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CPT-based classification of soft organic clays and peat

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ABSTRACT: An updated CPT-based classification system of organic clays and peat is proposed based on an extensive pairwise established database of classification tests and CPT measurements. This new classification system is proposed to supplement the existing dimensionless q_t/p_a-Rf-chart of Robertson (2010). The Robertson (2010) dimensionless classification system is selected for refinement because it appears to perform better than normalized systems for peats with very low stresses (<20 kPa). A combination with Robertson (2009 and 2016) is possible in cases where a stress normalization cut-off is used.

1 INTRODUCTION

1.1 *Application of CPTs in dike projects*

To successfully plan, design and construct a geotechnical project, various types of investigative techniques to obtain sufficient geotechnical information are required. Geotechnical field investigations generally comprise boreholes with sampling and in-situ cone penetration tests, performed with a friction cone penetrometer (CPT) or with a piezocone penetrometer (CPTU).

The use of CPTs in the design of dikes in the Netherlands has increased over the years. On a typical dike project, CPTs are performed typically every 100m along the center line and supplemented with 3 CPTs and 1 borehole along a cross section every 200m. The number of CPTs is typically 5 times greater than the number of boreholes. This is due to the relative costs and the increased possibilities associated with the use of CPTs.

1.2 *CPTs in organic soils*

Cone penetration testing 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. The initial soil texture-based classifications were based on direct measurement of cone resistance (q_c) and sleeve friction (f_s) e.g. Begemann (1965). The current CPT-based classification systems are based on behavior characteristics and are often referred to as a Soil Behavior Type (SBT) classification. These classification systems include pore pressure measurements from CPTU tests and the shear wave velocity from SCPT tests, e.g. Robertson (2016). Examples of CPT based empirical methods can be found in the Eurocode (EN1997-1, 2005, EN1997-2, 2007), where the cone resistance is used for the estimation of soil strength. In addition, there is a wide range of publications on CPT based estimation of geotechnical parameters. A comprehensive overview can be found in Kulhawy and Mayne (1990), (Lunne et al., 2002, Mayne, 2014).

To date, most published research in the field of CPT application is on mineral soils. Existing CPT-based correlations for mineral clays do not properly capture the behavior of organic clays and peats compared to other soils. The properties of peats have been investigated and extensively published, i.e., Den Haan (1997), (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 soils are frequently present within the Holocene deposits in the Netherlands and in other deltaic areas worldwide. Organic soils are characterized by a low unit weight and high compressibility. Organic soils can be identified by a high organic content and high CPT friction ratio. In contrast to other soft soils, the shear strength is not necessarily low.

1.3 *Aim of this publication*

The aim of this publication is to improve the applicability of CPTs for organic soils. To achieve

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this, results from soil investigations from dike reinforcement projects across the Netherlands have been collected. CPTs and boreholes that were performed in proximity of each other have been selected. The laboratory tests results and CPT measurements were taken at the same level, paired, and processed into a regional database. In this paper an improvement for CPT based classification systems for organic soils is proposed.

1.4 *Research approach and databases*

This research combines an existing database (Lengkeek et al., 2018) and a new compiled database for organic soil properties, referred to as the 2021 database. The 2018 database includes the sample unit weight and Class 2 CPTs of Holocene and Pleistocene sedimentary deposits in the Netherlands. An overview of the locations and number of CPT-borehole pairs is presented in Figure 1.

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

The 2021 database includes soil investigations from various dike reinforcement projects across the Netherlands. The 2021 database includes classification laboratory tests and Class 1 CPTs of Holocene organic clays and peats. The CPT data is taken from the same level as the samples, with a maximum allowable distance between borehole and CPT of 1 meter. These soil investigations were performed in the period 2010-2020. Recently, the Dutch Water Authorities required 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. The data of this research is available in the Delft University of Technology repository and published in Lengkeek (2022).

