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Research article

CiPPT—A new in situ method for sounding and strength determination in peat

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Abstract: In this article, a new probe and method, CiPPT (Circular Probe Penetration Test), is presented, which was developed for sounding and strength determination in peat. The probe is an inverted cone where the horizontal end surface is pushed down into the peat during sounding. The probe is connected to the same equipment used for cone penetration testing, with the cone replaced by an inverted cone. A larger CiPPT, 140 mm diameter for research purposes, and a smaller CiPPT, 70 mm diameter for production purposes, have been developed and tested, both with either pins on the end surface or a rough end surface. Additionally, a variant of the CiPPT 140 mm diameter called double-CiPPT with an inner and outer plate has been developed to study the effect of fiber tensile strength on sounding resistance. The functionality of the double-CiPPT were verified, and the CiPPT variants were tested at three field test sites with low- and medium- humified peat. To evaluate strength, the results from the CiPPT were calibrated against triaxial compression tests. Comparisons were made with other in situ methods. Moreover, peat that was loaded and compressed over a long period below railway embankments and peat not loaded and not compressed in bogs were investigated.

Keywords: peat; strength; in situ; method; sounding; fiber; embankment

1. Introduction

There is no verified and established field method to determine the strength and its variation with depth in both not loaded (not compressed) and loaded (compressed) fibrous peat. The methods primarily used to determine the strength characteristics of low and medium humified peat are T-bar, Ball, field vane testing, and CPT sounding. Mainly natural, not loaded peat has been studied, and peat that has been loaded (and compressed) for longer periods, such as peat under railway embankments, has been rarely studied.

Experiences show that there is a significant spread in strength determinations using field vane tests [1], meaning that individual measurements may give misleading values of strength. Furthermore, there is uncertainty regarding how field vane test values in peat should be corrected. This is because the failure in fibrous peat does not occur at the periphery of the vane, and not in the same way as it does in clay (where a cylindrical failure volume is created), due to the fiber effect and the tensile strength of the fibers. CPT sounding has previously been considered not suitable for assessing strength in peat in the field, mainly because the failure mode in fibrous peat is likely not the same as that assumed for clay and used when interpreting results from CPT. Despite this, we reinvestigate whether it is possible to assess strength in peat from CPT. The study provides opportunities to examine this to some extent since different field and laboratory methods are carried out for comparison and calibration. T-bar and Ball have shown promising results for determining strength in natural not loaded peat, but these methods need to be further verified and tested in loaded and compressed peat [2].

Furthermore, it is known that fibrous peat exhibits fiber effects, similar as reinforcement or textiles, and has a tensile strength that affects these geotechnical properties [3,4]. The fibers in peat create a reinforcement as in reinforced soil, except that the reinforcement is discontinuous [3]. This fiber effect on mechanical properties of peat has been very limitedly studied in the laboratory and in the field, but [3,5–7] are some contributions. The shear strength/shear resistance for peat is based on friction between fibers and tensile strength/tension forces in the fibers [3,6]. More knowledge is needed about how peat fibers affect mechanical properties such as tensile strength, and also how to quantify them. This is needed for future improved theoretical material models for fibrous peat.

In this article, we present a new probe and method, CiPPT (Circular Probe Penetration Test), which has been developed for sounding and strength determination in peat. Furthermore, a variant, a so-called double-CiPPT, has been developed to study the influence of fiber tensile strength on sounding resistance. Studies have been carried out at three field sites, both in peat below embankments and in peat within the bog beside the embankment, and for strength determination, the results have been calibrated against laboratory tests.

2. Test sites and materials

2.1. Location

The experimental test site at Missenträsk is along the railway between Jörn and Arvidsjaur, and the experimental sites at Kärrbäck and Oja are along the old Haparanda railway between Morjärv and Haparanda, all in northern Sweden, and are no longer used embankments that were built over 100 years ago [8].

2.2. Missenträsk

At site Missenträsk, the embankment thickness is approximately 1.5 m, and the peat thickness directly beneath the embankment is around 2.0 m, with about 2.2–2.4 m of peat within the bog beside the embankment. The peat is underlain by moraine, and the groundwater level is about 0.35 m below the ground surface both beside and under the embankment.

