CPT based classification with focus on organic soils

Arny Lengkeek[1]

[1]*Witteveen+Bos, Deventer, The Netherlands*
[#]*Corresponding author: arny.lengkeek@witteveenbos.com*

ABSTRACT

Most published research on CPT based SBT classification is on mineral soils. Consequently, these classifications do not accurately capture the classification of soft organic clays and peats. Organic soft soils are frequently present within the Holocene deposits in the Netherlands and in other deltaic areas worldwide. Organic soils can be identified by a specific combination of CPT parameters such as a high friction ratio, low cone resistance and low pore pressure response. In contrast to other soft soils, the strength is not necessarily low. This paper presents an updated CPT based classification with focus on organic soils, for the non-normalized SBT chart (Robertson, 2010, Lengkeek et al, 2022) as well as a new classification based on the stress normalized SBT chart (Robertson, 2016). In the new proposed classifications, additional boundaries are set based on the CPT pore pressure measurements, as this appears to be successful to separate organic soils from mineral soils. The performance of the classifications can be quantified by metrics such as the F1 score. The F1 score of the new proposed classifications all show significant improvement.

Keywords: ISC7; cone penetration testing (CPT), soil behavior type (SBT), pore pressure ratio (Bq), peat, organic clay

1. Introduction

Most published research on CPT based SBT classification is on mineral soils. From this research it is concluded that soft organic clays and peats are generally not well captured by CPT classifications (Mayne et al 2020). In particular plastic clays tend to overlap with organic soils. Organic soils are frequently present within the Holocene deposits in the Netherlands (Zwanenburg et al., 2019) and in other deltaic areas worldwide. Organic soils are characterized by high organic content (N), low unit weight and high compressibility (Den Haan, 2007). Organic soils can be identified by a specific combination of CPT parameters, such as a high friction ratio, a low cone resistance and a low pore pressure response. The low and sometimes negative pore pressures for organic soils, although often recognized (Zwanenburg et al 2019, Long, 2005), are not implemented in current CPT based classification.

This paper presents an updated CPT based classification with focus on organic soils. The organic soils are identified by laboratory and field classifications and paired with the CPT data. New in these proposed classifications, compared to (Lengkeek, 2022), is that (1) the organic soil classification is also applied to the stress normalized SBT classification of (Robertson, 2016) and (2) criteria for the pore pressure measurements are included to improve the performance. For that, various two-dimensional charts have been investigated to determine the most effective requirements. The performance of the classifications can be quantified by the F1 score. The new boundaries of the SBT for peat and for organic clay are iteratively determined by optimizing the F1 scores. Finally, the proposed classifications are validated at various sites in the Netherlands, with different soil conditions.

2. Method

2.1. Laboratory classification

Classification of laboratory samples is often based on different methods and standards. The current standard in place for identification and description of soils is (ISO14688-1, 2017). The identification of fine-grained soil is based on the plasticity of the soil. The identification of organic soils includes peats (fibrous to amorphous type), Gyttja, Detritus and Dy. In the former Dutch Standard (NEN5104, 1989) the boundary between peat and organic clay consists of a transition zone with organic content of 15 to 35%, measured by Loss on ignition (N), whereas the Dutch national annex (ISO14688-2, 2017) uses N=30% as boundary. To overcome the differences in classification methods, the method after (Huang et al., 2009) is applied in this research. This classification method of the Federal Highway Association (FHWA) matches well with the other two methods. The classification, based on organic content measured by the Loss on ignition (N), consists of the following soil categories:

- Mineral fine-grained soils with N≤3%: The majority of the soils in this research database is a mineral soil.
- Mineral fine-grained soils with organic matter with 3<N≤15%: Soils in this category, such as slightly organic clays, can be classified in the laboratory. However, when it comes to CPT based SBT classification this group overlaps fully with mineral clays and silts. Therefore, it is decided to let go of this category and include it with mineral soils.
- Organic fine-grained soils with 15<N≤30%: This category includes 'very organic Clay' and 'very clayey Peat', Gyttja, Detritus, and Dy with N in the range of 15% to 30%.

- Peats with N>30%: This category includes fibrous to amorphous (low mineral) peats and slightly clayey peats.

2.2. Databases

The aim of this research is to update the two most commonly used CPT based SBT classifications, with and without stress normalization, to account for organic soils. Therefore, a database has been set up that includes both mineral and organic soils, as it should be applicable to both soils. The organic soils database is taken from earlier performed research as well as new compiled databases form organic soils in the Netherlands. The mineral soils database is taken from (Mayne, 2014) and as well as new compiled databases from mineral soils in the Netherlands.

Each datapoint in The Netherlands is based on a paired adjacent boring and CPT, less than 10 m but mostly less than 2 m apart. Each pair is taken from the same level and at least 10 cm from the boundary with other layers. The CPT parameters are averaged over at least 10 cm. Most of the CPTs taken in soft organic soils are ISO class 1 (ISO22476-1, 2012), the deeper CPTs performed in sands are generally class 2. The specifications for the global database on mineral soils are not exactly known. The total number of pairs for each type of soil is presented in Table 1. The pairs are collected from three databases. The properties of each database are described below.

Database 1: Organic soils database from (Lengkeek, 2022), consisting of peats, organic clays, slightly organic clays and some mineral clays from Holocene deposits. The peats are classified in the laboratory according to NEN5104 or ISO14988 and are primarily defined by an organic content higher than 30% and a secondary unit weight less than 12 kN/m^3. The organic clays are primarily classified in the laboratory by an organic content between 15 and 30% and secondary by a unit weight between 12 and 14 kN/m^3. The mineral clays and slightly organic clays have an organic content of less than 3% (occasionally up to 15%) and unit weight higher than 14 kN/m^3. The number of tests and the average organic content and unit weight as well as the range in unit weight are presented in Table 2.