2 CLASSIFICATION OF ORGANIC SOILS

2.1 *Laboratory classification*

Existing classification systems are based on geomorphology, topography, chemical properties, botanical origin, genetic processes, or physical characteristics. From a geotechnical engineering perspective, the physical characterization is the most relevant. Several classification systems for organic soils are used in various countries and are based on similar grounds. In many cases, a certain degree of humification Von Post (1922) is used for the classification of peat, together with the normal geotechnical parameters, such as water content, Atterberg limits, organic content, bulk density etc. Understanding the stratification and properties in a soil profile is made easier if the geological history and the environmental conditions at deposition of the sediments are known.

Examples of classifications for geotechnical engineering can be found in Landva et al. (1983), (NEN5104, 1989, Huang et al., 2009, ISO14688-1, 2017, ISO14688-2, 2017, Von Post, 1922). Both the term 'organic content' and 'ash content' are used to identify organic soils. The classification systems differ, in particular for organic content in the range [20,50] %, where peats and organic clays overlap.

2.2 *CPT-based classification methods*

CPT-based classification methods provide two-dimensional charts for soil type classification based on the CPT measurements. These charts were developed through direct correlation between the CPT data and the corresponding soil type determined from adjacent borings. The initial soil texture-based classifications were based on direct measurement of cone resistance and sleeve friction (Begemann, 1965, Schmertmann, 1978).

Robertson et al. (1986) developed a non-normalized soil behavior-based classification, initially with 12 zones. In Robertson (2010) this is updated to 9 zones based on dimensionless cone parameters (q_t/p_a, R_f) and the non-normalized SBT-index I_{SBT}. Robertson (1990) presented the normalized soil behavior classification for 9 zones based on the linear normalized cone parameters (Q_{t1}, F_r, B_q). The soil behavior type index I_{c1} is added to this in Robertson and Wride (1998). In (Robertson, 2009, Zhang et al., 2002) the classification system SBTn is adjusted with a variable stress exponent n and non-linear normalized cone resistance Q_{tn} and nonlinear SBT-index I_{cn}.

Since 1990, more CPT soil behavior-type charts have been developed including (Been and Jefferies, 1993, Eslami and Fellenius, 1997, Schneider et al., 2008). In Robertson (2016) a modified SBT classification system is presented with 7 zones and charts based on Q_{tn} versus the small-strain rigidity index I_G and versus the normalized pore pressure U_2. Furthermore, a new hyperbolic shaped modified SBT-index I_B is introduced.

Existing CPT based classifications generally relate to mineral soils which are present worldwide. The major disadvantage of existing CPT based classification methods is that the classification of organic soils is inaccurate. In many cases a peat layer is classified as clay (SBT=3) instead of organic material (SBT=2). Furthermore, it does not distinguish between peats and organic clays. Engineering of dike projects in the Netherlands, where peat is often present, is therefore mostly based on local experience or the non-stress normalized q_t/p_a-Rf chart of Robertson (2010). CPTUs are generally performed; however, the pore pressure classification charts are not used due to the presence of gas in organic soils, which causes a reduced and unreliable pore pressure response.

2.3 *Organic soil type categories*

The 2021 database includes classification tests according to different standards and systems (NEN, EN, ISO).The organic content is measured for most samples. The fine grained soils are classified according to one system: FHWA (Huang et al., 2009). The FHWA classification system is based on the organic content measured by the loss on ignition (N) and 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%.

For samples where the organic content is unknown, the classification is based on the unit weight; Peat: $\gamma_{sat} \leq 12$, Org.Clay: $12 < \gamma_{sat} \leq 14$, Clay (org.mat): $14 < \gamma_{sat} \leq 17$, Clay (mineral): $\gamma_{sat} > 17$, all in kN/m³.

3 UPDATED SBT ZONES FOR ORGANIC SOILS

3.1 *Stress normalization*

The samples of the combined database (2018 and 2021) are taken from 0.5 to 15m depth and effective vertical stresses in the range of 5 to 150 kPa. For situations with the presence of peat layers and high-water tables, stresses are sometimes less than 20 kPa at 10m depth. Therefore, care should be taken with CPT-based classifications that include stress normalization, as illustrated in the following example.

