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Organic Soil Identification by CPTu

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ABSTRACT

A soil behavior type (SBT) chart was developed to more reliably identify organic soil deposits at sites in the state of Michigan based on piezocone (CPTu) data. Organic soils are often highly compressible organic silts, clays, and peats. Many of these soils are fluvial with high void ratios and large compressibilities. These soils are typically removed prior to the construction of roadways and shallow bridge foundations due to the risk of excessive settlement. CPTu soundings were strategically performed alongside companion soil borings in which standard penetration testing (SPT) was performed and from which split-spoon and Shelby tube samples were recovered and tested. While many of the widely used SBT charts characterize the inorganic soils with reasonable agreement to the soil descriptions presented in the soil boring logs, the organic soils are often mischaracterized as inorganic clays. A hybrid SBT approach was therefore developed that yields more accurate characterization of the organic soils. The inorganic soils are reliably characterized by plotting the normalized tip resistance versus the normalized friction ratio. This SBT approach, however, ignores the valuable piezometric data provided by the CPTu. For organic soils, piezometric data helps to more reliably distinguish between inorganic clays and organic soils. As such, a screening tool was implemented to flag likely organic soils by plotting a parameter that accounts for both the tip resistance and pore pressure versus the normalized friction ratio before characterizing the likely-inorganic soils using existing approaches.

Keywords: CPTu; organics; soil behavior type.

1. Introduction

Organic soils vary from organic silts and clays to amorphous or fibrous peats, mucks, and marls. Some organic deposits are located near the ground surface while others are buried under layers of mineral soils. Organic soils are generally unsuitable as roadway subgrade and foundation bearing strata due to their characteristically high void ratios and large compressibility potential. Because their natural state is not ideal as a foundation material, organic soils are typically treated or excavated prior to foundation construction.

The standard of practice for identifying organic soils has historically been through standard penetration testing (SPT) and visual-manual inspection, as organics are marked by very low SPT blow counts and distinctive color, texture, and odor. Field classification of organic soils is verifiable in the laboratory by loss on ignition (LOI) testing or by comparing the oven-dried liquid limit to the natural liquid limit (ASTM D2487).

Identification and characterization of organic soils via the CPT is presently challenging due to a limited amount of global CPT data on organic soils relative to the wealth of data available for mineral soils. The convenience of the CPT rapidly yielding a continuous soil profile with correlations based on the cone tip resistance and sleeve friction warrants further development specifically focused on organic soil profiles, starting with the use of the CPT for identifying the organic soil layers during initial project site investigations.

One disadvantage of the CPT, however, is its inability to recover a soil sample for visual-manual inspection and laboratory testing. This makes reliable identification of organic soil deposits through CPT correlations alone even more crucial. This paper details a screening approach for identifying organic soil deposits based on CPT data from sites located within the state of Michigan.

2. Background

The CPTu collects virtually continuous data of tip resistance, sleeve friction, and porewater pressure. The data produced from CPT soundings likewise yields continuous profiles of soil behavior type (SBT) with depth. The use of the SBT is an alternative approach to laboratory soil classification with a physical soil sample. The SBT describes how the in-situ soil behaves rather than strictly classifying the soil. The SBT can also inform estimates of other soil properties, such as unit weight, friction angle, and overconsolidation ratio (e.g., Robertson 2009).

3. Case Studies

3.1. Test Site Locations

There are a total of 16 CPT soundings (spanning 8 different test sites) in the Michigan Department of Transportation (MDOT) CPT database that contain at least one layer of a predominantly organic soil type – as identified in companion soil boring log descriptions assigned to each sounding. Table 1 lists each of these sites, the number of soundings at each site containing organic soil, and a brief description.

Table 1. List of CPT sites and soundings with organic soil

Site	No. of Soundings	Site Description
1	1	M-55 over Manistee River
2	2	M-66 over Monroe Creek
3	2	I-96 over Norton Creek
4	2	M-66 over Tributary to Black Creek
5	2	US-23 over No Name Creek
6	1	I-94 Eastbound Clear Lake Road Exit
7	1	I-275 over Schoolcraft
8	5	US-131 over No. 102 Drain

Figure 1 shows a map of the CPT test sites considered in this analysis. Four sites (3, 5, 6, and 7) – representing 6 soundings – are in southeast Michigan. Two sites (4 and 8) – representing 7 soundings – are located towards the center of the lower peninsula. The remaining two sites (1 and 2) – representing 3 soundings – are located on the northwestern shore of the lower peninsula.

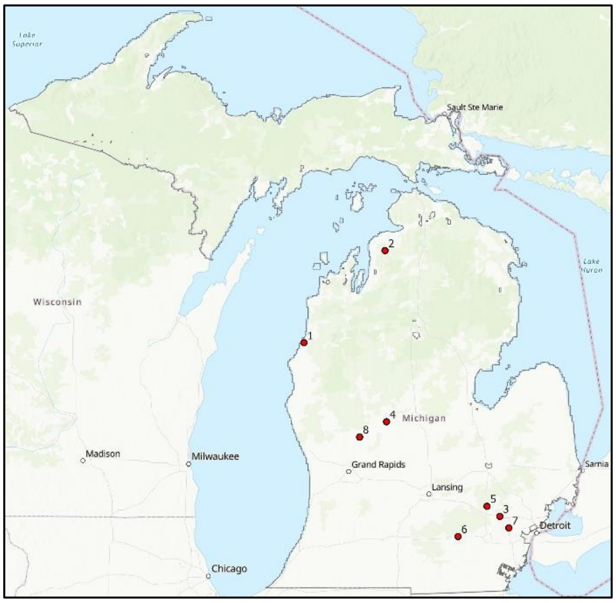

Figure 1. Map of CPT sounding sites with organics identified in the companion soil boring logs.