Database 2: Newly compiled database with pairs selected at same level from adjacent borings and CPTs in The Netherlands. The samples are classified based on the borehole field description. This database contains two groups. The first group is consisting of 'loams' and 'very sandy mineral clays' (Transitional soils). The second group consists of 'overconsolidated very plastic mineral clays' such as Potclay. These groups are added as they can act as a bounding surface for organic soils.

Database 3: This worldwide database originates from (Mayne, 2014) and mainly consists of mineral soils from all over the world, onshore and offshore, clays, silts, sands and sensitive soils. The number of sites, number of pairs, average unit weight as well as the range are presented in Table 3.

Table 1. Databases with pairs.

Type	Database	Location	Pairs
Peat [N>30]	1	NL	129
Organic clay [15<N<30]	1	NL	47
Clays & silts, slightly organic	1	NL	102
Sands*	1	NL	84
Gyttja, Detritus, very organic Clay, very clayey Peat	2	NL	193
Transitional soil, very sandy Clay, loam*	2	NL	65
Overconsolidated plastic Clay, Potclay*	2	NL	72
Onshore Clay & Silt*	3	Global	439
Offshore Clay & Silt*	3	Global	532
Offshore sand*	3	Global	29
Onshore sand*	3	Global	39
Total			1731

*) mineral soils

Table 2. Organic soils database.

	#N	N_{av} (%)	#γ_{sat}	$\gamma_{sat;av}$ (kN/m^3)	$\gamma_{sat;min}$ (kN/m^3)	$\gamma_{sat;max}$ (kN/m^3)
Peat [N>30]	63	75	84	10.6	10.1	13.1
Organic Clay [15<N<30]	34	17	52	13.2	11.6	16.2
Clay & Silt, slightly organic	49	6	83	15.9	14.2	20.0
Sand	5		84	19.6	17.2	21.5

Table 3. Mineral soils database.

	#N	#pairs	$\gamma_{sat;av}$ (kN/m^3)	$\gamma_{sat;min}$ (kN/m^3)	$\gamma_{sat;max}$ (kN/m^3)
Onshore Clay & Silt	44	439	17.0	11.7	22.9
Offshore Clay & Silt	27	532	16.4	11.7	21.5
Offshore Sand	3	29	19.9	16.9	21.8
Onshore Sand	10	39	19.3	17.3	21.0

The main purpose of this research is to classify peats and organic soils, it is not the intention to verify the existing boundaries between other soil types. Therefore, the databases are split in four groups, peats, organic clays, mineral clays and silts, mineral sands. The number of pairs and the average, minimum and maximum values of the relevant CPT and stress parameters are presented in Table 4 to 6.

Table 4. Average CPT and stress parameters.

Type	# pairs	$q_{t;av}$ (kPa)	$R_{f;av}$ (%)	$u2_{av}$ (kPa)	$\sigma_{v;av}$ (kPa)	$\sigma'_{v;av}$ (kPa)
Peat	129	751	7.5	128	116	54
Organic Clay	240	569	3.4	152	113	58
Clay & Silt	1210	1793	2.2	659	327	149
Sand	152	17901	0.9	260	349	214

Table 5. Minimum CPT and stress parameters.

Type	$q_{t;min}$ (kPa)	$R_{f;min}$ (%)	$u2_{min}$ (kPa)	$\sigma_{v;min}$ (kPa)	$\sigma'_{v;min}$ (kPa)
Peat	95	3.84	-9	12	5
Organic Clay	95	1.35	-18	13	3
Clay & Silt	61	0.13	-672	15	2
Sand	1741	0.22	-70	37	25

Table 6. Maximum CPT and stress parameters.

Type	$q_{t;max}$ (kPa)	$R_{f;max}$ (%)	$u2_{max}$ (kPa)	$\sigma_{v;max}$ (kPa)	$\sigma'_{v;max}$ (kPa)
Peat	1834	11.90	510	263	156
Organic Clay	1596	6.66	560	325	204
Clay & Silt	12966	7.07	6078	3204	1474
Sand	118000	2.33	2339	1274	684

3. Results

3.1. SBT classification

The pairs are plotted in the SBT charts for comparison and optimization of the boundaries. The non-normalized chart (Robertson, 2010) is in this paper abbreviated as R2010. The updated classification with organic soils (Lengkeek et al., 2022a) is abbreviated as L2022-R2010. The stress normalized chart (Robertson, 2016) is abbreviated as R2016. The new proposed classifications are abbreviated as L2024-R2010 (non-normalized) and L2024-R2016 (stress normalized). For definitions of existing CPT parameters reference is made to the original publications. The equations for newly defined parameters and charts are presented in this publication.

3.2. R2010

Figure 1 shows the R2010 SBT chart with the 1731 pairs. Some of the pairs plot outside the existing axis boundaries. For the newly proposed charts the boundaries are extended. Organic clays overlap to a large extend with mineral clays. The original SBT zone for organic clays, typically at I_{sbt} values lower than 3.5, only captures a small portion of the normally consolidated organic soils. The I_{sbt}=2.9 line is plotted in Figure 1 for as an indicative lower value boundary for organic soils in R2010. This line excludes most of the transitional soils and overconsolidated plastic clays (Potclay) but is not successful to separate mineral clays from organic clays. The definition of Isbt is shown in equation 7.

