Experience of in situ geotechnical tests and their interpretation in organic soils and peat

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ABSTRACT

This paper reviews the use of piezocone (CPTU) testing to characterise and identify peats and organic soils. Examples of data for peat sites from several countries are given, including some experience of the use of T-bar and piezoball penetrometers in peat. These "full flow" devices show smoother resistance profiles than the equivalent from the CPTU and are perhaps representative of the peat mass with a reduced fibre effect. In CPTU tests, organic soils and peat are often characterised by low corrected cone resistance (q_t) and high friction ratio (R_f). CPTU penetration in peat is often drained with data showing low pore water pressure coefficient (B_q) values. R_f broadly decreases with increasing degree of decomposition of the peat. However care needs to be taken in using R_f values in peat given the characteristically very low sleeve friction values (f_s) encountered. It would seem that it is not always easy to distinguish between peat and underlying soft soils using CPTU alone. There may be some promise in inclusion of CPTU "add on" sensors particularly a seismic element to yield shear wave velocity (V_s). However there is some uncertainty in measuring V_s in peat both offshore and onshore so care is needed in this regard. Recently developed Soil Behaviour Type (SBT) charts from the Netherlands have also been trialled on several sites. This new formulation shows promise and warrants further study.

Keywords: piezocone testing; full flow probes; shear wave velocity; peat; organic soils; soil behaviour type charts.

1. Introduction

There is an increased interest in understanding the geotechnical properties of peat and organic soils for engineering projects both onshore and offshore. In the past, where peat or highly organic soil was encountered at an onshore site, it was often simply excavated and replaced by engineered fill material. The environmental consequences of such work can be significant with loss of carbon storage potential as well as damage to an area's natural biodiversity. In response planning authorities, in Norway for example, have adopted new regulations prohibiting the cultivation of peat areas (Norsk-Lovtidend 2020; NPRA 2015).

As a result, major highways are being constructed directly on peat in Ireland, Norway and other places (Kissane et al. 2024). This is a development of work on smaller scale roads in the past, for example access roads to upland energy infrastructure sites, which were "floated" on peat (Munroe 2004).

In Ireland, Scotland for example landslides in peat are an increasing geohazard. often due to increased rainfall intensities caused by global warming (Warburton 2022).

In the offshore environment, an important consideration is the effect of peat and organic soils on the performance of submarine high-voltage (HV) cables. These deposits typically have high thermal resistivity and thus heat generated in the cables is not easily dissipated to the surrounding soil. This can result in elevated operating temperatures in the HV cables (Emeana et al. 2016). Peats and organic soils can have low bearing capacities, and peats can be fibrous, which can both be problematic for trenchers used for HV cable installation.

Piezocone testing (CPTU) is frequently carried out on these deposits both onshore and offshore. However interpretation of CPTU data in these deposits is not well understood as for mineral soils.

In an attempt to improve the characterisation of peat and organic soils, in this paper CPTU and full flow probe data for sites in several countries will be presented.

2. Characterisation of peat and organic soils

Organic matter in soil is usually identified by its ability to be combusted. Therefore, in geotechnical engineering, perhaps the most common method of measuring the organic content is the loss on ignition method (LOI). LOI testing is usually carried out on a 10g sample of oven dried material at 440±40°C for 4 hours according to ASTM D2974 (ASTM 2020).

The soil can then be classified as "slightly organic" (LOI or alternative test giving organic content 2-6%), "organic" (6-20%) or "very organic" (>20%) according to ISO 14688-1 (ISO 2017a) and ISO 14688-2 (ISO 2017b). Guidance is given in ISO 14688-1 on the use of soil colour to help identify organic content.

Low organic content soils are often grey in colour whereas high organic content material is mostly black.