The list of test sites includes all the sites within the MDOT CPT database that meet the following criteria:

1. The CPT sounding was performed alongside companion soil borings that recovered samples for validation.
2. The CPT sounding was located no more than 40 feet away from the companion soil boring.
3. The companion soil boring indicated at least one layer of predominantly organic material.
4. The organic soil had not been previously treated.

3.2. Evaluation of Existing SBTs

For each of the CPT soundings listed in Table 1, the associated companion soil boring log was used to identify the layers consisting of a predominantly organic soil. For every presumed-organic soil layer, all the CPT data points within that depth range were evaluated using various SBTs to characterize each of the data points as either organic soil (matching the boring log description) or mineral soil (contradicting the boring log description).

3.2.1. Robertson 2009 Normalized SBT

One of the most widely accepted SBTs is the normalized SBT chart proposed by Robertson (2009), displayed in Figure 2.

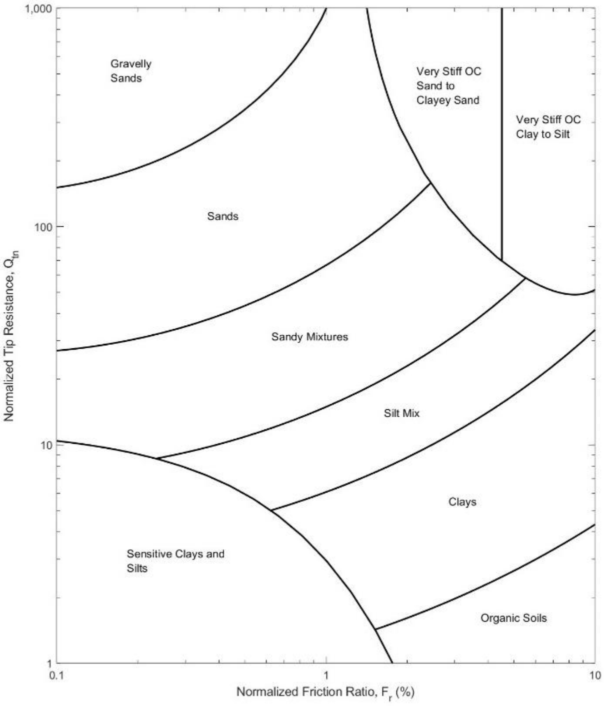

Figure 2. Robertson (2009) normalized SBT chart, after Mayne et al. (2023).

This SBT chart plots the normalized cone resistance, Q_{tn}, defined in equation 1 (Robertson and Wride 1998), against the normalized friction ratio, F_r, defined in equation 4, on a log-log scale and identifies different regions within the plotted area that correspond with different soil behavior types. The SBT chart suggests that organic soils have higher friction ratios and lower cone resistances relative to their mineral counterparts.

$$Q_{tn} = \left({q_t - \sigma_{vo}}/{p_a} \right) \left({p_a}/{\sigma'_{vo}} \right)^n \quad (1)$$

$$n = 0.381(I_c) + 0.05\left({\sigma'_{vo}}/{p_a} \right) - 0.15 \leq 1.0 \quad (2)$$

$$I_c = [(3.47 - \log_{10} Q_{t1})^2 + (1.22 + \log_{10} F_r)^2]^{0.5} \quad (3)$$

$$F_r = {f_s}/{(q_t - \sigma_{vo})} = {f_s}/{q_n} \quad (4)$$

To evaluate how reliably the Robertson (2009) normalized SBT identifies Michigan organic soils, the presumed-organic data points within every sounding listed in Table 1 were plotted on the SBT chart. The results of this analysis are presented in Figure 3.

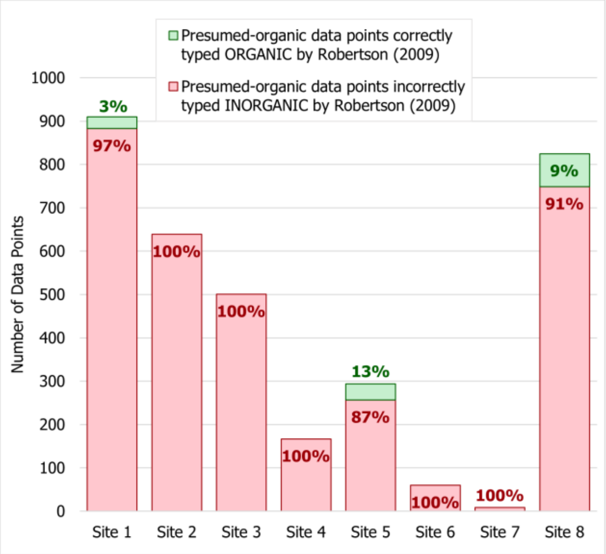

Figure 3. Distribution of the presumed-organic CPT data points at each site that were: (a) correctly typed as organic (shown in green) vs. (b) incorrectly typed as inorganic (shown in red) by the standalone Robertson (2009) SBT.