3.3. L2022-R2010

Figure 2 shows the L2022 chart after (Lengkeek et al., 2022a) with the 1731 pairs. This chart has been used in The Netherlands for various geotechnical projects, such as the national railway embankment stability assessment (LNA project) and flood defense assessment (HWBP projects). The advantage of this SBT classification is that peats (SBT=2a) and organic soils (SBT=2b) are classified separately.

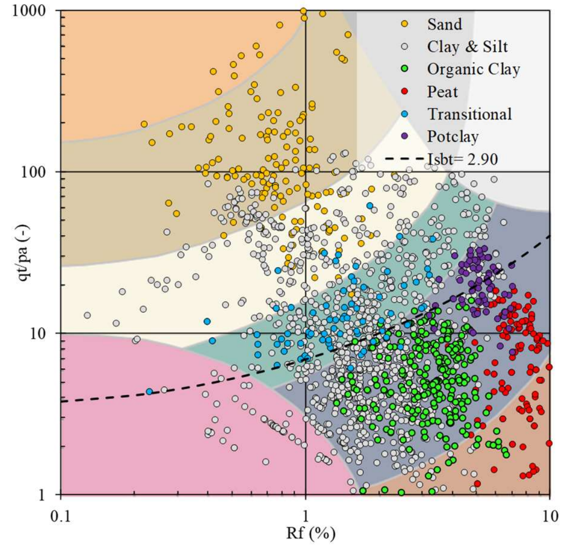

Figure 1. Classical SBT classification R2010 with data.

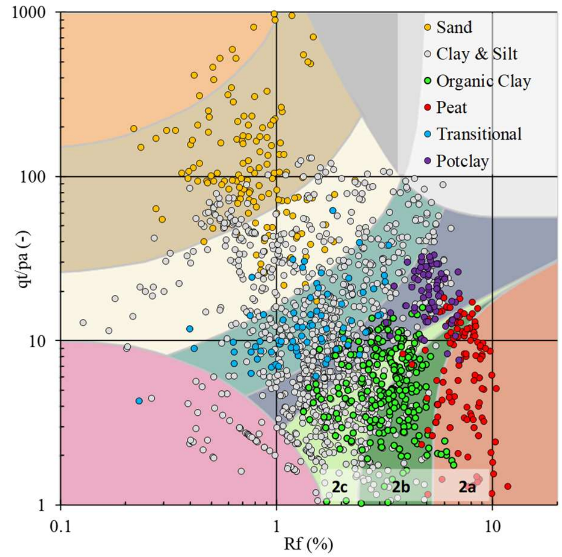

Figure 2. SBT classification L2022-R2010 for organic soils.

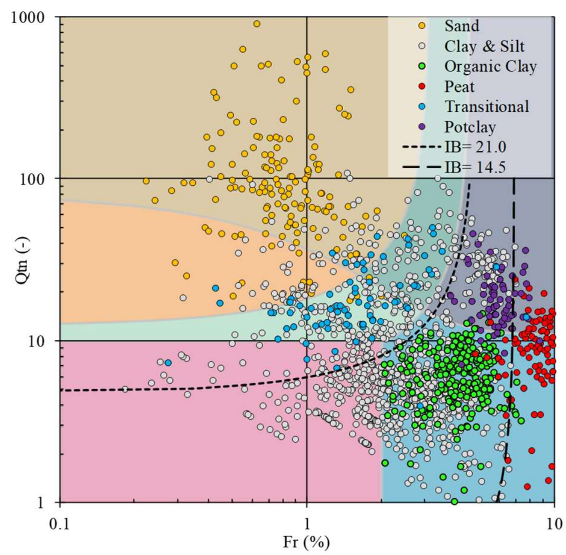

Figure 3. Normalized SBT classification R2016 with data.

The disadvantage of the L2022-R2010 SBT classification is that slightly organic clays (SBT=2c) overlap too much with mineral clays. Based on the assessment within this research it is decided to leave this category out. Furthermore, the overconsolidated peats are often not identified because they overlap with overconsolidated clays (Potclay).

3.4. R2016

The R2016 classification Robertson, 2016) is based on stress normalized SBT charts. Most peats and organic soils are present in superficial layers with low effective stresses. Therefore, it makes sense that in practice mostly non-normalized SBT charts are used when organic soils are encountered. For deeper CPTs stress normalized SBT chart would be beneficial. Normalized SBT charts require the total, water and effective stresses. This has a few downsides. Firstly, the ground water level is not always known and might also fluctuate in time. Secondly, the unit weight has to be known for the whole CPT. The unit weight is not always known by lack of adjacent borings with laboratory tests. This can be overcome with CPT based correlations. However, most correlations overestimate the unit weight of peats and organic clays (Lengkeek et al., 2022b). Lastly, as the unit weight of peats is very low, stresses are low and hence stress corrections can be very high. If no limit is applied to stress normalization factor 'C_n', defined in (Idriss et al., 2004) as overburden correction factor, this might result in a correction factor up to 10, as is the case with Q_{t1}. This will place peats above overconsolidated clays in the stress normalized SBT charts. Hence, the performance of stress normalized SBT charts for organic soils has some challenges. For this research the C_n has been varied between 1.5 and 3.0. Based on the assessment the C_n is set to 2.0 as this provided the best metrics and classification result. The application of C_n as used in conjunction with (Robertson, 2016) is presented in equation 1 and 2.