A peat layer below a dike with a high stress level of about 100 kPa is originally classified as SBT=2 (Robertson, 2010) and SBTn=2 (Robertson, 2009), but the same peat layer beside the dike with a low stress of 20 kPa moves up to SBTn=3 and will be classified as clay. This second classification is not correct as the soil type is the same, but only the stress state is different. Consequently, the soil profiling beside the dike can be incorrect, and the wrong parameters will be appointed to this layer. In this example, the normalized cone resistance Q_{tn} is 5 times higher than Q_t. These high stress corrections are not included in the international databases where most of the stresses are typically in the range of 50 to 300 kPa.

Particularly for dike projects there is a second argument not to apply a large stress correction. The peat layers beside the dike are generally over-consolidated by an OCR of 2, due to a combination of water level changes and aging. The same peat layer below the dike, which has been raised periodically, is only slightly over-consolidated. As the cone resistance is related to the preconsolidation stress more than the vertical effective stress, the actual stress correction should be about 2 to reflect the state properties.

The proposed adjustments to the SBT charts, as will be presented in the next paragraphs, are valid for the non-stress normalized SBT chart (Robertson, 2010) and the stress-normalized SBT chart (Robertson, 2009) with the application of the stress normalization cut-off $C_n \leq 2$.

3.2 *Proposed SBT adjustment*

This paragraph presents the adjustment to the SBT classification for organic soils, such as those encountered in deltaic areas in the Netherlands. The results from the combined database are plotted on the (Robertson, 2010) template in Figure 2. The soil categories consist of the categories in Table 1, including one category for sand.

The data coincides to a large extent with SBT zones, which is expected for the mineral soils. A few datapoints coincide with SBT=1 (sensitive soils) and no points coincide with SBT=7, 8 and 9. Soils of SBT=7 can be present in Pleistocene sand deposits and gravelly deposits, which are present along the river Meuse in the South of the Netherlands. Soils of SBT=8 and 9 are not expected in a deltaic area up to 15 m depth.

There are major differences in SBT=2 and 3, where a significant amount of organic soils plot in SBT=3. The performance results based on the existing Robertson (2010) classification of organic fine-grained soils are presented in Table 2. It is concluded that most of the organic soils, including most of the peats, plot in

SBT=3 ($I_c \leq 3.6$). The performance is about the same for I_{cn} based on stress normalization including $C_n \leq 2$. Without the C_n cut-off almost all points plot outside of SBT=2.

Table 1. CPT results of 2018 and 2021 database.

	average		range	
	q_t	R_f	q_t	R_f
Soil type	(MPa)	(%)	(MPa)	(%)
Peat [N>30]	0.5	7.8	0.1 - 1.8	3.2 - 11.0
Org. Clay [15<N≤30]	0.4	3.8	0.1 - 0.9	1.0 - 9.6
Clay (org.mat) [3<N≤15]	0.6	2.5	0.1 - 2.1	0.6 - 6.5
Clay (mineral) [N≤3]	1.7	2.4	0.2 - 5.1	1.1 - 4.6
Sand	10.2	0.9	2.2 - 33.1	0.4 - 1.9

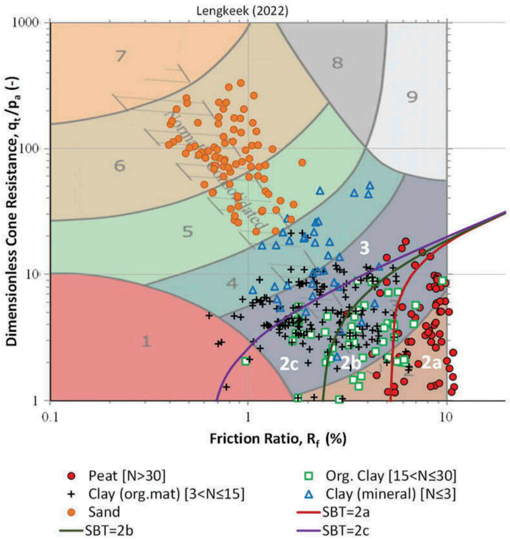

Figure 2. 2018 and 2021 database results and proposed SBT adjustment for organic soils, presented on top of Robertson (2010) SBT template.