Figure 3 clearly shows that the Robertson (2009) normalized SBT is not identifying most of the organic soils encountered. The SBT erroneously assigned inorganic soil behavior types to known organic soil deposits. Across the dataset, only 4.1% of the presumed-organic soils were correctly identified as such by the Robertson (2009) normalized SBT. Good agreement, however, was generally observed between the soil boring log descriptions and the SBT results for the mineral soil layers. This was expected given that most CPT correlations are developed for inorganic soils. These results indicate that the Robertson (2009) normalized SBT can be trusted to reliably classify inorganic soil layers, but first a preliminary screening tool needs to be implemented to identify, flag, and filter out the organic data points.

3.2.2. Jefferies and Been 2016 Normalized SBT

The Jefferies and Been (2016) SBT, displayed in Figure 4, was the next SBT to be evaluated as a potential organics screening tool because it includes an additional, and very valuable, CPT parameter: porewater pressure.

This SBT plots the grouped normalized cone and porewater pressure parameter against the normalized friction ratio and identifies regions of different soil behavior types, similar to that of Robertson (2009). The grouped normalized cone and porewater pressure parameter is equivalent to the normalized effective cone resistance, i.e.:

$$Q_t\left(1-B_q\right)+1 = {}^{(q_t-u_2)}\!/_{\sigma'_{\mathrm{vo}}} \qquad (5)$$

By using the Jefferies and Been (2016) normalized SBT as an organics screening tool alongside the default Robertson (2009) normalized SBT, CPT data points can be identified as an organic soil in one of two ways:

1. The proposed Jefferies and Been (2016) organics screening tool identifies the data point as organic in nature, overriding any soil behavior type that would have been otherwise assigned by the Robertson 2009 SBT.
2. The proposed Jefferies and Been (2016) organics screening tool does not identify the data point as organic in nature, whereby the soil behavior type defaults back to that which would be assigned using the Robertson (2009) SBT, which may still classify the data point as organic, even though it was not initially identified as such by the proposed screening tool.

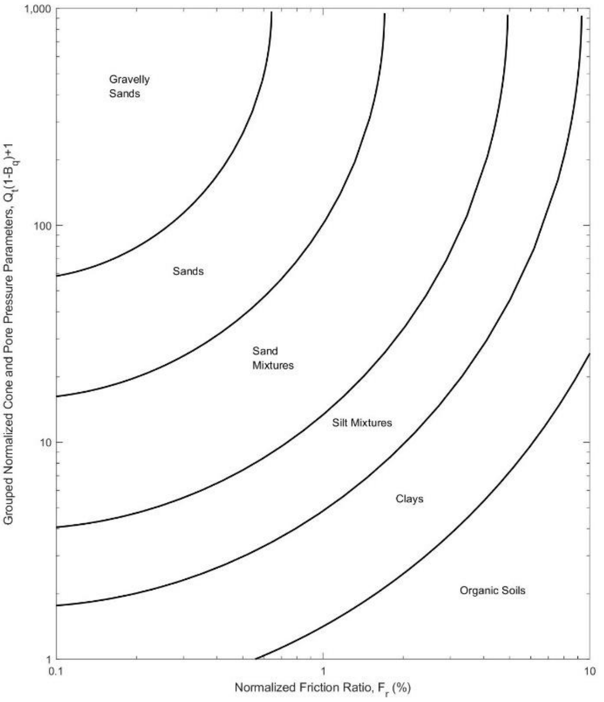

Figure 4. Jefferies and Been (2016) normalized SBT chart.

This approach creates a degree of redundancy because any data point may be identified as organic if either the proposed Jefferies and Been (2016) screening tool or the Robertson (2009) SBT identify it as such. To evaluate how well this framework performs, the presumed-organic CPT data points were re-plotted using both SBT charts and the results of this analysis are presented in Figure 5.

Figure 5 clearly shows that the inclusion of a porewater pressure term significantly increases the likelihood of correctly identifying the organic soil layers at Michigan test sites. With the addition of the Jefferies and Been (2016) organics screening tool, 49.7% of the presumed-organic soils are correctly identified, a substantial improvement from the prior 4.1% success rate achieved with the standalone Robertson (2009) SBT.

To ensure that the introduction of the Jefferies and Been (2016) organics screening tool was not producing too many false positives (i.e., incorrectly identifying mineral soils as organic), the success rates were also tabulated for the presumed-inorganic soil layers. The standalone Robertson (2009) SBT boasted a very low rate of false positives at 0.3%. This, however, is a function of the fact that the Robertson (2009) SBT hardly identified any data points as organic, let alone those associated with mineral soils. With the addition of the Jefferies and Been (2016) organics screening tool, the false positive rate only increased to 2.3%. Considering the rate of correctly identified organic soil data points increased by an entire order of magnitude, this slight increase in false positives is tolerable.