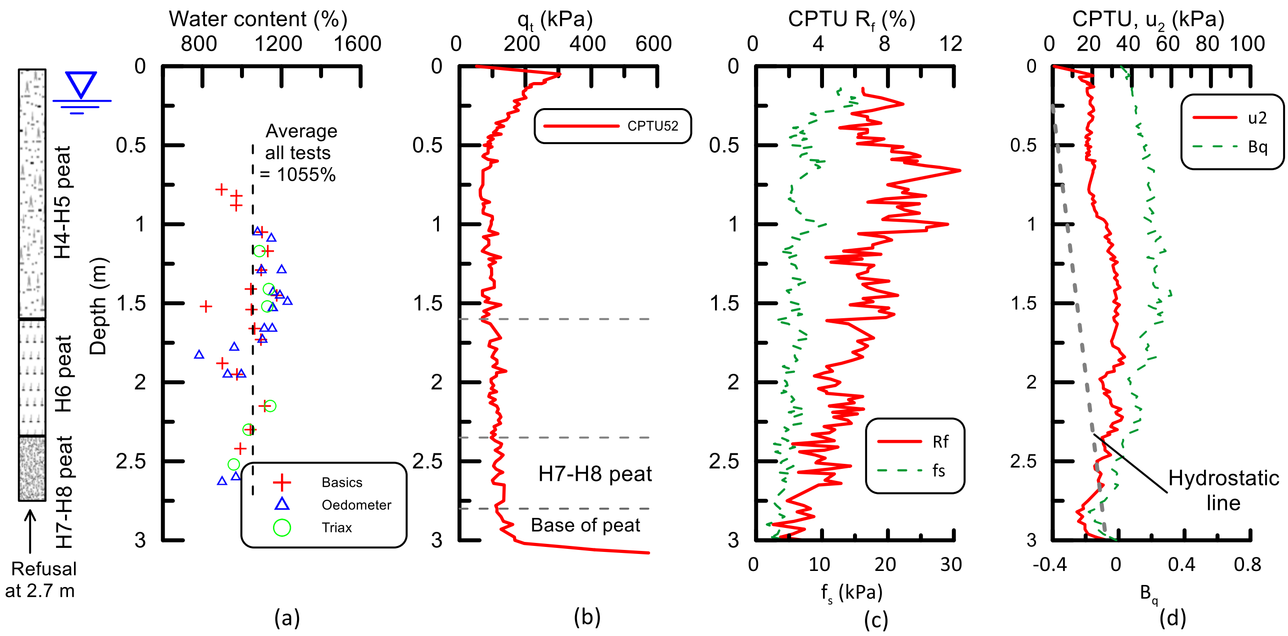

Figure 1. Typical peat characteristics for site in west Ireland (a) water content, (b) q_t, (c) R_f and f_s and (d) u_2 and B_q (Long and Jennings 2006)

The organic content at which soil is classified as "peat" ranges widely e.g. from 30% in the Dutch system (Lengkeek 2022) to 75% according to ASTM D2487 (ASTM 2010). Peat can be categorised as "fibrous peat", "pseudo-fibrous peat" or "amorphous peat", according to ISO 14688-1, using a simple hand squeezing test. To understand the full nature of the peat, a full classification should then be carried out according to the von Post system (von Post and Granlund 1926) as extended by Hobbs (1986). The system is based on categorisation of degree of humification (H), water content, content of fine (F) and coarse (R) fibres and content of woody remnants (W) and the tensile strength of the fibres (T). A visual inspection of the peat and the simple hand squeezing test are used to classify the peat on a scale of H1 (no decomposition) to H10 (completely decomposed fibre free amorphous material). The F, R, W and T indices are assigned values between 0 and 3.

Although other classification systems exist, in the author's experience the von Post system is the most common in engineering practice and it will be used here.

3. A typical onshore peat site

Some typical classification and CPTU parameters for a peat site in County Mayo, Ireland are shown in Figure 1. At this site the peat becomes gradually more decomposed with depth, with H increasing from about 4 at the surface to 8 with depth. It is very common to find the most decomposed peat at the base of the sequence. Water content is very variable but has an average value of 1055%. Average bulk density is 1.03 Mg/m^3, i.e. just greater than that of water. The material is nearly completely organic (average LOI = 98%). The water table varies seasonally but is always close to the surface.

4. Some typical CPTU profiles in peat

The following referred tests were all carried out using standard 10cm^2 CPTU devices as part of commercial projects. As a backdrop to the following, consideration can be given to information presented by Lunne, Robertson, and Powell (1997) which gives several examples of CPTU profiles in peat from the Netherlands and Germany. The data in peat for these two areas was broadly characterised by low corrected cone resistance ($q_t \approx 500$ kPa) and a high friction ratio ($R_f = f_s/q_t$ where f_s is the CPTU sleeve friction) of around 4% to 6%. Some experience from the Vancouver area of Canada was also summarised and it was found that both fibrous and amorphous peat had low q_t and high R_f but the amorphous peat had higher u_2 and B_q than the fibrous peat.

4.1. Case study 1: Irish peat

For the Mayo site (Figure 1), CPTU corrected tip resistance (q_t) values are very low being typically 100 kPa, except for values up to 300 kPa in the highly fibrous dry crust. Friction ratio (R_f) values are high ranging from about 12% in the upper H4/H5 peat reducing to 4% in the deeper thin H7/H8 peat sublayer. Generated pore pressure (u_2) values are slightly higher than the hydrostatic pressures (u_0) giving B_q (pore pressure parameter = q_{net}/u_2-u_0) values of about 0.1 to 0.2. These findings are broadly consistent with what would be expected for peat (see Section 4) except that B_q decreases with increasing degree of decomposition.

CPTU and T-bar data for a site in Ennis, County Clare is presented in Figure 2. T-bar tests were carried out immediately adjacent to the CPTU tests. The T-Bar was 250 mm long and 40 mm in diameter, hence it had a projected are ten times that of the CPTU. Only $q_{T\text{-}bar}$ measurements are available from this equipment.