In Missenträsk, the peat within the bog outside the embankment, the degree of humification has been classified by depth (according to von Post [9]; see chapter 4) as follows: 0.2–0.6 m: H3; 0.6–1.5 m: H2; 1.5–2.5 m: *H3–H5*. The peat under the embankment has been classified as: 0.0–1.1 m: H2; 1.1–2.0 m: *H3–H4*. The water content for peat samples from the bog varies between 665–858%, and from under the embankment it varies between 453–655%. The bulk density for peat samples from the bog is 0.98–1.02 t/m³ and from under the embankment, 0.98–1.00 t/m³. Figure 1 presents the water content, degree of humification, and bulk density for peat samples from the bog, and Figure 2 shows tip resistance from CPT at the bog, for the three sites. Photos of samples of peat from each site are shown in Figures 3–5.

A detailed continuous determination of the variation in degree of humification with depth within the bog, through the analysis of peat samples taken in the field, has not been possible. However, by studying the three sites and the size and variation of the sounding resistance in the zones where the degree of humification for the taken samples has been determined, values for the degree of humification have been estimated at the fewer depths where experimental determinations could not be performed. These estimated values for the degree of humification are marked in italics in the above and below running text description of the field sites.

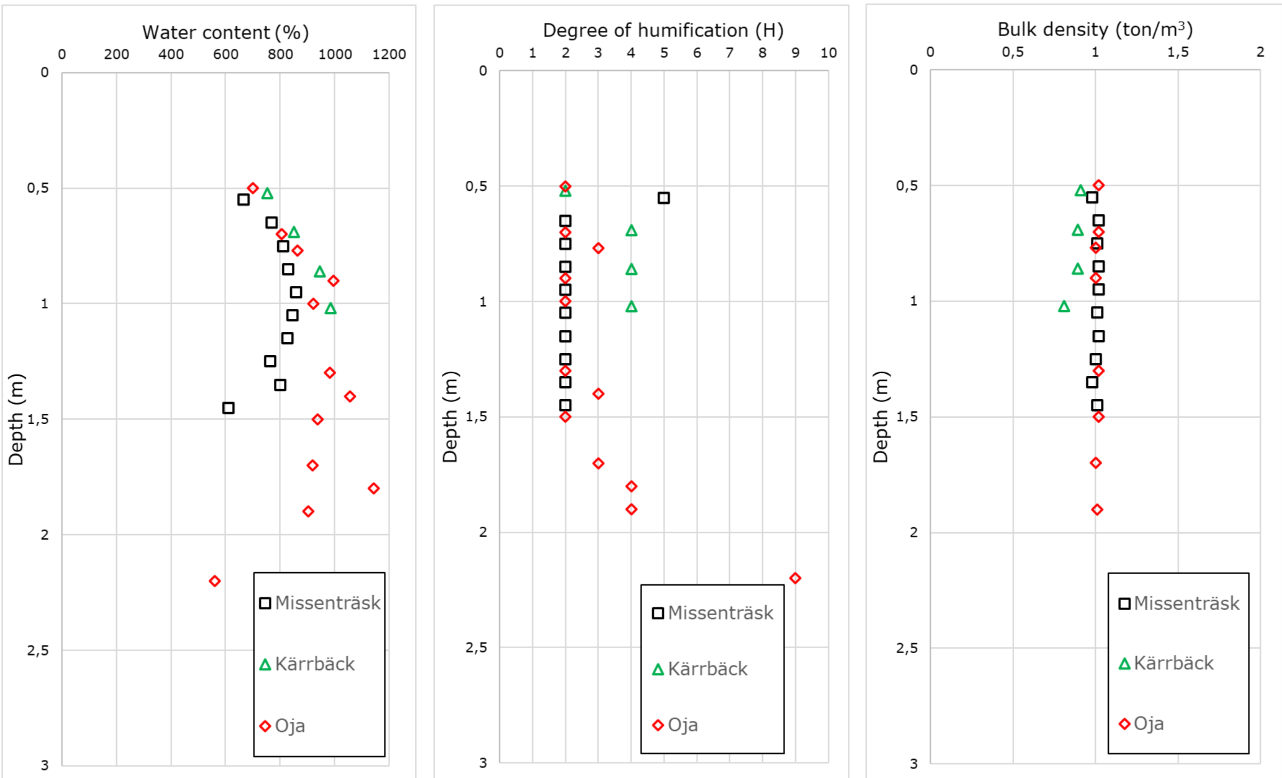
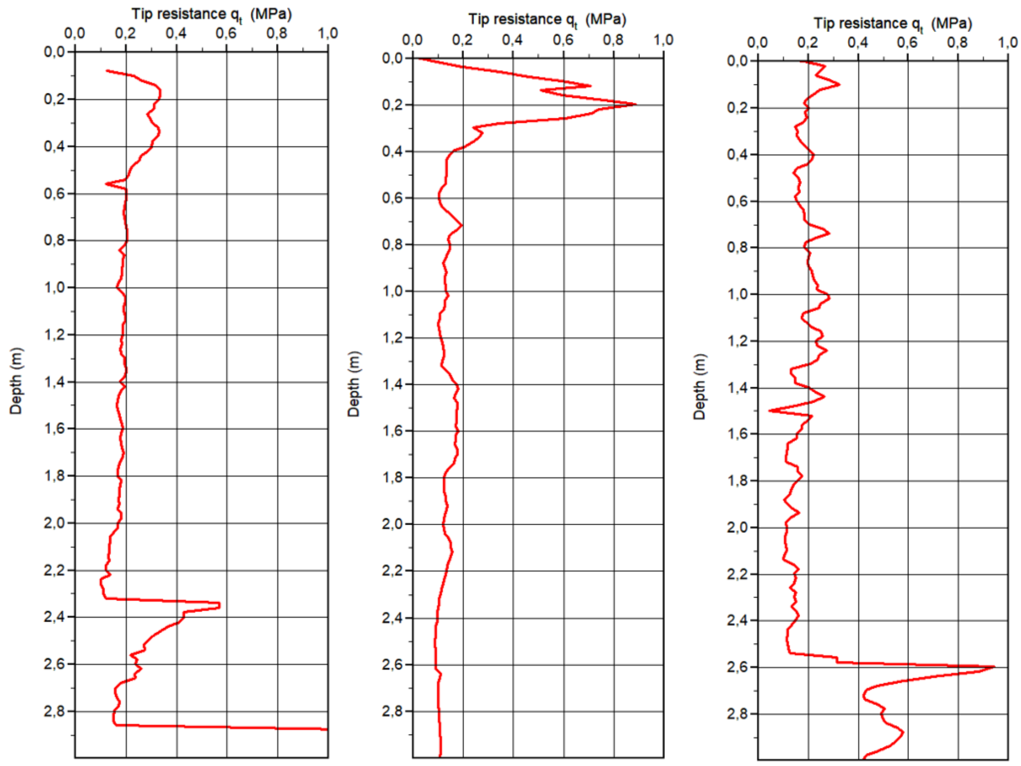