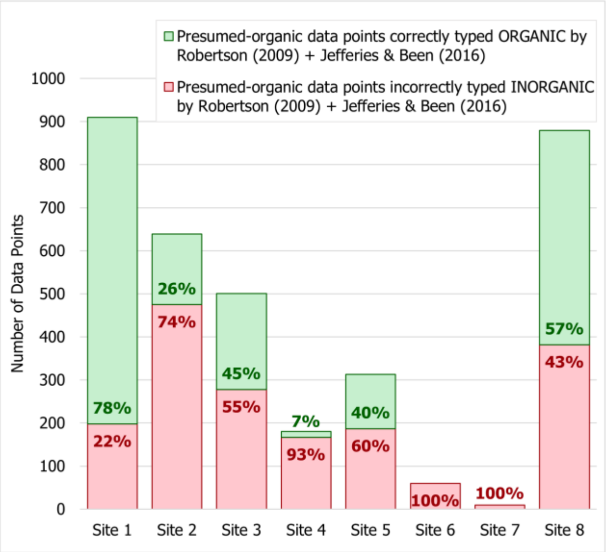

Figure 5. Distribution of the presumed-organic CPT data points at each site that were: (a) correctly typed as organic (shown in green) vs. (b) incorrectly typed as inorganic (shown in red) by the Robertson (2009) SBT + Jefferies and Been (2016) SBT.

3.2.3. Lengkeek and Brinkgreve 2022 Modification to the Robertson 2010 SBT

A recent paper published in 2022 by Lengkeek and Brinkgreve explores the expansion of Robertson's organic soil zone. The new upper boundary of their proposed organic soil zone is shifted upwards and to the left, thus encroaching into the mineral clay and sensitive clay zones.

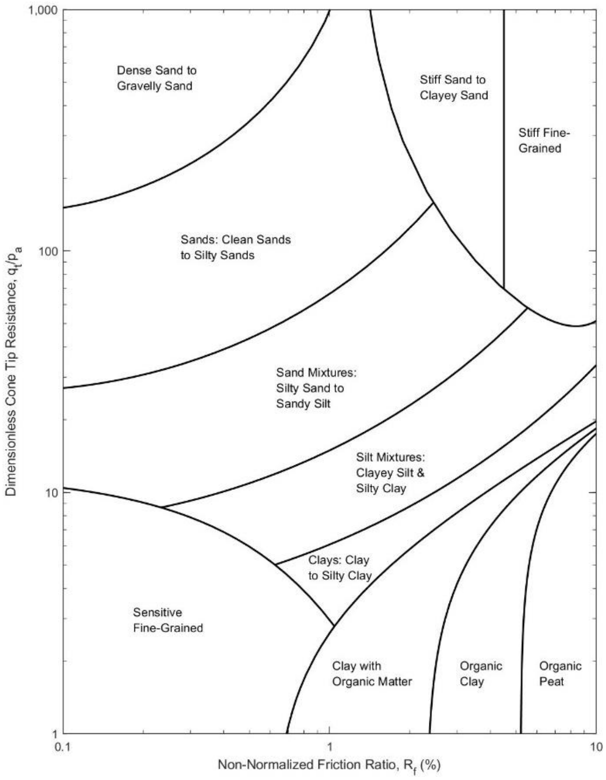

Figure 6. Lengkeek and Brinkgreve (2022) organic soil SBT superimposed onto Robertson (2010) dimensionless SBT.

Lengkeek and Brinkgreve (2022) argue that this expanded organic soil zone can be further divided into three sub-zones, shown in Figure 6, which are defined based on the organic content, as measured by the loss on ignition (LOI) test:

- Organic peat (30% < LOI)
- Organic clay (15% < LOI ≤ 30%)
- Clay with organics (3% < LOI ≤ 15%)

They also suggested that their expanded organic soil zone could be interchangeably applied to both the Robertson (2010) dimensionless SBT (using the cone tip resistance divided by atmospheric pressure) as well as the Robertson (2009) normalized SBT. To determine which option best identifies the organic soil deposits in Michigan, both options were evaluated head-to-head.

This analysis is binary in design, i.e., a soil is either predominantly organic, or predominantly mineral. As such, all three proposed organic SBT zones were combined into one. The boundaries between the Lengkeek and Brinkgreve (2022) expanded organic soil zone and the adjacent mineral SBT zones for clays and sensitive soils are given by equations 6 and 8 for the dimensionless and normalized SBTs, respectively.

$$^{q_t}/_{p_a} = 4.7\left(R_f - 0.60\right)^{0.64} \tag{6}$$

$$R_f = {}^{f_s}/_{q_t} \tag{7}$$

$$Q_{tn} = 4.7(F_r - 0.60)^{0.64} \tag{8}$$

Note that equation 6 is applied in Figure 6 and equation 8 can be applied in Figure 2. To compare the success rate of the Lengkeek and Brinkgreve (2022) SBT modification applied to the dimensionless (Figure 6) versus normalized (Figure 2) chart, the presumed-organic CPT data points were evaluated against both equations 6 and 8. The results of these analyses are presented in Figures 7 and 8 for the dimensionless and normalized SBTs, respectively.