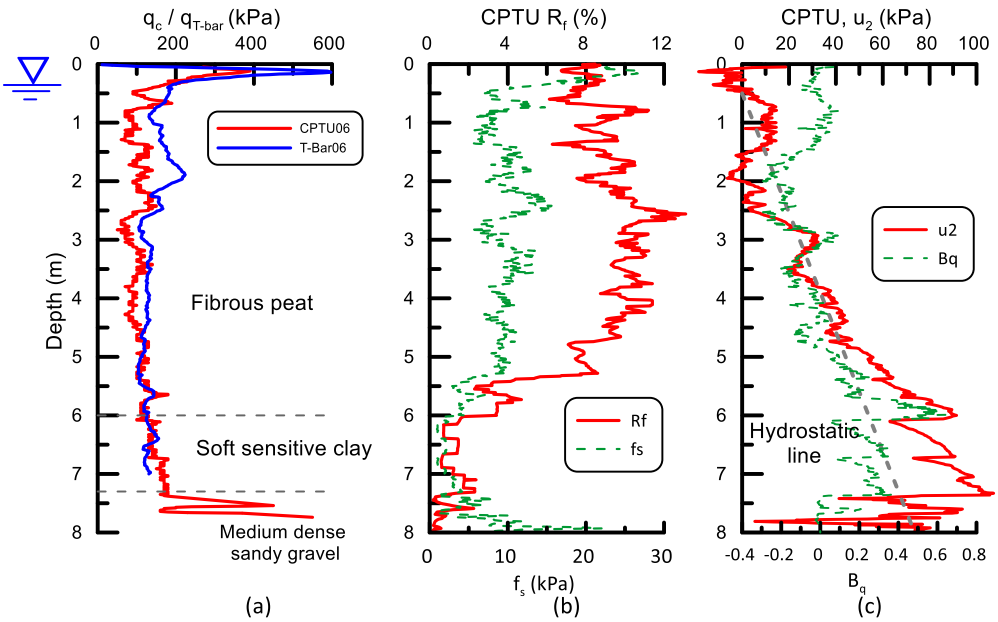

Figure 2. CPTU data for site in Ennis, Co. Clare, western Ireland (a) q_t, (b) R_f and f_s and (c) u_2 and B_q (UCD files)

The fibrous peat at this site has very low q_c (≈100 kPa) and f_s (≈ 10 kPa) and high R_f (8% to 10%). It is not easy to distinguish between the peat and the underlying soft clay using q_c alone but the f_s and R_f (which both reduce) pick up the boundary clearly. The u_2 data follows the u_0 profile very closely, indicating that peat behaviour around the CPTU cone during penetration is close to fully drained with very low B_q values (0-0.1).

The T-bar $q_{T\text{-}bar}$ profile mirrors that of CPTU q_c. Arguably the T-bar profile is smoother, likely due to it being less sensitive to localised effects of penetrating fibrous material and therefore is arguably more representative of the mass behaviour the peat.

4.2. Case study 2: Norwegian peat

CPTU data for the Tiller-Flotten peat site near Trondheim in Norway is presented in Figure 3 (Paniagua and Long 2024).

Peat at the site is typical of other peats in this area of Norway and in Norway in general (Long et al. 2022). There are two distinct layers of peat at the site. The upper layer has a relatively low degree of decomposition (H = 3) and a high water content of around 1200%. The lower layer is more decomposed (H = 4/5) and has a lower water content of about 800%.

The CPTU q_t and R_f data clearly distinguishes between the two peat layers with the upper less decomposed layer having relatively higher q_t and higher R_f, similar to the finding of Figure 2 (higher f_s data). The f_s / R_f values are lower than those at Ennis (and later at the Clonmore Road site).

However the q_t and R_f data do not clearly identify the difference between the peat and the underlying soft clay. This boundary however is defined well by the u_2 / B_q data with penetration in the peat being largely drained and that in the soft clay showing high u_2 / B_q values.