Figure 1. Water content, degree of humification and bulk density for peat samples from bog at sites Missenträsk, Kärrbäck and Oja.



a) b) c)

Figure 2. Tip resistance from CPT at bog at sites a) Missenträsk (peat down to about 2.2 m depth), b) Kärrbäck (peat about 2.0 m depth), and c) Oja (peat about 2.1 m depth).

Figure 3. Fibrous peat sample (split in a vertical plane) from 1 m depth at bog in Missenträsk.

Figure 4. Fibrous peat sample (cut with knife and split in a vertical plane) from 0,7 m depth at bog in Kärrbäck.

Figure 5. Fibrous peat sample from below the embankment in Oja.

2.3. Kärrbäck

At site Kärrbäck, the embankment thickness is approximately 3.2 m, and the peat thickness directly beneath the embankment is about 0.8–0.9 m, with around 1.9–2.0 m of peat within the bog beside the embankment. The peat is underlain by sulphide silt, and the groundwater level is about 0.0 m below the ground surface both beside and under the embankment.

In Kärrbäck, the peat within the bog outside the embankment has been classified by depth as follows: 0.4–0.6 m: H2–H3; 0.6–1.0 m: H4; 1.0–1.4 m: H5–H6; 1.4–1.7 m: *H4*; 1.7–1.9 m: *H9*. The peat under the embankment has been classified as: 0.0–0.2 m: H2; 0.2–0.8 m: H5. The water content for peat samples from the bog varies between 754–984%, and from under the embankment, it varies between 277–395%. The bulk density for peat samples from the bog is 0.89–0.91 t/m^3. Figure 1 shows these parameters from the peat at the bog.

2.4. Oja

At site Oja, the embankment thickness is approximately 2.4 m, and the peat thickness directly beneath the embankment is about 1.1–1.2 m, with around 2.3–2.5 m of peat within the bog beside the embankment. The peat is underlain by a 0.4 m layer of silty clay and beneath that, moraine, and the groundwater level is approximately 0.0 m below the ground surface both beside and under the embankment.

In Oja, the peat within the bog outside the embankment has been classified by depth as follows: 0.4–1.2 m: H2; 1.2–1.5 m: H3; 1.5–1.8 m: H4; 1.8–2.2 m: H9. The peat under the embankment has been classified as: 0.0–0.3 m: H2; 0.3–0.5 m: H3; 0.5–0.8 m: H4; 0.8–1.1 m: H9. The water content for peat samples from the bog varies between 699–1144%, and for a sample from under the embankment, it is 378%. The bulk density for peat samples from the bog has been determined to be 1.00–1.02 t/m^3 and from under the embankment, it is 1.03 t/m^3. Figure 1 shows these parameters from the peat at the bog. In Figure 5, a peat sample from below the embankment is shown, with a clear layering.

3. CiPPT—Development of a new probe

The CiPPT has been developed with inspiration from earlier model experiments at SGI [7], where displacements and failure in fibrous peat have been described. The CiPPT has been developed in two variants: A research one with a diameter of 140 mm and a production one with a diameter of 70 mm. The latter is intended to be used through a standard-sized casing tube (opening approximately 85 mm). The production CiPPT is designed, for example, to investigate the strength properties of peat beneath existing railway embankments in use for traffic, by first pre-drilling and installing a casing tube from above the track and then sounding beneath the casing tube.

Both variants (70 mm and 140 mm) of the CiPPT are based on standard CPT equipment and intended for 44 mm steel, where the CPT cone (15 cm^2) is replaced with the CiPPT device, as shown in Figures 6–8. The CiPPT sounding works by pushing a horizontal plate on the probe vertically downwards at a constant speed. For pore pressure measurement, a normal pore pressure transducer from the CPT probe is used, and at the center of the CiPPT bottom plate, a bronze filter is placed (see the orange-brown colored bronze filter in Figures 6–8).

When using the 70 mm CiPPT, the components of the CiPPT are mounted in place of the regular CPT cone, Figures 7–8. The 70 mm CiPPT has been developed with two different types of end surfaces:

One with pins and one with a flat surface on which an anti-slip mat has been glued to create roughness in the interface between the probe and the fibrous peat. Resistance is recorded on the horizontal surface of the CiPPT using the CPT equipment's point pressure sensor.

When installing the 140 mm diameter research CiPPT, the CPT probe's regular cone, in addition to the friction sleeve, needs to be removed and replaced with the CiPPT device, an "upside-down cone", as shown in Figure 8a. Resistance registration on the 140 mm CiPPT with a single plate is done in the same way as for the 70 mm CiPPT, i.e., with the point pressure sensor.

For the 140 mm CiPPT, there is also a variant with double plates, Figures 6 and 8, a so-called double-CiPPT, where the inner and outer plates have equal areas. The resistance when using the double plate function is recorded by the point pressure sensor (inner plate) and the friction sensor (outer plate).

The purpose of the double-CiPPT and the outer plate is to study the impact of fiber effects in peat. Low- and medium- humified peat contains fibers of various lengths and arrangements, which contribute to increased strength and stiffness under load. The hypothesis is that when pressing the CiPPT downwards, the fiber effect will generate increased resistance (pressure) on the outer surface of the CiPPT bottom plate due to tensile stresses in the peat at and just outside the edge of the plate, thereby activating the tensile strength of the peat in that zone.