$$Q_{tn} = C_n \cdot \frac{(q_t - \sigma_v)}{p_a} \tag{1}$$

$$C_n = \min\left[2, \frac{p_a}{\sigma'_v}\right] \tag{2}$$

Figure 3 shows the R2016 SBT chart with the 1731 pairs. Sands are generally better classified in R2016 compared to R2010, as there is less overlap with various clay types (calcareous clay, fissured clay, hard clay, till). Organic clays overlap to a large extend with mineral clays. The IB=21 line is plotted in Figure 3 as an indicative upper value boundary for organic clays in R2016. The IB=14.5 line is plotted in Figure 3 as an indicative upper value boundary for peats in R2016. The definition of IB is shown in equation 8. There seems to be a distinct boundary with little overlap between overconsolidated plastic clay (Potclay) and organic soils, both in R2010 and R2016. In R2016 significant more clay pairs plot in sensitive zone compared to R2010. This is not in line with the sample description. Apparently, the square zone in R2016 is oversized and a rounded zone as in R2010 would be better.

3.5. New proposed SBT classifications

The boundaries for organic soils in L2022-R2010 are defined by equation 3. The same definition has been used for the updated L2024-R2010 classification. In L2024-R2010 the SBT 2c, clay with organic content has been taken out as this one overlaps with mineral clay. Similar boundaries are applied to L2024-R1016 classification, see equation 4. The boundaries are determined with C_n=2. These boundaries for organic soils are applicable for a stress normalization cut-off between 1.7 and 2.5.

$$q_t/p_a = a_{org} \cdot \left(R_f - R_{f,min}\right)^{b_{org}} \tag{3}$$

$$Q_{tn} = a_{org} \cdot \left(F_r - F_{r,min}\right)^{b_{org}} \tag{4}$$

With: a_{org} and b_{org} presented in Table 7.

As a first step, the boundaries are assessed by analyzing the data in the classical two-dimensional q_t/p_a-Rf-chart and Q_{tn}-F_r-chart, excluding the u2 measurements. The boundaries are determined by optimizing the F1 scores for peats, organic clays and the mineral soils (clays and sands). The score ranges from 0 to 1, with 1 being optimal. The F1 score is based on precision and recall and is defined in equation 5.

$$F1 = \frac{TP}{TP + 0.5 \cdot (FP + TN)} \tag{5}$$

With: TP=true positives, FP=false positives, TN=true negatives

As a second step the pore pressure measurements are taken into account, as all pairs include u2 measurements. Organic soils generally have lower pore pressure response than mineral soils. This should therefore be beneficial for the classification of organic soils where they show some overlap with mineral clays in the 2D classical charts. Various two-dimensional charts have been investigated where the u2 measurements are transferred into B_{qt}, B_q, $\Delta u/p_a$ and $\Delta u/\sigma'_v$, combined with q_t/p_a, Q_{tn}, R_f, F_r, I_{sbt}, I_{cn} and IB. The two most common graphs are presented in Figure 4 and 5.

Further assessment resulted in the conclusion that for R2010 as for R2016 the best additional classification requirements for organic soils are defined by a B_{qt}-I_{sbt} plot. B_{qt} and I_{sbt} are defined in equation 6 and 7. Apparently, the uncertainties associated with correction for total stress in B_q and Q_{tn} doesn't increase the F1 score. The same applies to the correction by the effective stress as in (Robertson, 2016), based on the updated Schneider plot.

$$B_{qt} = \frac{(\mathrm{u2} - \mathrm{u0})}{q_t} \tag{6}$$

$$I_{sbt} = \sqrt{\left(3.47 - \log\frac{q_t}{p_a}\right)^2 + \left(1.22 + \log R_f\right)^2} \tag{7}$$

$$IB = \frac{100 \cdot (Q_{tn} + 10)}{(Q_{tn} \cdot F_r + 70)} \tag{8}$$

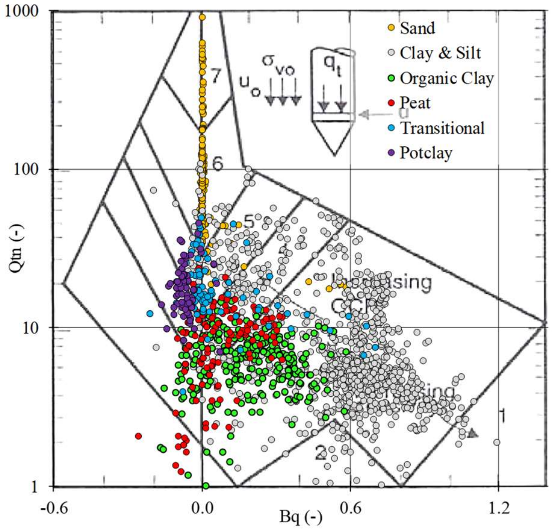

Figure 4. Pore pressure chart R2010 with data.

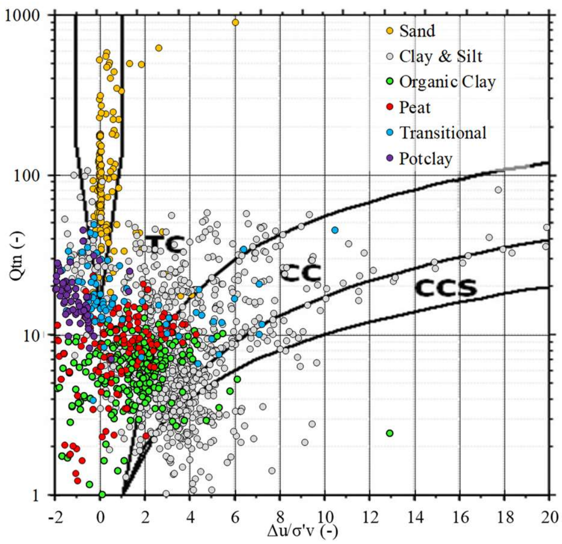

Figure 5. Pore pressure chart R2016 with data.