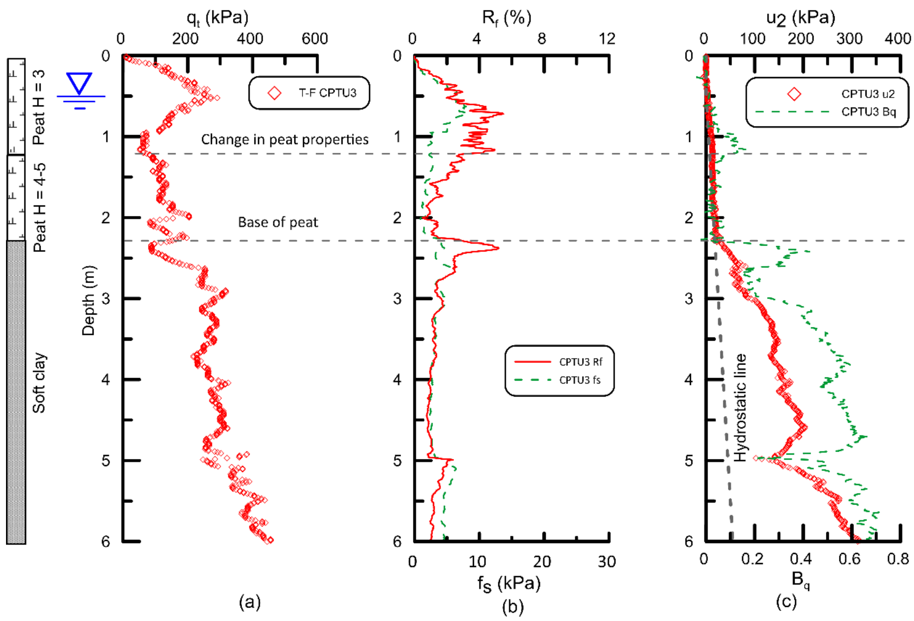

Figure 3. CPTU test for Tiller-Flotten peat site, Trondheim, Norway (a) q_t, (b) R_f and f_s and (c) u_2 and B_q (Paniagua and Long 2024)

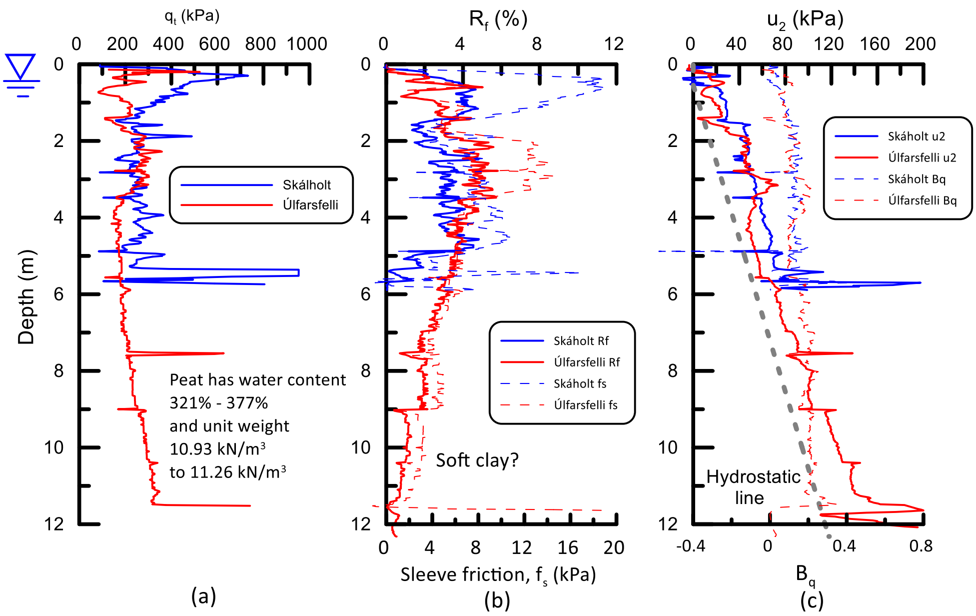

Figure 4. CPTU tests for two peat sites in Iceland (Personal communication Gisli Gudjonsson)

4.3. Case study 3: Icelandic peat

Some CPTU data for two Icelandic peat sites is presented in Figure 4. The peat at these sites has significantly lower water content (≈350%) and higher unit weight (1.13 Mg/m^3) than for the Irish and Norwegian sites. Nonetheless similar CPTU parameter characteristics are observed with this peat having low q_t (≈200kPa), high R_f (3-4%) and showing drained or at best partially drained behaviour ($B_q \approx 0.2$).

5. Distinguishing peat from adjacent organic clays

It has been shown through Figures 2 and 3 that it may not be straightforward to distinguish between peat and the adjacent organic clay layers using CPTU data.

This is further explored using data from the Färgelanda site in Southern Sweden and the Clonmore Road site in County Westmeath, Ireland, see Figures 5 and 6 respectively.

At the Färgelanda site a layer of peat (mean water content w_{mean} = 630%), overlies gyttja (w_{mean} = 190%) and soft clay (w = 68%). As seen from previous cases the CPTU data shows much higher R_f (5-7%) and lower u_2 / B_q (0.1-0.2) in the peat than in the other underlying materials. The q_t and f_s in the peat is higher than the gyttja with a clear drop off as the CPT penetrates into the gyttja. Potentially, this change in behaviour could be explained by the presence of fibres in the peat.

At Clonmore Road the "calcareous marl" underlying the peat is a lake bed sediment with a typical LOI of between 8% and 22% (Diefendorf et al. 2008). There is a significant contrast between the water content, bulk density and LOI in the peat and the calcareous marl.