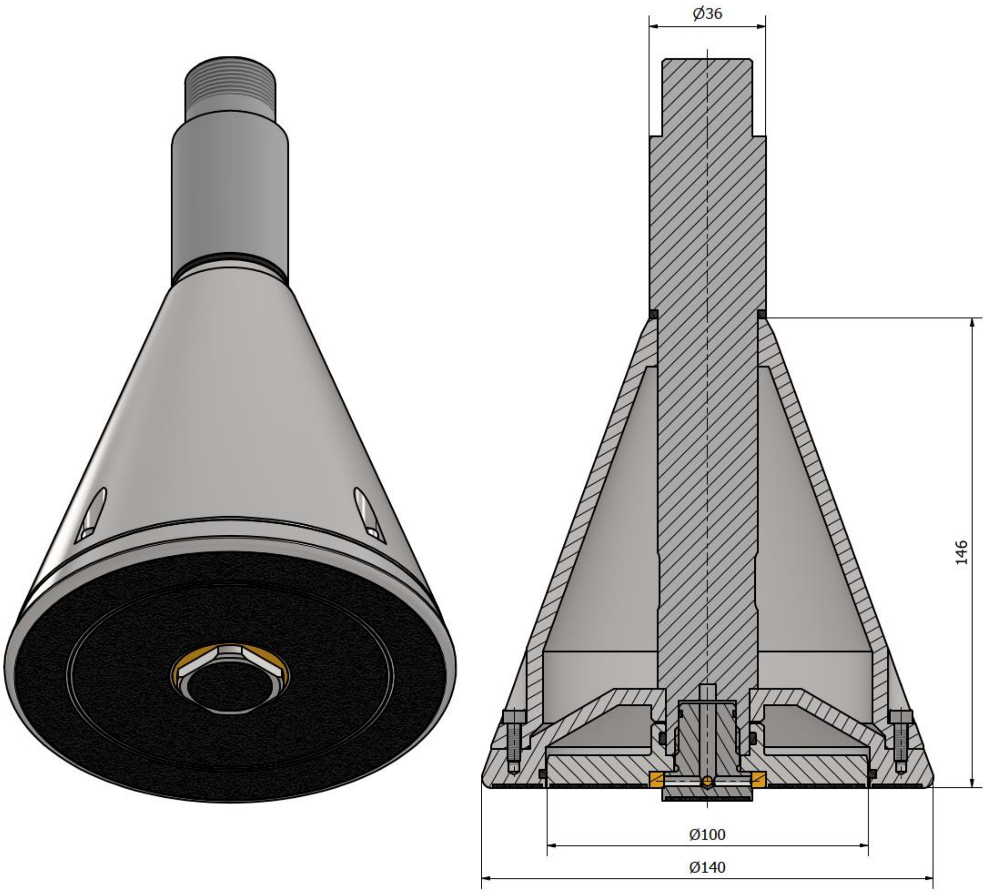


Figure 6. Drawing of double-CiPPT 140 mm diameter with a rough surface.