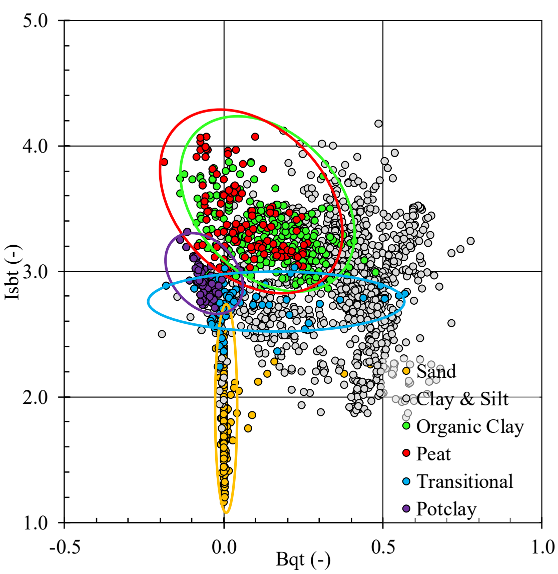

Figure 6. Proposed pore pressure chart (I_{sbt}-B_{qt}) with data.

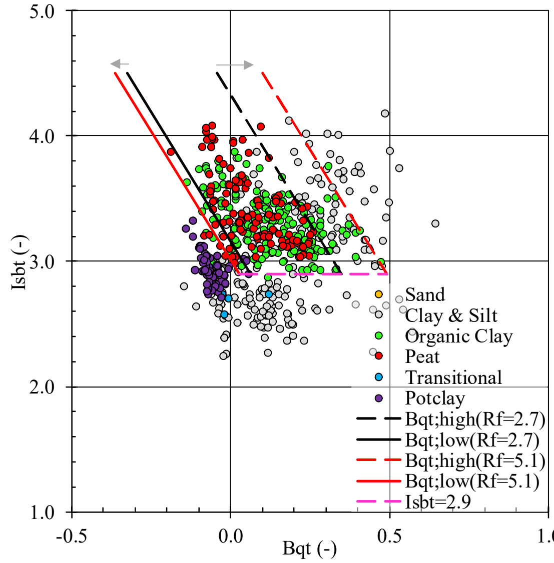

Figure 7. Isbt-Bqt chart with proposed boundaries, showing data with R_f>2.7%.

The 1731 pairs are plotted in Figure 6 with the normalized pore pressure parameter (B_{qt}) on the horizontal axis and the I_{sbt} on the vertical axis. The I_{sbt} is used instead of the normalized cone resistance, although this is also possible. The intention of the chart is to determine the best criteria for organic soils, but it can as well be used for classifying other soils. The boundaries for organic soils are set by 3 lines, defined in equation 9 to 11. The boundaries are a function of I_{sbt}, B_{qt}, and R_f.

$$I_{sbt} > 2.9 \quad (9)$$

$$I_{sbt} > 3.33 - 0.06 \cdot R_f - 4.1 \cdot B_{qt} \quad (10)$$

$$I_{sbt} < 3.66 + 0.25 \cdot R_f - 4.1 \cdot B_{qt} \quad (11)$$

The boundaries are plotted in Figure 7 for all pairs with R_f>2.7%. The black lines are applicable for organic clays with R_f=2.7. The red lines are applicable for organic clays or peats with R_f=5.1. For peats with higher friction ratios this boundary is less strict.

The additional criteria for organic soils resulted as expected in a higher F1 score, in particular for organic clays. The new proposed values for L2014-R2010 and L2024-R2016 are presented in Table 7. One set of boundaries is selected for each classification, as this way the classification can be used to mixed databases, with and without u2 measurements. The new proposed classifications with the pairs are plotted in Figure 8 and 9.

Table 7. Proposed SBT boundaries.

	L2024-R2010		**L2024-R2016**	
SBT	2a Peat	2b Org.Clay	2a Peat	2b Org.Clay
a_{org}	16.7	10.3	20.6	10.0
b_{org}	0.25	0.15	0.25	0.10
$R_{f;min}$, $F_{r;min}$	5.1	2.7	6.6	3.5