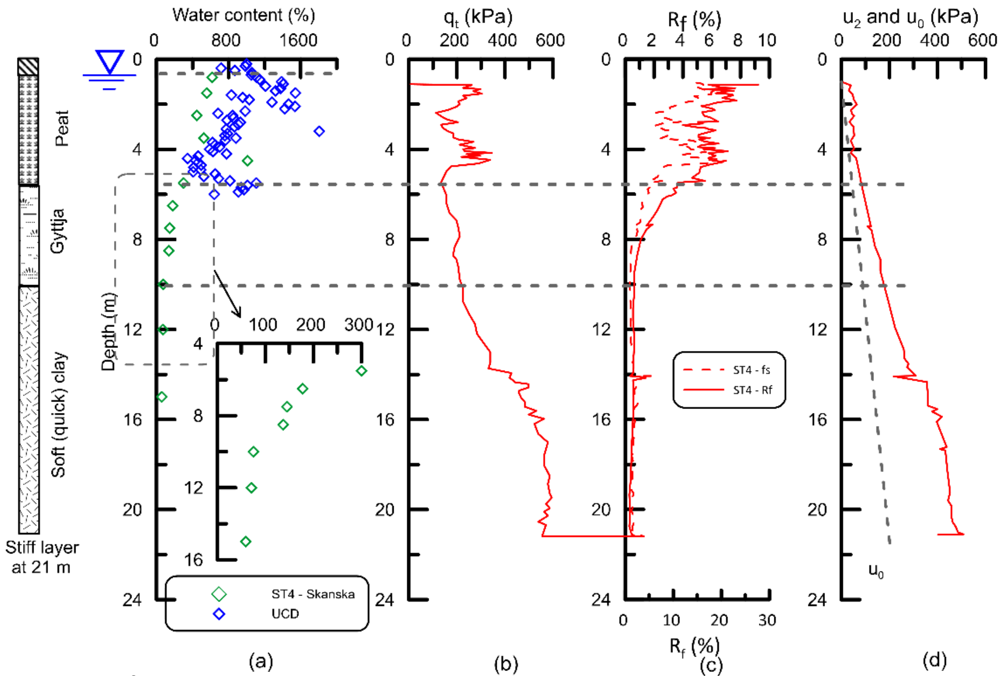

Figure 5. CPTU data from Färgelanda site in Sweden (a) water content, (b) q_t, (c) f_s / R_f and (d) u_2 (Long, Grimstad, and Trafford 2022)

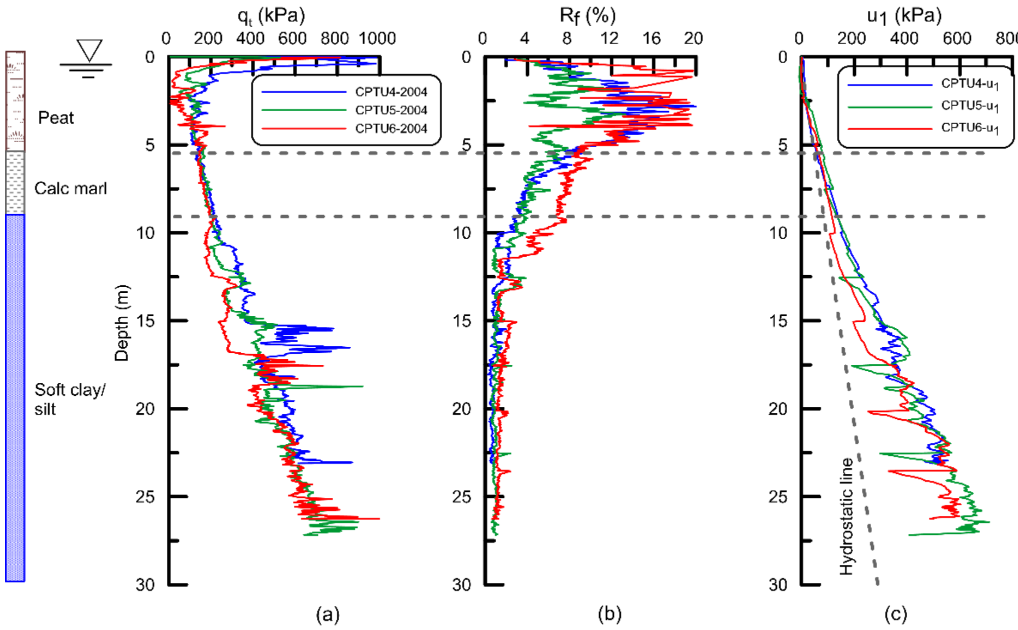

Figure 6. CPTU data from the Clonmore Road site in Ireland (a) q_t, (b) f_s and (c) u_1 (Long 2018)

The peat water content varies between 200% and 850% with the calcareous marl showing much lower values of between 100% and 250%. Bulk density for the calcareous marl is typically 1.25 Mg/m^3 compared to 1 Mg/m^3 for the peat. LOI values in the peat are very high and often close to 100%

Again the peat at Clonmore Road site has higher R_f (8-18%) than the underling calcareous marl (R_f = 4-8%). Pore pressure measurements were taken with a u_1 sensor. No u_2 data was available to assess B_q. Nonetheless both materials have u_1 close to u_0, before these values subsequently pick up in the underlying soft clay / silts.