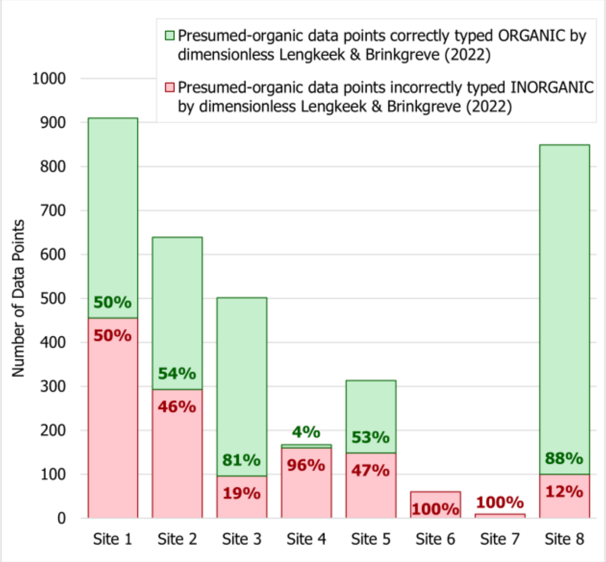

Figure 7. Distribution of the presumed-organic CPT data points at each site that were: (a) correctly typed as organic (shown in green) vs. (b) incorrectly typed as inorganic (shown in red) by the dimensionless Lengkeek and Brinkgreve (2022) SBT.

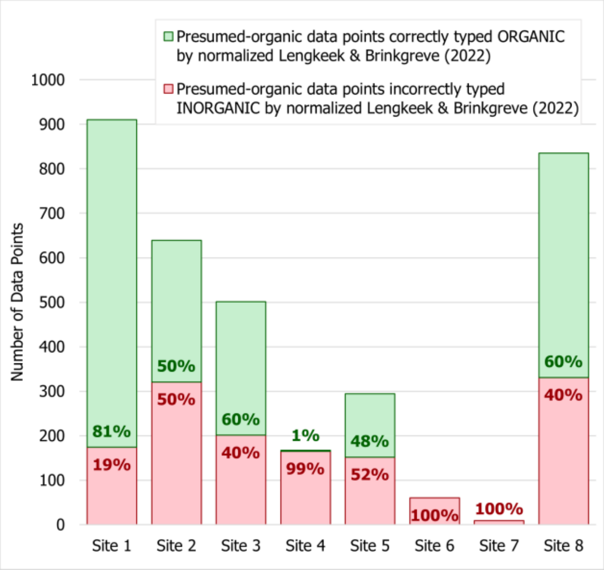

Figure 8. Distribution of the presumed-organic CPT data points at each site that were: (a) correctly typed as organic (shown in green) vs. (b) incorrectly typed as inorganic (shown in red) by the normalized Lengkeek and Brinkgreve (2022) SBT.

The Lengkeek and Brinkgreve (2022) modification is another promising organics screening tool, using either the dimensionless or the normalized option. Ultimately, 61.7% of the presumed-organic soils were identified correctly using the dimensionless SBT, as compared to 58.6% for the normalized SBT. The dimensionless version also outperformed its normalized counterpart with respect to false positives. The dimensionless SBT yielded only 2.4% false positive results versus 3.5% for the normalized SBT; therefore, the Lengkeek and Brinkgreve (2022) SBT modification applied to the dimensionless SBT yielded slightly better results overall.

3.3. Michigan Soil Behavior Type (MI-SBT)

It has now been established that for Michigan soils:

- The Robertson (2009) normalized SBT works well for mineral soils but underperforms with respect to identifying organic soil layers.
- The Jefferies and Been (2016) normalized SBT, with the introduction of the porewater pressure parameter, is much more successful at identifying organic soil layers compared to Robertson (2009).
- The Lengkeek and Brinkgreve (2022) SBT modification performs even better at identifying organics than the Jefferies and Been (2016) SBT, regardless of which SBT (dimensionless or normalized) it is applied to.
- The dimensionless Lengkeek and Brinkgreve (2022) SBT modification slightly outperforms the same modification applied to the normalized SBT.

Ultimately, it is optimal to implement multiple screening tools simultaneously to maximize the likelihood of successfully flagging any organic soil layers. Based on the results presented in this paper, it is recommended that the Robertson (2009) normalized SBT be the primary SBT (applied to all soil types: organic and mineral), and that the Jefferies and Been (2016) normalized SBT and the dimensionless Lengkeek and Brinkgreve (2022) SBT modification both be used in tandem as supplemental organics screening tools. Together, this proposed framework is henceforth referred to as the MI-SBT.

The major advantages of the MI-SBT are that (a) all three SBTs included in the MI-SBT are individually capable of identifying organic soil data points, and (b) none of the SBTs share the exact same pair of parameters. For example, some organic soils may have a particularly identifiable porewater pressure signature, resulting in more reliable identification using the Jefferies and Been (2016) SBT. Some soundings may have larger error in the unit weight estimates for the overburden soils, thus skewing the vertical stress estimates, resulting in more reliable organics identification by the non-normalized, dimensionless Lengkeek and Brinkgreve (2022) SBT modification.

To prove the success of the proposed MI-SBT, the presumed-organic CPT data points were, once more, simultaneously evaluated against all three SBTs: Robertson (2009) normalized, Jefferies and Been (2016) normalized, and the Lengkeek and Brinkgreve (2022) dimensionless SBT modification. So long as a data point classifies as organic according to at least one of the three SBTs, it gets assigned to the organic soil zone. The results of the analysis are presented in Figure 9.