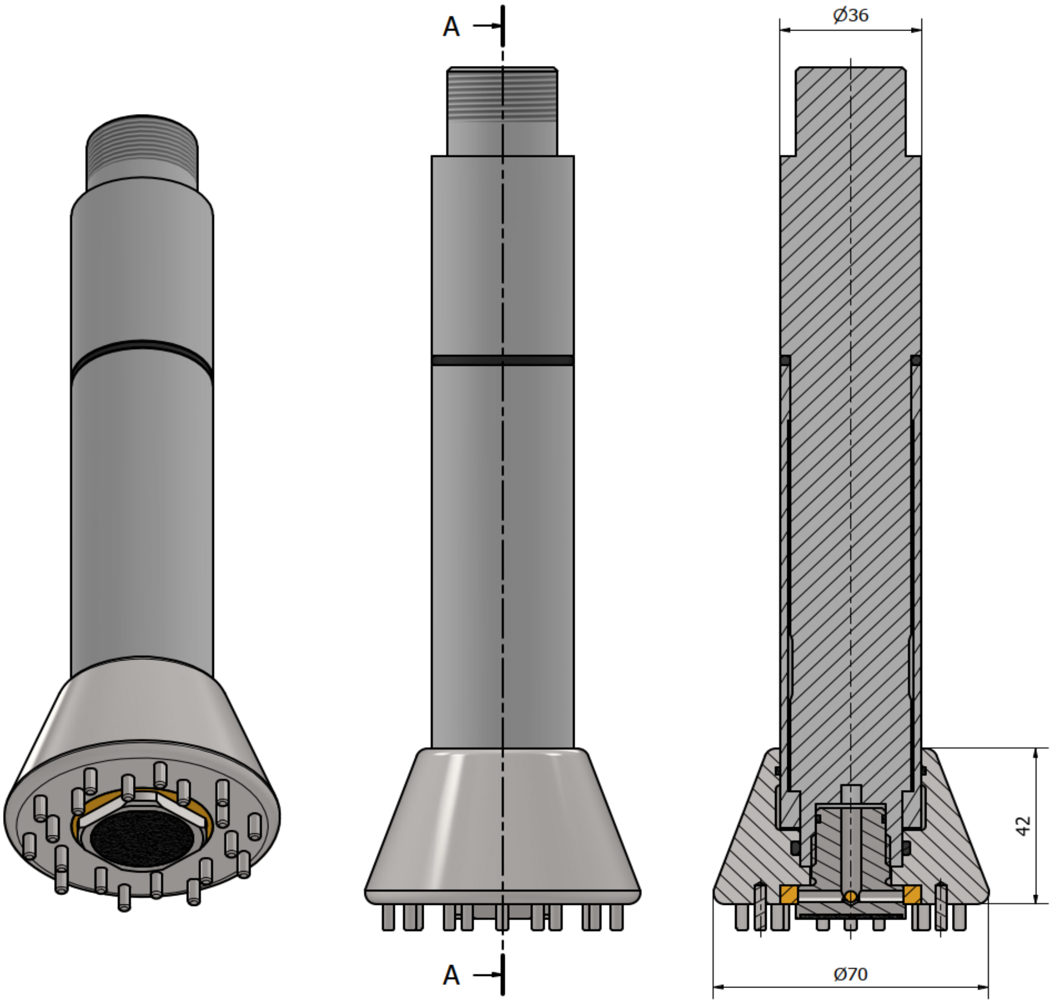


Figure 7. Drawing of CiPPT 70 mm diameter with pins.

a) b)

Figure 8. a) Four different end surfaces (140 mm or 70 mm diameter) of CiPPT and the cone for 140 mm, and b) Double-CiPPT assembled for testing.

4. Methods

Studies have been conducted at three field sites, both in peat below embankment and in peat within the bog beside the embankment, in order to compare results from natural not loaded (not compressed) peat with those from during long time loaded (compressed) peat [8]. The embankments were excavated down to just above the peat layer in order to take peat samples and to conduct soundings. In the field, soundings were carried out with various variants of CiPPT as well as with T-bar, CPT, and field vane tests, and sampling was performed using SGI's 100 mm diameter peat sampler [10]. Laboratory tests included undrained active triaxial tests as well as determining the degree of humification (H class according to von Post [9]), water content, and density. The von Post classification system divides the degree of humification of peat from H1 to H10, where H1 is non-humified peat and H10 is completely humified peat, and the classes grouped with H1 to H4 denoted as low humified, H5–H7 medium humified, and H8–H10 high humified peat.

All field tests were conducted according to standard procedures, and for CiPPT and T-bar, the standard CPT penetration speed of approximately 2 cm per second was used. The triaxial tests were performed with so-called friction-free ends (see e.g., [11]), but otherwise, according to standard procedures.

To translate measured sounding resistance in the field from CiPPT, T-bar, and CPT to strength in peat, the results were calibrated against measured strength from laboratory tests. In this study, undrained active triaxial tests, shear strength evaluated as the shear stress at 15% axial strain, were used as reference tests for shear strength. This was mainly because active loading most closely resembles the vertical penetration (loading) that occurs during sounding with CiPPT and T-bar, among available standard laboratory tests. The K_0 (horizontal effective stress divided by vertical effective stress) applied at the consolidation phase in the triaxial tests most often was between 0.20–0.60. The point pressure (minus the vertical total stress) obtained from the three sounding methods was corrected with a chosen constant value, the N_{kt} factor, to match the strength values from the triaxial tests. Peat from the bog beside the embankment (natural not loaded) and peat from beneath the embankment (loaded by the overlying embankment) were studied.