In Figures 5 and 6 it can be seen that the q_t profile in the gyttja and calcareous marl appears to be smoother than in the peat. This is potentially an effect of the fibrous nature of the peat.

However there are several examples from Sweden (Larsson and Mulabdić 1991) and Poland (Mlynarek, Wierzbicki, and Bogucki 2015) where the q_t profiles in gyttja are equally as variable as that in peat.

6. Use of soil behaviour type charts in peat

Several authors have reviewed the use of CPTU soil behaviour type (SBT) charts in peat and found them to give inconsistent results in the resulting classification (Mollé 2005; Long 2008).

In an attempt to improve the charts for the classification of organic soils and peats Lengkeek (2022) and Lengkeek and Brinkgreve (2022) proposed an adjustment of the well-known Robertson (2010) SBT chart as shown on Figure 7. The proposed adjustment was that SBT = 2 and part of SBT = 3 were to be redefined and split up into SBT = 2a (Peat), 2b (Organic Clay) and 2c (Mineral Clay, with organic matter).

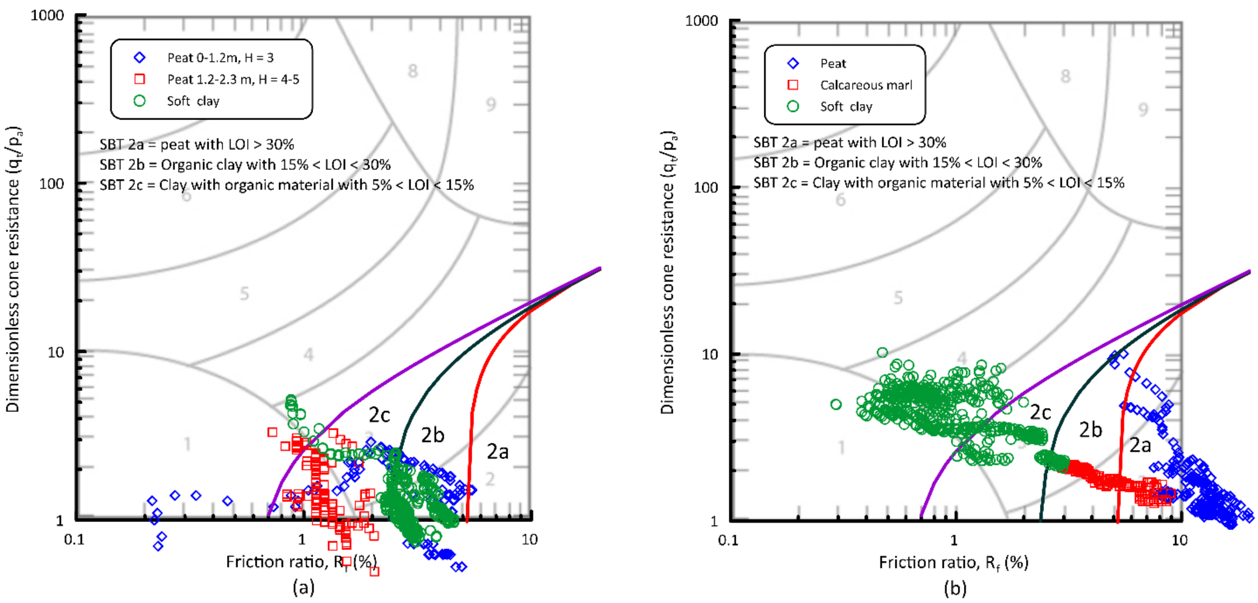

Figure 7. SBT chart for (a) Tiller-Flotten and (b) Clonmore Road using Lengkeek (2022) / Robertson (2010) formulation