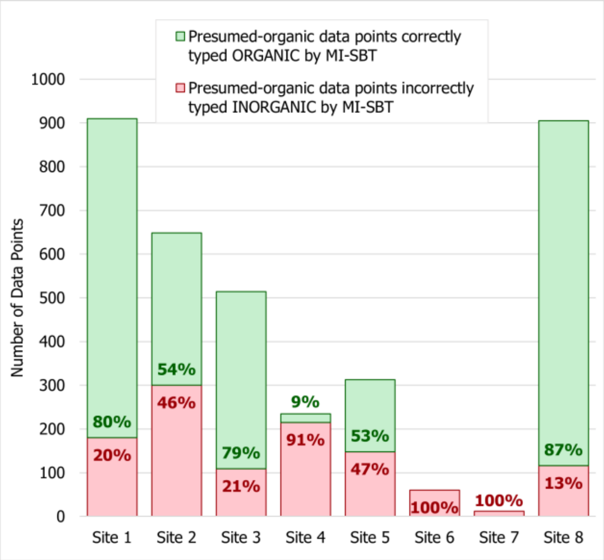

Figure 9. Distribution of the presumed-organic CPT data points at each site that were: (a) correctly typed as organic (shown in green) vs. (b) incorrectly typed as inorganic (shown in red) by the proposed MI-SBT (Robertson (2009) SBT + Jefferies and Been (2016) SBT + dimensionless Lengkeek and Brinkgreve (2022) SBT).

Figure 9 shows that the combined MI-SBT framework yields better organics classification results than any of the three SBTs on their own. The MI-SBT correctly identifies 68.3% of the presumed-organic soils, and still boasts a low false positive rate of 3.7%. A summary of the accuracy of each iteration of the organics screening tool is presented in Table 2.

Table 2. Summary of the accuracy of each iteration of the organics screening tool

Organic soil screening SBT	% of organics identified	% of false positives
Roberston (2009)	4.1%	0.3%
Robertson (2009) + Jefferies & Been (2016)	49.7%	2.3%
Robertson (2009) + Jefferies & Been (2016) + Lengkeek & Brinkgreve (2022)	68.3%	3.7%

4. Discussion

To further illustrate the impact of the MI-SBT on the SBT zone profile plot associated with an actual sounding that encountered organic soils, Figure 10 shows:

- Cone tip resistance (q_t) profile with field standard penetration numbers (N) superimposed
- Sleeve friction (f_s) profile with friction ratio (R_f) superimposed
- Porewater pressure (u_2) profile with hydrostatic water pressure (u_0) superimposed
- SBT zone profile based on Robertson (2009) only
- SBT zone profile based on Robertson (2009) and Jefferies and Been (2016)
- SBT zone profile based on the final MI-SBT

All plots also have the presumed soil stratigraphy layers from the companion soil boring log superimposed as horizontal dashed lines.

All three SBT zone profile plots adhere to the following legend:

Zone 1. Sensitive soils
Zone 2. Organic
Zone 3. Clay
Zone 4. Silty Mix
Zone 5. Sandy Mix
Zone 6. Sands
Zone 7. Gravelly Sands
Zone 8. Stiff Clayey Sand
Zone 9. Very Stiff Clays and Silts

Figure 10 clearly shows how initially, using only the Robertson (2009) SBT, most of the soil in the profile was characterized as SBT zone 3, i.e., mineral clay. The next plot shows the impact of the first improvement: the implementation of the Jefferies and Been (2016) organics screening tool. Many of the data points noticeably shift from being identified as a clay (SBT zone 3, in purple), to being flagged as an organic soil (SBT zone 2, in pink). The final SBT profile plot shows the impact of using both the Jefferies and Been (2016) SBT and the dimensionless Lengkeek and Brinkgreve (2022) SBT modification together as simultaneous organics screening tools (i.e., the MI-SBT).