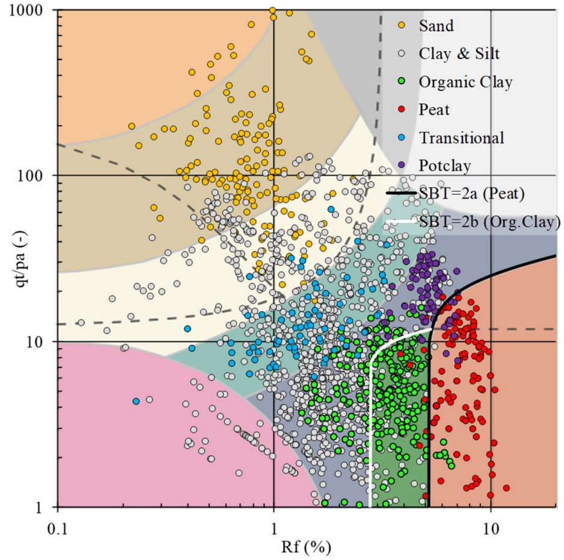

Figure 8. L2024-R2010 SBT charts with proposed boundaries and all pairs

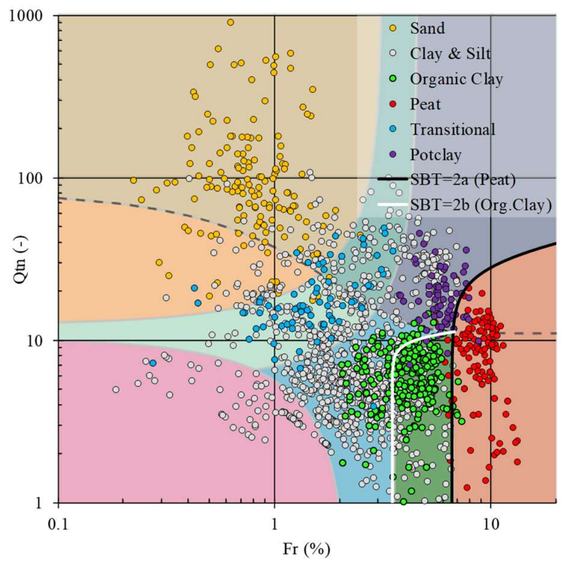

Figure 9. L2024-R2016 SBT charts with proposed boundaries and all pairs.

3.6. Other features

There are a few lines added to the proposed classifications, not strictly related to organic soils. The two lines in L2024-R2010 are informative. The line in L2024-R2016 is an adjusted boundary.

The equivalent line of IB=32 in R02016 is plotted in L2024-R2010 as an informative boundary to separate sands from transitional soils. This line is added because the F1 score for sands in R2016 is higher than in R2010. The F1 score for the equivalence of both lines is 0.88.

Furthermore, the equivalent line of CD=70 in R2016 is plotted L2024-R2010. This line is determined by optimizing the metrics and starts between SBT=6 and SBT=7, splits overconsolidated plastic Potclay from organic clays (SBT=2b) and intersects the peats (SBT=2a). The majority of the peats above this line are peats consolidated to higher stresses at more than 10m depth, such as base peats. The F1 score for the equivalence of both lines is 0.90.

A new boundary for sensitive soils (CCS) is applied in L2024-R2016. The F1 score for sensitive soils, classified in R2010 and R2016 is about 0.4, which illustrates that SBT sensitive soils are difficult to capture by SBT classification. The adjusted boundary in L2024-R2016 is the equivalent boundary of the one in R2010. The new CCS boundary is defined by equation 12. The F1 score for the equivalence of both boundaries increases from 0.34 to 0.68.

$$Q_{tn;CCS} = 10.48 - 4.8 \cdot F_r \tag{12}$$

4. Performance

The performance of the classifications can be expressed by the F1 score. The F1 scores are optimized for peats and organic clays, as well as for the combined group of organic soils (peats & organic soils), the combined group of mineral soils (clays and sands), and all groups. Table 8 shows the F1 scores for the case with and without the additional u2 requirements, based on the new proposed B_{qt}-I_{sbt} plot.

Table 8. F1 scores CPT based classifications.

SBT	**R2010**	**L2022-R2010**	**L2024-R2010**		**L2024-R2016**	
B_{qt} bounds included	no	no	no	yes	no	yes
Peat		0.78	0.86	0.90	0.89	0.92
Organic Clay		0.61	0.67	0.72	0.59	0.72
Group organic soils	0.31	0.67	0.74	0.79	0.68	0.80
Group mineral soils	0.89	0.92	0.93	0.95	0.90	0.95
All groups	0.81	0.87	0.88	0.92	0.84	0.92

Table 9. Effect Bqt-boundaries on group of organic soils.

SBT	**L2024-R2010**		**L2024-R2016**	
B_{qt} bounds included	no	yes	no	yes
False positives	112	45	192	45
False positive rate	8%	3%	14%	3%
Specificity	92%	97%	86%	97%
Sensitivity	76%	73%	78%	74%

Adding the B_{qt} boundaries mainly reduce the number of incorrectly classified minerals soils as organic soils. This is illustrated by the metrics in Table 9. The remaining false positives are mineral soils classified as organic soil. From the database it appears that quite some of the pairs relate to a few sites, such as offshore clays from West Africa NGOMA and onshore Mexico City clay, both clays with very low unit weights and high plasticity. For such sites it makes sense to the exclude organic soil SBTs from a geological perspective. When organic soils cannot be excluded in advance, it is recommended to apply the new proposed classifications preferably with class 1 or 2 CPTs. In case no pore pressures are measured L2024-R2010 is the preferred SBT classification. With u2 measurements the L2024-R2016 SBT classification can be used as well.

