPT measurement data
- No iterative procedure is required
- The application domain is extended to the soft and organic soils typically found in The Netherlands

The analytical formulation is given by Equation 4. Similar to the proposed relation by Robertson & Cabal (2010), contours of equal unit weight can be drawn in the q_t-R_f plane (see Figure 4).

$$\gamma_{sat} = \gamma_{sat,ref} - \beta \cdot \frac{\log\left(\frac{q_{t,ref}}{q_t}\right)}{\log\left(\frac{R_{f,ref}}{R_f}\right)} \tag{4}$$

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 a measure for the inclination of the equal unit weight contours.

The functional form of Equation 4 implies that for all cone tip resistances lower than $q_{t,ref}$ the saturated unit weight decreases with increasing friction ratio. Although the functional form allows for the calculation of values of γ_{sat} lower than 9.81 kN/m^3 (bottom right corner of Figure 4) it is recommended to use this value as a practical cut-off since the saturated unit weights will never be far less than the unit weight of water. Peats however often contain gas and therefor the natural unit weight can be as low as 9.0 kN/m^3 as shown in Figure 3.

The basic formulation is such that the reference values can easily be chosen and the inclination parameters easily be fitted. This can be done for a specific soil type, a site specific layer or in general for projects or even large regions as done here.

3.3 *Verification with data*

To verify the proposed framework and Equation 4, values of saturated unit weight obtained from laboratory measurements are compared with CPT measurement data at mid sample depths. Data is obtained at multiple locations and at various depths. Requirement for this verification procedure is that the borehole from which the sample is taken and the CPT are in close proximity (at maximum 1 m) and the variation in CPT measurement data is not too large. On some locations this turned out to be an issue because the Holocene deposits in The Netherlands show significant variation in vertical and horizontal direction and the layer thickness is limited.

Using the proposed framework the whole range of soils and unit weights can be addressed as is shown in Figure 4 to Figure 6. By combining

a regression analysis with expert judgment the adopted values to be implemented in Equation 4 are presented in Table 3. For this purpose the 300 data points mentioned in Table 2 are used.

A comparison between the measured and the calculated saturated unit weights is also made for other available correlations. Graphically this is presented in Figure 5, where for the sake of clarity the correlation by Mayne (2014) is not shown. The observed trend, namely that the calculated values are too high when organic soils are considered, is equal. Table 4 gives the R^2 values and slopes for the four considered methods. From these values it is obvious that over the whole considered range the proposed framework is superior to the correlations.

The general trend (Pearson R^2 and slope [1:x]) of the proposed correlation has improved significantly. The variation is large but the standard error on regression (Sxy) is reduced. As noted earlier in the method by Robertson & Cabal (2010) no values of γ_{sat} below 15 kN/m^3 were considered and Mayne

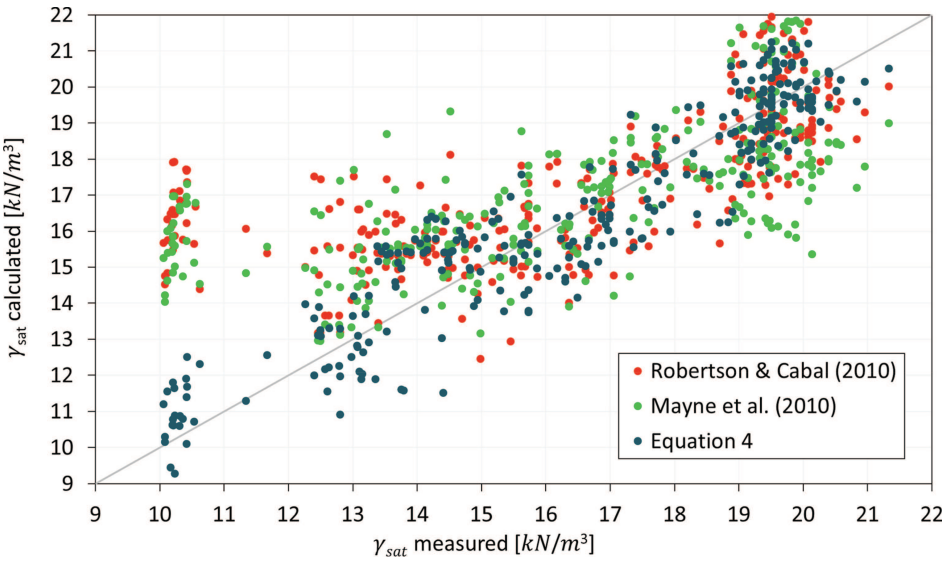

Figure 5. Measured versus calculated saturated unit weights using some of the different correlations from Table 4. Note that herein no cut-off value is applied for the minimum value of the calculated unit weight.