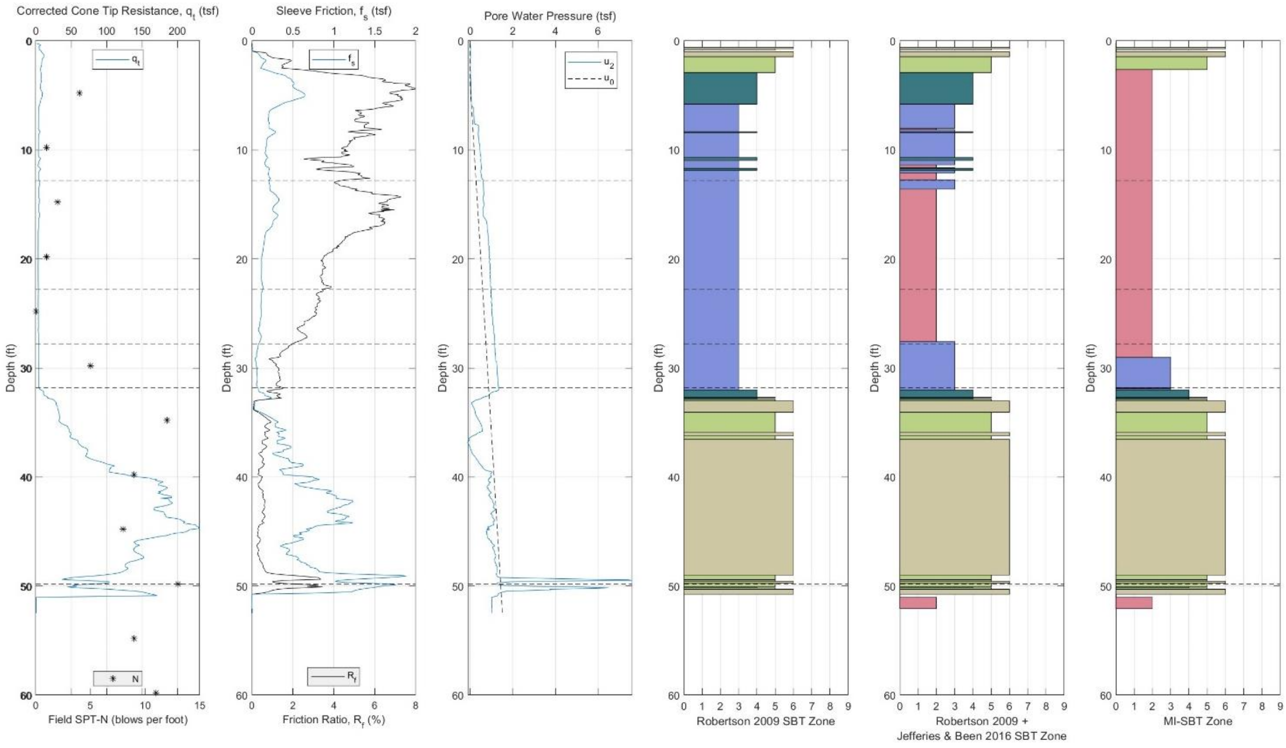

Figure 10. Data profiles for with CPT-1 at Site 3 (left to right: (1) corrected cone tip resistance and field SPT-N, (2) sleeve friction and friction ratio, (3) porewater pressure and hydrostatic groundwater pressure), and (4-6) side-by-side SBT profiles illustrating the improvement in successful identification of organics with each iteration of the organics screening tool.

Figure 11 shows the same data from Figure 10, now displayed on all three SBT charts that are used in the MI-SBT. It also includes a color-coded legend of soil descriptions. In each plot, the points that are shown in the same color are data points that exist within the same presumed soil layer, according to the companion soil boring. The soil descriptions from the soil boring log are shown in the legend, for reference.

In Figure 10, it was observed that many of the data point classifications updated from that of a mineral clay to that of an organic soil once the MI-SBT was implemented, but without an intimate knowledge of that particular sounding and that specific test site location, it is not immediately clear whether or not the reclassified data points are truly organic, according to the soil boring log, or if they are false positives.