Table 2. Performance results for organic soils based on existing Robertson (2010) SBT classification. Percentage is number of samples per category plotted in a SBT zone.

SBT zone: Soil type	SBT2 (Ic>3.6)	SBT3,4 (Ic≤3.6)
Peat [N>30]	35%	65%
Org. Clay [15<N≤30]	21%	79%
Clay (org.mat) [3<N≤15]	6%	94%
Clay (mineral) [N≤3]	0%	100%

Table 3. Performance results for organic soils based on proposed adjustments to Robertson (2010) SBT classification.

SBT zone: Soil type	SBT=2a	SBT=2b	SBT=2c	SBT=3, 4
Peat [N>30]	**78%**	15%	1%	4%
Org. Clay [15<N≤30]	16%	**42%**	40%	2%
Clay (org.mat) [3<N≤15]	3%	22%	**38%**	37%
Clay (mineral) [N≤3]	0%	11%	3%	**86%**

The proposed adjustment is that SBT=2 and part of SBT=3 are redefined and split up into SBT=2a (Peat), 2b (Organic Clay) and 2c (Mineral Clay, with organic matter). No adjustments are proposed to the boundaries between SBT=3, 4 and higher. This is also not possible as this database does not distinguish between silts and clays due to the lack of Atterberg limits tests. Most of the classified points plot in the correct SBT zone when using the proposed adjustment, although there is still some overlap with the adjacent SBT zones. The selection of the boundaries is determined by maximizing the group of positives and minimizing the number of false positives and false negatives.

In addition, the boundaries are selected to separate over-consolidated organic soils from over-consolidated plastic clays, such as Pot clay (Pleistocene) and Boom clay (Oligocene) encountered in the Netherlands. The maximum cone resistance occasionally measured in peats at high stress levels is about 2 MPa. This results in a rather sharp transition from SBT=2a to SBT=3. The new boundaries are extended to a friction ratio of 20%, which is occasionally measured in peats at low stress levels.

The performance results are presented in Table 3. It is concluded that majority (78%, 86%) of the classified points in SBT=2a, 3, 4 are correct. For SBT=2b and 2c, it is concluded that a significant number of points plot in the adjacent SBT zone but still the largest subgroup (38%, 42%) complies with the proposed SBT zone. The number of false positives outside of the adjacent SBT zones is less than 5%.

The formulation for the new proposed boundaries is shown in Equation (1). The parameter values are shown in Table 4.

$$q_t/p_a = a\left(R_f - R_{f,min}\right)^b \tag{1}$$

Figure 3 presents a CPT according to the adjusted classification system. From the borehole and samples, the following layers are identified: organic clay from surface, soft clay with organic material

Table 4. Parameter values for boundaries of proposed adjustments to Robertson SBT (2010) and SBTn (2009) classification.

SBT & SBTn boundary: Parameter	SBT=2a	SBT=2b	SBT=2c
a (-)	8.0	5.2	4.7
b (-)	0.50	0.62	0.64
$R_{f,min}$ (%)	5.2	2.3	0.60

(-1.5 m NAP), peat (-2.0 m NAP), sand (-4.3 m NAP). The layers are well captured except that based on the CPT classification an intermediate layer is shown between the peat and sand layer, which is likely a transition effect.