For peat from the bog, shear strength was evaluated from triaxial tests with low effective stresses, approximately 7 kPa vertical effective stress during consolidation, and used as reference values. For peat from beneath the embankment, the prevailing vertical effective stresses at the top of the peat layer were calculated based on the pressure from the overlying embankment and the position of the groundwater level. Based on these calculated vertical effective stresses and an assumed or determined earth pressure coefficient K_0 value for determining horizontal effective stresses, samples from beneath the embankment were consolidated to between 28–45 kPa vertical effective stress, varying between the three sites, before the shear phase. Furthermore, the shear strength from the active triaxial tests at larger strains, 15% axial strain, was evaluated, as failure in field tests occurs at large movements (deformations). The chosen shear strength value from triaxial tests on peat beneath the embankment was based on multiple tests at each site.

5. Results and discussion

5.1. CiPPT—Penetration resistance in peat within a bog

When sounding with CiPPT in peat within a bog at the three field sites, the penetration resistance (point pressure) reaches a clear maximum value between 0.2–0.5 meters depth, as shown in figures 9a-c. Immediately after the maximum value, the penetration resistance decreases significantly over the next approximately 0.2 meters of penetration. After that, the penetration resistance generally decreases slightly with depth or remains roughly constant (fluctuating around an average value). There are smaller depth intervals where the penetration resistance varies locally, for example, it increases slightly before decreasing again, or it decreases significantly, with some difference in these small local variations between the different field sites. The penetration resistance at the bottom of the peat layer within the bog is approximately the same at all three sites, around 100 kPa.

The degree of humification generally increases with depth at the studied sites Kärrbäck and Oja, from H2 to H4/H5 and then to H9 at the bottom, which explains the decreasing penetration resistance with depth in peat within the bog. At the Missenträsk site, the peat is classified as H2 down to about 1.5 meters depth. The decreased water content at 1.5 meters depth and the variation in penetration resistance with depth suggests that the peat likely transitions to H3–H5 below that.

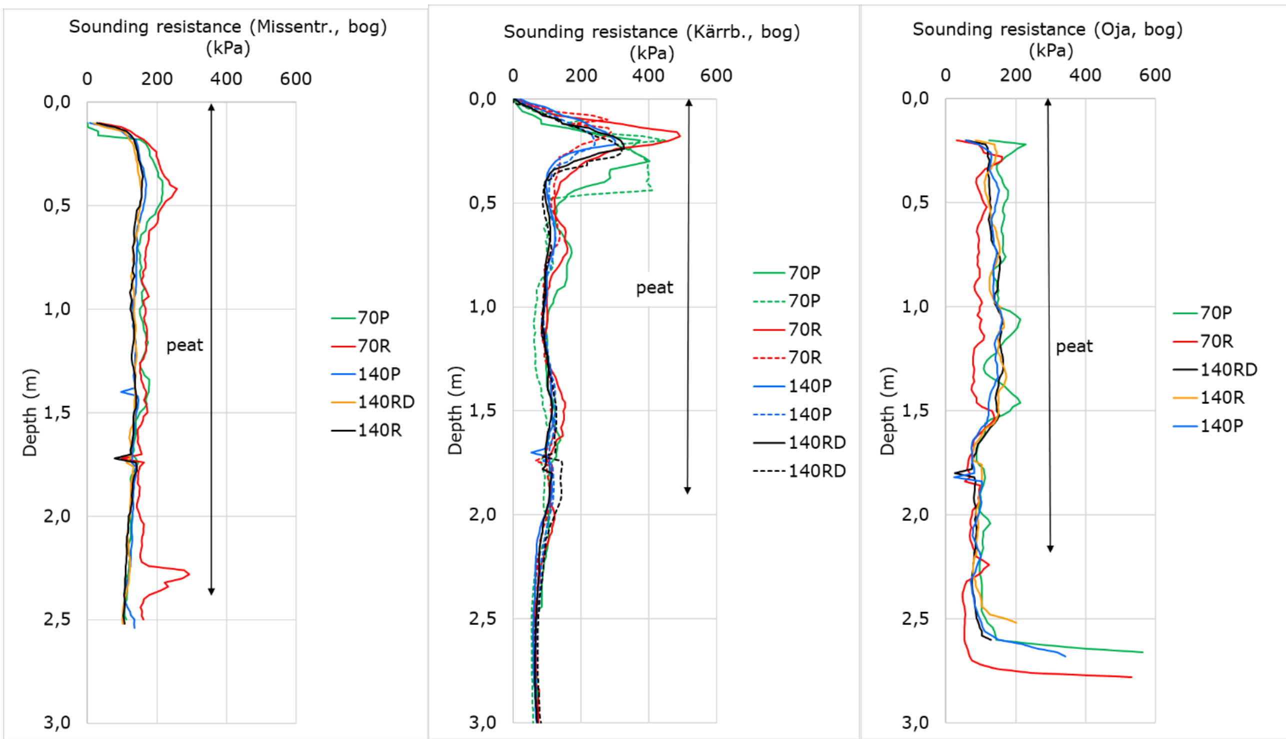
In the peat profile within the bog, effective stresses are relatively constant with depth and essentially zero due to the density being about 1.0. Therefore, variations in effective stress with depth are not expected to affect penetration resistance. A larger amount of fibers, and particularly more long fibers, expected for peat with a lower degree of humification, is expected to result in higher penetration resistance (and strength) during sounding than for more decomposed peat. It is common for this decrease in penetration resistance with depth, as shown at the three sites, to occur in previously natural not loaded peat and is often linked to an increasing degree of humification with depth [12].