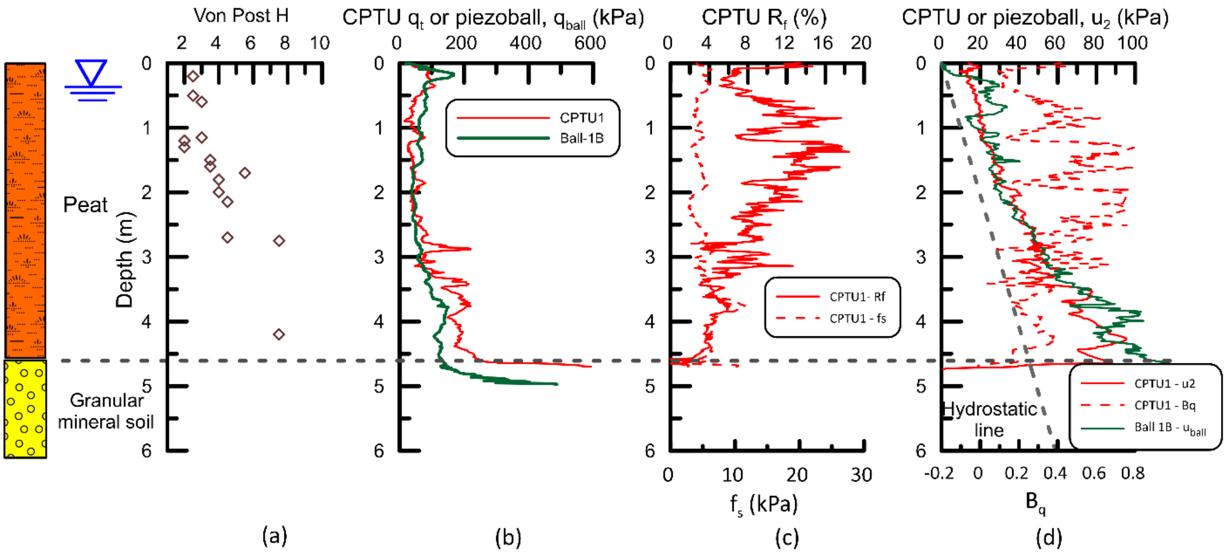

Figure 8. CPTU and piezoball data for Crockagarron wind farm site, Northern Ireland (a) H, (b) q_t or q_{ball}, (c) R_f and (d) u_2 or u_{ball} (UCD files)

The modifications were based on 233 sets of CPT and borehole pairs involving a wide variety of Dutch soils including peat, organic clay, clay with some organic material, inorganic clay and sand.

This formulation has been trialled for the Tiller-Flotten and Clonmore Road sites, which were discussed in Sections 4.2 and 5 respectively, on Figure 7. For Tiller-Flotten, the adjusted SBT chart fails to distinguish between the upper and lower peat layers and the underlying soft clay. It is possible that the f_s values measured at this site are lower than those encountered in the Dutch database. For the Clonmore Road site, the adjusted chart works better in placing data for the three soils in the corresponding SBT zone. The peat falls into Zone 2a, the calcareous marl into Zone 2a and 2b and the soft clay into Zone 2c, and then outside Zone 2, consistent with the other engineering classification characteristics of the materials.

Based on these findings the extent to which this chart could be applied warrants further study. It would be valuable to extent this study to a wider range of peat and organic clay soils.

7. Use of piezoball in peat

Various authors have advocated the use of the piezoball in the Netherlands (Zwanenburg and Erkens 2019), (Greeuw 2007), in Ireland and the Netherlands (Boylan, Long, and Mathijssen 2011) and in Canada (Siddiqua, ElMouchi, and Wijewickreme 2023). An advantage of the full flow probes was the smoother profile of q_{ball} or q_{Tbar} when compared to that of q_t as has been discussed in Section 4.1.

The piezoball has become more popular than the T-bar in recent times due to the ball being more compatible with the diameter of temporary steel casings that the rod string passes down through. There have also been several cases where the T-bar was broken when one side of the instrument came into contact with a hard material, e.g. a piece of timber.

An example of some CPTU and a co-located piezoball tests from the Crockagarron wind from in Northern Ireland is shown on Figure 8. Note the piezoball has its pore water pressure transducer at the instrument tip and the ball has a cross sectional area of 100 cm^2.

The peat at Crockagarron becomes more decomposed with depth with increasing from H2/H3 near the surface to H7/H8 with depth. The data shows very low q_t or q_{ball} values (≈100 kPa) with high R_f (4-16%). R_f values are highest in the less decomposed peat. These are similar responses to CPTU and T-bar data presented in the previous figures. In contrast to some of the other sites the pore pressure values indicate a penetration pattern closer to undrained behavior with the equivalent B_q or B_{ball} values being of the order of 0.2 to 0.5.

8. Use of and shear wave velocity profiling in peat and organic soils

Some onshore examples from Sweden are shown on Figure 9 where the shear wave velocity (V_s) values for three Swedish peat sites fall below the limits of data recorded on Swedish organic clays. The Swedish example and data published more broadly in the literature shows peat generally has very low V_s, of the order of 20-30 m/s compared to 50 m/s or greater for soft organic clays, thus allowing it to be distinguished from the underlying organic clays.

V_s can be measured using a variety of in situ invasive and non-invasive techniques such as the seismic CPTU (SCPTU) and by use of surface wave methods e.g. multichannel analysis of surface waves (MASW).

Some examples of successfully measuring V_s in peat using SCPTU are given by Campanella et al. (1994), Kramer (2000) and Tanaka (2014) for onshore sites in Canada, the US and Japan respectively.