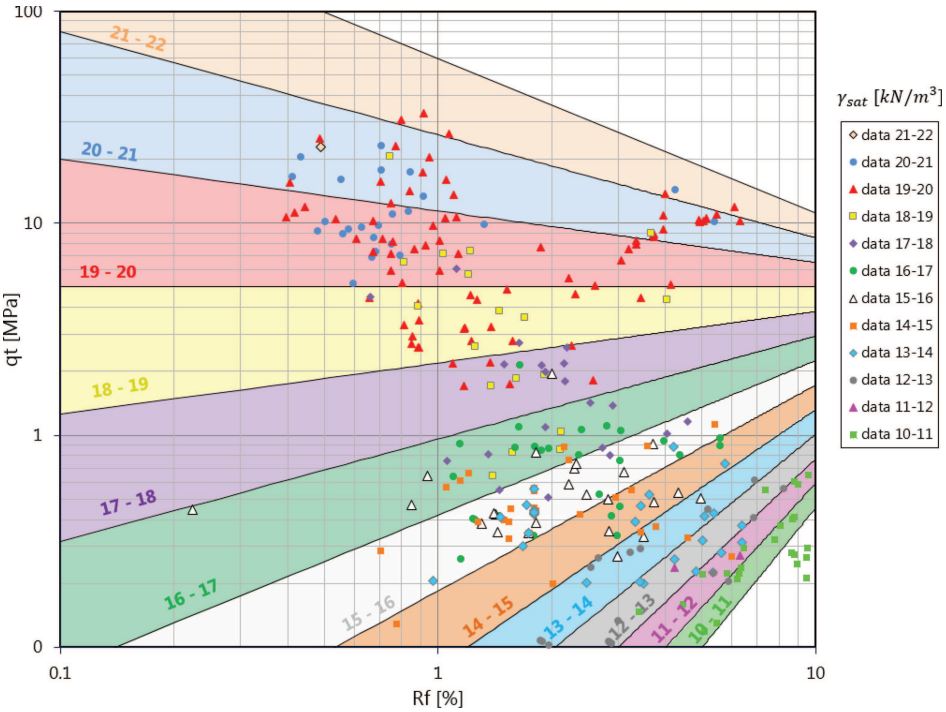

Figure 6. Graphical representation of the measurement data in the proposed framework at discrete unit weight intervals.

Table 3. Proposed parameters for Equation 4.

Parameter	Adopted best fit values
$\gamma_{sat,ref}$	19.0
$q_{t,ref}$	5.0
$R_{f,ref}$	30.0
β	4.12

Table 4. Results for multiple methods.

Method	R^2	slope [1:X]	Sxy
Equation 4	0.88	0.95	1.13
Robertson & Cabal (2010)	0.49	0.45	1.46
Mayne et al. (2010)	0.45	0.47	1.65
Mayne (2014)	0.39	0.42	1.68

et al. (2010) focus mainly on soft clays and silts with a minimum considered γ_{sat} of about 12 kN/m^3.

Therefore a comparison is also made for measured $\gamma_{sat >}$ 15 kN/m^3 based on 193 measurements. The R^2 is 0.77 for Equation 4 compared to 0.28–0.60 for the existing correlations. This means that also for non-organic soils a better estimation is found.

The standard error of the estimated unit weight is typically ± 1 kN/m^3. This error is first of all caused by the distance between CPT and borehole and the variation in lateral and vertical direction. Furthermore the measurement accuracy of the CPTs, in particular for peats with very low cone resistance and sleeve friction. But also the accuracy of the laboratory tests as it turned out that in about 5% of the samples the measured unit weight and water content were inconsistent. Finally the error is inherent to the variation in soil types, effective stress, over-consolidation, aging, organic content, saturation etc.

In addition a comparison has been made between Class 1 and Class 2 CPTs for $\gamma_{sat <}$ 15 kN/m^3. The R^2 is respectively 0.71 and 0.78. The difference is not much but still it is surprising that the Class 1 CPTs have a lower R^2. This could be explained by the very low measured q_c and f_s values of peats that where mainly investigated by Class 1 CPTs.

4 CONCLUSIONS AND RECOMMENDATIONS

- The correlations by Mitchell & Soga (2005) and Den Haan & Kruse (2006) are confirmed, where it appears that the former can be slightly improved. This will enhance better prediction of the density and classification parameters of organic soils.
- The new framework and proposed equation for estimating the saturated unit weight based on q_t and R_f measurements can be applied to the entire range of firm sandy soils to organic soils and peat, as typically can be found in Holocene sedimentary deposits in The Netherlands.
- For the considered soil data, the proposed relationship outperforms other considered correlations. The variation in the estimation is however still considerable and comparable to earlier studies.
- It is recommended that care is taken when applying the relation to other non-sedimentary soils. The authors are curious to see how the proposed framework performs for other type of soils as the framework allows for adjusting the fitting parameters.

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