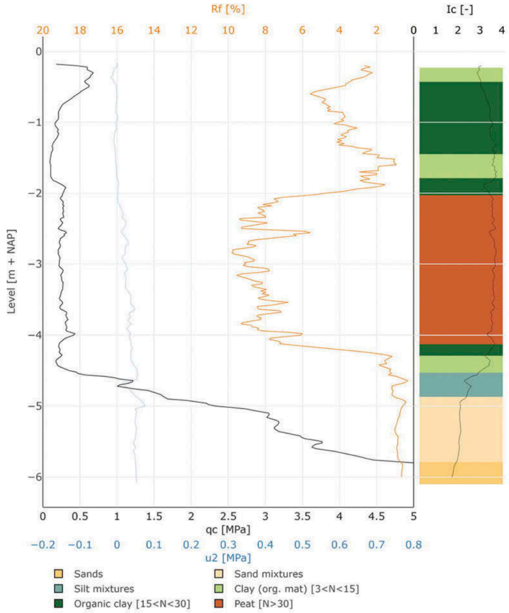

Figure 3. CPT LKMP33 at Eemdijk the Netherlands classified with the proposed system to include soils.

The proposed boundaries are optimized such that they can also be applied as adjustment to (Robertson, 2009, Robertson, 2016), in combination with a stress normalization cut-off equal to $C_n \leq 2$. The parameters in Equation 1 are replaced by Q_{tn} and F_r. These boundaries for organic soils do not apply if there is no stress normalization cut-off applied. The results of the 2021 database are plotted in Figure 4 on top of the combined 2009 and 2016 template. In this figure C_n=1.7 is applied in line with recommended practice by (Boulanger and Idriss, 2016). The mineral clays and sands are not included, as not all stresses required for normalization are known. Most

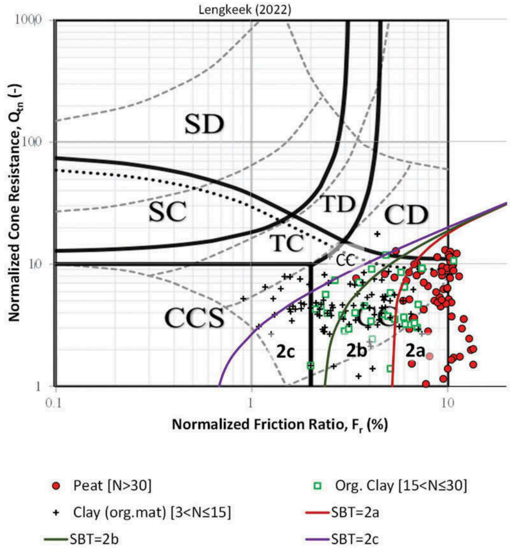

Figure 4. 2021 database results and proposed SBT adjustment for organic soils, presented on top of Robertson (2009 & 2016) SBT template.

points plot in the CC category, contractive clays, although quite some points plot in the CCS, contractive clays sensitive, category which is larger than the SBT=1 (2009) category. A few points plot in the CD category, dilative clays. Those points correspond to the organic soils with high stresses or large overconsolidation.

4 CONCLUSIONS AND RECOMMENDATIONS

This publication presents the challenges in CPT-based classification of organic soils. One of the challenges is that the identification and estimation of unit weight for organic clays and peats from CPT data is often in accurate using existing methods.

The coarse grained and fine-grained soils classified as mineral soils correspond well with existing SBT classifications. The organic soils, classified according to the FHWA method, do not match well with the SBT classification. In the proposed adjustment to Robertson (2010), SBT=2 (Organic soils) and SBT=3 are redefined and split up into SBT=2a (Peat), SBT=2b (Organic Clay) and SBT=2c (Mineral Clay with organic matter). The classification is based on data pairs up to 15 m depths and 150 kPa vertical effective stresses. The new SBT zones can also be applied in the SBTn classifications by Robertson (2009) and (Robertson 2016) in combination with a C_n=1.7 as stress normalization cut-off.

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). The pairwise established 2021 database of classification test results and CPT measurements provides valuable insight in the properties of organic soils and an improved classification system.

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