For use of SCPTU in offshore conditions it is important to note Section 8.6.3 of ISO (2023) which says "shear wave velocity cannot reliably be derived in the upper 2 m to 5 m below seafloor, depending on the system characteristics and site conditions".

Onshore a practical issue with undertaking SCPTU testing in peat is access to the test location is often very difficult due to the very soft subsoils and high water table.

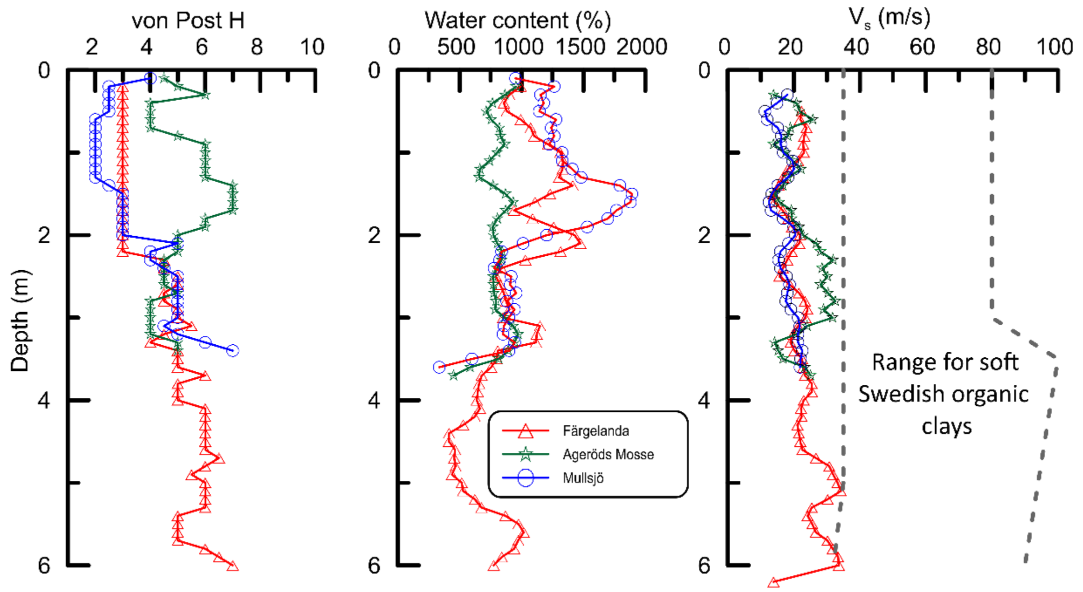

Figure 9. Comparison of V_s values at three Swedish peat sites (Long, Grimstad, and Trafford 2022) compared to the range of V_s values in Swedish organic clays (Long 2022)

Trafford (2017) developed a lightweight hand portable probe for measuring the V_s in peat. The device is in principle very similar to the SCPTU.

Onshore multichannel analysis of surface wave techniques (MASW) have also been used in peat, for example in Malaysia by Basri et al. (2020). Care needs to be taken in inverting the MASW data so as to produce reliable high frequency (low wavelength) data to accurately characterise the shallow peat layers.

There is some limited experience of the use of MASW offshore, e.g. by McGrath et al. (2016) but no examples of such offshore surface wave studies in peat are publicly available.

9. Conclusions

This paper identifies a key challenge for industry, i.e. that of classifying peat and organic soils with CPTU. The data presented has shown that CPTU is a very useful tool for profiling these soils. These materials will consistently show low q_t, high R_f and low u_2 / B_q. It would also seem that R_f will decrease with increasing degree of decomposition (increasing H). Care needs to be taken with interpretation of the very low f_s values usually encountered.

However in some cases it is possible that the underlying soft strata may show similar CPTU characteristics to that of the peat. In addition it may be difficult to distinguish between a soft inorganic soil from a soft organic soil using standard CPTU data alone. There may be promise in using additional sensors such as those which determine V_s. However there can be uncertainty in measuring V_s using SCPTU up to 5 m below seafloor and the very low values involved mean that care needs to be taken when determining this property onshore.

Both the T-bar and the ball-penetrometer give smoother profiles than the equivalent from the CPTU, possibly because of the lower influence of the fibres with these full-flow devices.

Future work on this topic should include a more detailed study of CPTU parameters (R_f, B_q) versus other classification parameters such as von Post H, LOI and water content. The overall aim would be to determine a unified method for classifying peats and organic soils which is less dependent on classification by the geologist/engineer logging the soil samples.

Recently developed SBT charts from the Netherlands show promise and warrant further study, particularly in the materials with very low f_s such as those described in this paper.

To that end an assessment of some well characterised controlled research sites would be very valuable.

Future studies could include the influence of the very low effective stresses involved on the f_s readings, together with the impact of frost and the depositional environment (e.g. saline conditions).

Acknowledgements

The authors are grateful to Tom Lunne of NGI who provided useful comments on a draft of the paper.

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