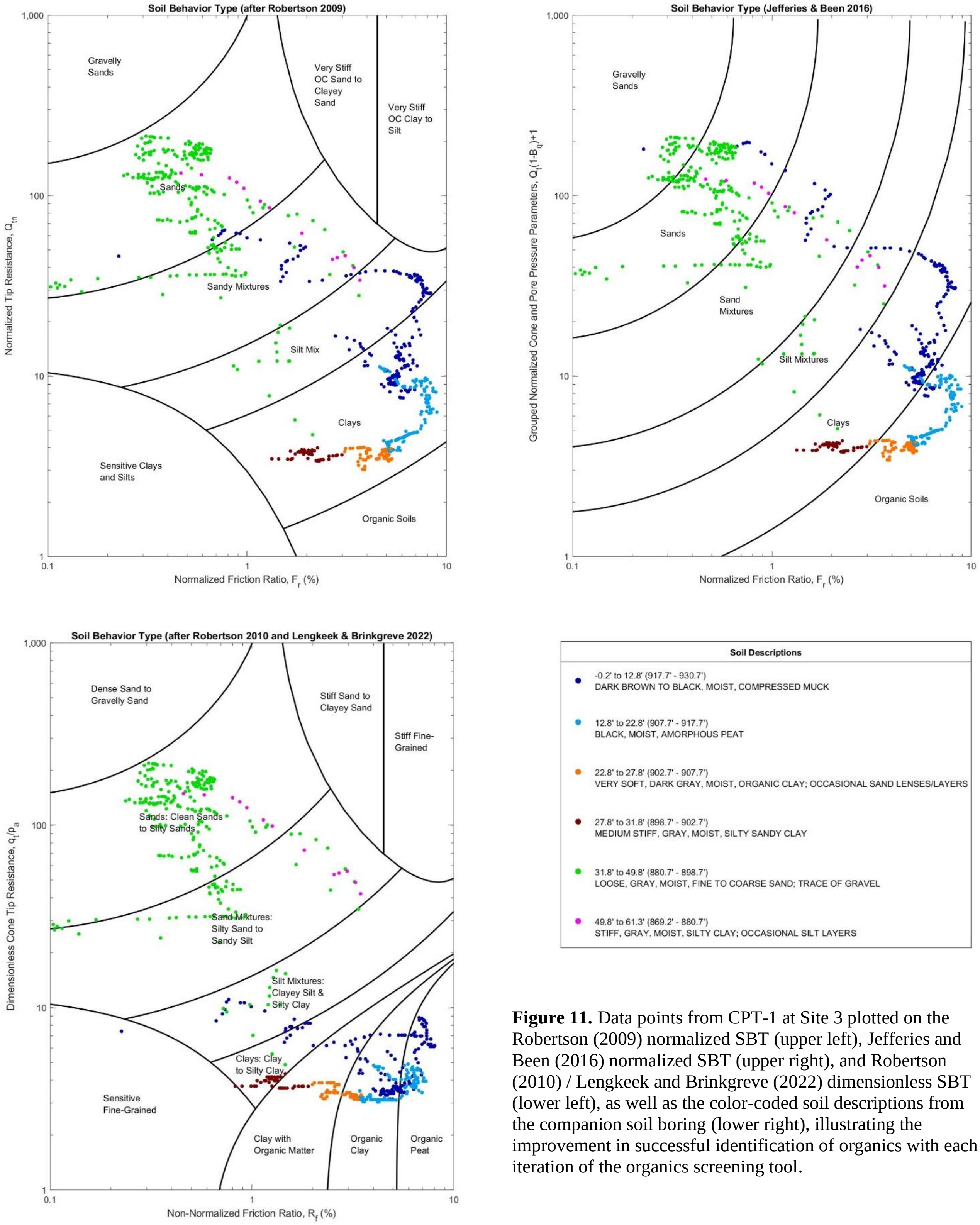

Figure 11. Data points from CPT-1 at Site 3 plotted on the Robertson (2009) normalized SBT (upper left), Jefferies and Been (2016) normalized SBT (upper right), and Robertson (2010) / Lengkeek and Brinkgreve (2022) dimensionless SBT (lower left), as well as the color-coded soil descriptions from the companion soil boring (lower right), illustrating the improvement in successful identification of organics with each iteration of the organics screening tool.

Figure 11 shows clearly that the organic soils are those represented by the purple, blue, and orange data points, because in the legend those entries are described as compressed muck, amorphous peat, and organic clay. It is also evident that none of the purple, blue, nor orange points classify as organic using the Robertson (2009) normalized SBT.

Once the Jefferies and Been (2016) SBT is introduced, most of the blue and orange data points (representing peat and organic clay, respectively) are properly classified as organic, yet the purple points (representing the muck) still plot as clay.

Finally, once the Lengkeek and Brinkgreve (2022) SBT modification is applied to the dimensionless Robertson (2010) SBT, most of the purple points are properly classified as organic. Notably, the majority of the data points associated with the inorganic silty sandy clay layer immediately beneath the organic clay (colored in red) do not get erroneously characterized as organic.

4.1. Sources of Error

While the MI-SBT shows tremendous improvement in the identification of organic soils, the results are not perfect. Much of this error is attributed to the nature of empirical correlations and the subjective characterization of soil as organic in soil boring logs.

The difference in reliability between the soil boring interpretations and the CPT data likely leads to the underestimation of the effectiveness of the proposed framework. The presumed organic soil layer boundaries and transition depths used to assess the reliability of the MI-SBT were obtained from the soil boring logs. Because the soil boring logs are aggregates of borehole point-source data, as opposed to the continuous data collection enabled by the CPT, these layer boundary depths are the field engineer’s best estimates. If these layer boundaries are slightly shifted from ground truth, then it is possible that any number of the “presumed-organic” data points allegedly mischaracterized by the MI-SBT are not actually organic at all due to an imprecise soil layer boundary.

This study is also limited by its binary approach. Each soil layer presented in the companion soil boring logs was categorized as either primarily mineral or primarily organic. Some of the error in the MI-SBT framework could be attributed to the fact that some primarily mineral soil layers contain “some”, “little”, or “trace” organics, and vice versa. These phenomena were not considered in the evaluation of the SBTs; therefore, the CPT could be appropriately identifying some of these mixtures and lenses, resulting in “false error”.

4.2. Future Work

Future studies may consider using the CPTu profile plots (such as cone tip resistance, friction ratio, and pore pressure) to discern soil layer boundary depths more accurately. This can then be used to adjust the soil layer boundaries listed on the soil boring log before using the boring log data to assess the validity of the MI-SBT. This study should also be expanded beyond the state of Michigan.

5. Summary and Conclusions

Organic soils are unsuitable subgrade materials for roadways and foundations; thus, their identification is an important part of subsurface investigation. While the Robertson (2009) normalized SBT proves effective at characterizing the soil behavior types of mineral soil profiles with reasonable agreement to the soil boring logs, it only accurately identifies 4.1% of the data points that the soil boring logs indicate as organic material. Conversely, when the organic soil regions from the Jefferies and Been (2016) normalized SBT are used with the dimensionless Lengkeek and Brinkgreve (2022) SBT modification as organics screening tools prior to characterizing the remaining mineral soil profile using the Robertson (2009) normalized SBT, 68.3% of the data points that the soil boring logs indicated as organic material were correctly identified.

The data presented in this study indicates that the use of these screening tools along with the Robertson (2009) SBT, collectively referred to as the MI-SBT, has made it more than 15 times more likely that an organic soil deposit will be accurately flagged using only CPT data. Implementation of this tool will help engineers more reliably identify organic deposits on their sites with the CPTu, allowing for more targeted subsequent borehole investigations, less site uncertainty, and increased cost savings.

Acknowledgements

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