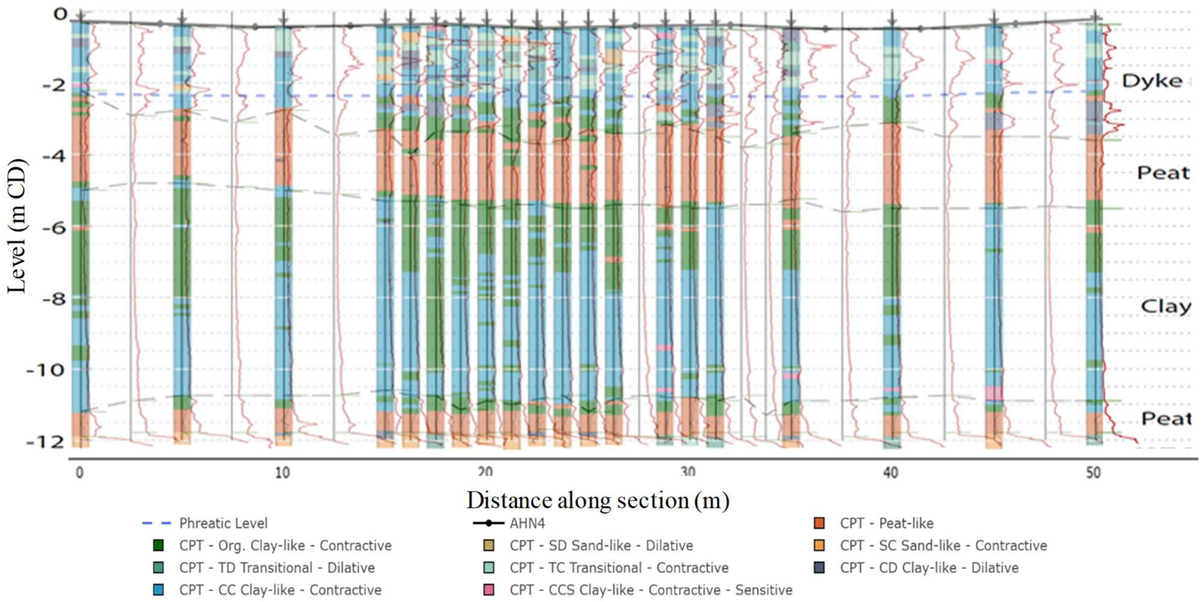

Figure 10. Longitudinal profile (De Gast et al., 2021) at Leendert de Boerspolder, L2024-R2016 overlay.

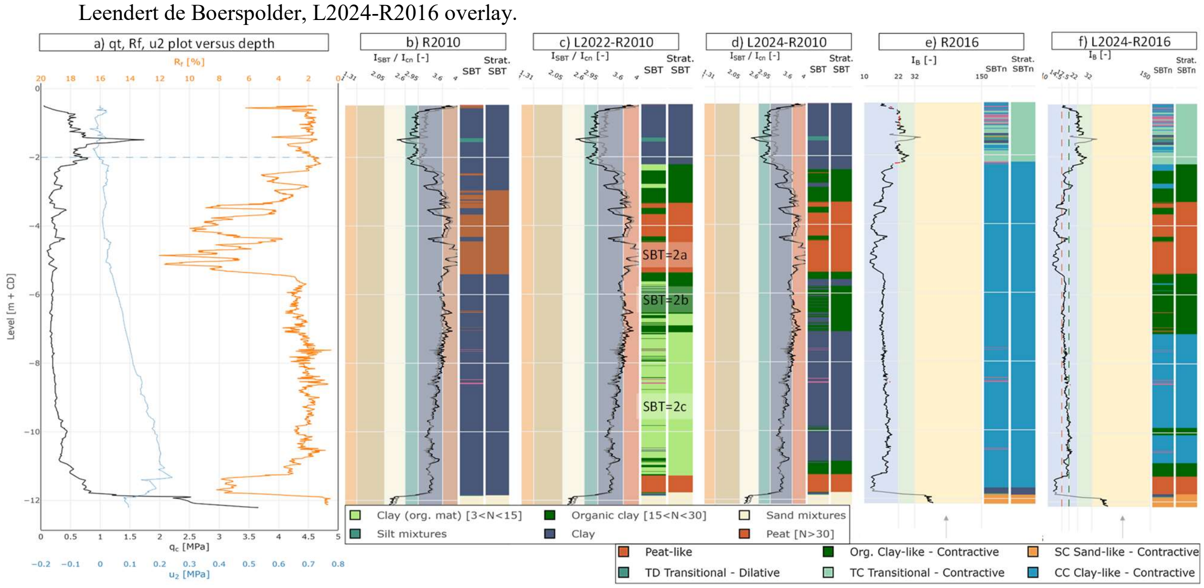

Figure 11. Comparison of CPT-DKP239 at the Leendert de Boerspolder with different SBT classifications.

5. Validation

The proposed classifications are validated on various sites which were not included in the databases, such as along the river Hollandse IJssel (KIJK project) and the IJssel (Reevediep project). This paper presents the validation at the Leendert de Boerspolder. The Leendert de Boerspolder is intensely investigated for the full-scale dike failure tests performed in 2015. Over 100 CPTs are performed for the spatial variability research. The data can be found on the TC304 website (http://140.112.12.21/issmge/tc304.htm).

The interpreted soil profile along the dike taken from (De Gast et al., 2021) is presented in Table 10. The overlay of the interpreted soil profile for the proposed L2024-R2016 SBT classification is presented in Figure 10. The layer boundaries are almost identical. The dike material is manmade and consists of clay, sand and some organic material. Both the shallow peat layer (Hollandveen) as the deeper peat layer (Basisveen) are correctly classified. The organic clay layer below the peat layer varies in thickness and is underlain by clayey silt layer. A similar profile is found for L2024-R2010.

Table 10. Layer boundaries of interpreted profile

Layer	level (m NAP)	Thickness (m)
dike material	0.4 ± 0.1	2.9
peat	-3.3 ± 0.5	2.0
organic clay	-5.3 ± 0.5	1.5
clayey silt	-6.8 ± 1.0	4.0
peat	-10.9 ±0.5	1.0
sand	-11.8 ±0.2	>1

In Figure 11 the five SBT classifications are presented side by side for the CPT in the middle of the dyke section. The left figure (11a) show the CPT readings. Figure 11d shows the proposed L2024-R2010 classification and figure 11f shows the proposed L2024-R2016 classification. All the layers are correctly identified in these new classifications. Figure 11b shows the R2010 classification. The organic soil and base peat are not identified. Figure 11c shows the L2022-R2010 classification. The clayey silt layer is incorrectly classified as SBT=2c (clay with organic material). This is the reason why in the new proposed classifications this soil type is excluded. Figure 11e shows the R2016 classification. Both peat layers and the organic clays are not identified.

From this comparison it is concluded that both new proposed SBT classifications are capable to classify peats and organic soils under different stress conditions.

5.1. Conclusions

The aim of this paper is to extend the organic soils classification to the stress normalized SBT classification of (Robertson, 2016) and to include criteria for the pore pressure measurements to improve the performance. Both goals are achieved. Furthermore, it is concluded that:

- The original F1 score for organic soils in R2010 is very low. Most of the organic soil have higher cone resistances and plot above the SBT=2 zone.
- All F1 scores improve when CPTu and B_{qt} boundaries are used.
- The F1 scores of L2024-R2010 are better than L2024-R2016 when no CPTu and B_{qt} boundaries are used.
- The F1 scores are almost similar for L2024-R2010 and L2024-R2016 when CPTu with B_{qt} boundaries are used.
- The F1 scores of organic clays are the lowest of all groups. The F1 scores of peats are very high.
- The false positive rate (FPR), the so called 'false alarm rate', reduces from about 10% to 3%.
- The validation at the Leendert de Boerspolder shows adequate performance of both new proposed SBT classifications.

5.2. Recommendations

- The recommended SBT classification for regular CPTs without pore pressure measurements is L2024-R2010.
- For CPTu with B_{qt} requirements it is recommended to use both L2024-R2010 and L2024-R2016 SBT classifications.
- Since there is overlap between some plastic clays and organic soils, it is recommended to perform follow-up sampling to verify the classification.

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References

De Gast, T., Hicks, M.A., Van den Eijnden, A.P., and Vardon, P.J. 2021. On the reliability assessment of a controlled dyke failure. Géotechnique, **71**(11): 1028-1043. doi:10.1680/jgeot.19.SiP.003.

Den Haan, E.J., and Kruse, G.A.M. 2007. Characterisation and engineering properties of Dutch peats. *In* Characterisation and engineering properties of natural soils. Taylor & Francis Group, London. pp. 2101-2133.

Huang, P.-T., Patel, M., Santagata, M.C., and Bobet, A. 2009. Classification of organic soils. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, FHWA/IN/JTRP-2008/02.

Idriss, I. M., and Boulanger, R. W. 2004. Semi-empirical procedures for evaluating liquefaction potential during earthquakes, in Proceedings, 11th International Conference on Soil Dynamics and 106 Earthquake Engineering, and 3rd International Conference on Earthquake Geotechnical Engineering, D.Doolin et al., eds., Stallion Press, Vol. 1, pp. 32–56.

ISO14688-1. 2017. Geotechnical investigation and testing - Identification and classification of soil - Part 1: Identification and description. International Organization for Standardization.

ISO14688-2. 2017. Geotechnical investigation and testing - Identification and classification of soil - Part 2: Principles for a classification. International Organization for Standardization.

ISO22476-1. 2012. Geotechnical Investigation and Testing - Field Testing - Part 1: Electrical Cone and Piezocone Penetration Test. International Organization for Standardization.

Lengkeek, H.J. 2022. CPT-based classification and correlations for organic soils. 4TU.ResearchData. doi:https://doi.org/10.4121/19139651.v2.

Lengkeek, H.J., and Brinkgreve, R.B.J. 2022a. CPT-based classification of soft organic clays and peat. In CPT'22, Bologna. p. 6.

Lengkeek, H.J., and Brinkgreve, R.B.J. 2022b. CPT-based unit weight estimation extended to soft organic clays and peat: an update. In CPT'22, Bologna. p. 6.

Long, M. (2005). Review of peat strength, peat characterisation and constitutive modelling of peat with reference to landslides. *Studia Geotechnica et Mechanica*, *27*(3-4), 67-90.

Mayne, P.W. 2014. Interpretation of geotechnical parameters from seismic piezocone tests. *In* Proceedings, 3rd International Symposium on Cone Penetration Testing. pp. 47-73.

Mayne, P.W., Agaiby, S.S., and Dasenbrock, D. 2020. Piezocone Identification of Organic Clays and Peats. *In* Geo-Congress 2020. pp. 541-549.

NEN5104. 1989. Classificatie van onverharde grondmonsters (In Dutch), Classification of unconsolidated soil samples. Nederlands Normalisatie-instituut.

Robertson, P.K. 2010. Soil behaviour type from the CPT: an update. *In* 2nd international symposium on cone penetration testing, USA. pp. 9-11.

Robertson, P.K. 2016. Cone penetration test (CPT)-based soil behaviour type (SBT) classification system — an update. Canadian Geotechnical Journal, **53**(12): 1910-1927. doi:10.1139/cgj-2016-0044.

Zwanenburg, Cor & Erkens, Gilles. (2019). Uitdam, the Netherlands: test site for soft fibrous peat. AIMS Geosciences. 5. 804-830. 10.3934/geosci.2019.4.804.