The variation in penetration resistance in peat within the bog from around 0.5 meters and downwards, i.e., after the maximum value has been reached, is linked to variation in humification degree. For example, at 1–1.5 meters depth, the degree of humification is H2 in Missenträsk and Oja with penetration resistance around 150 kPa, and at the corresponding depth, H4 in Kärrbäck with penetration resistance around 100 kPa. In the Kärrbäck site, the penetration resistance shows two local maximum values at around 0.7 and 1.5 meter depth respectively, indicating lower humification in these zones compared to the peat above and below. In the Oja site, penetration resistance decreases significantly between 1.5–1.6 meters depth, which suggests that the degree of humification increases.

5.2. CiPPT—Penetration resistance in peat below embankment

When sounding with CiPPT in the peat below the embankment, the penetration resistance (point pressure) reaches a distinct maximum value at a depth of 0.1–0.2 meters, as shown in Figure 10a-c. Immediately after the maximum value, the penetration resistance decreases significantly over the next 0.1–0.2 meters of penetration. After that, penetration resistance decreases with depth at the Missenträsk and Oja sites. At the Kärrbäck site, however, a high penetration resistance is observed throughout the peat layer under the embankment, with two local maximum values: One at the top and one at the lower part of the peat layer.

The size of the penetration resistance (point pressure) and its variation with depth in the peat under the embankment is affected by the degree of humification at each depth and by the weight of the overlying embankment (or more precisely, the vertical effective stress at the top of the peat layer). The variation in the degree of humification in the peat under the embankment is, as expected, about the same as in the peat within the bog.



a) b) c)

Figure 9. Sounding resistance of different CiPPT in peat on bog, a) Missenträsk, b) Kärrbäck, and c) Oja. Legends for CiPPT: 70/140 = 70/140 mm diameter, P = pins, R = rough, D = double plate (combined).

For peat below the embankment, penetration resistance generally decreases with depth (after the maximum value at the top). There has also been a significant increase in penetration resistance in the lower part of the peat layer below the embankment compared to the not loaded peat beside the embankment within the bog. The increase in penetration resistance in the peat below the embankment, compared to the penetration resistance in the peat within the bog, is approximately the same in both the upper and lower parts, at all three sites. The largest increase in penetration resistance (around 6–7 times) occurs under the heaviest embankment (Kärrbäck) and the smallest increase (around 3 times) occurs under the lightest embankment (Missenträsk). This suggests that the stress increase is approximately the same throughout the peat layer below the embankment and that the degree of humification, which varies between H2–H5 (H9) in these three sites, does not significantly affect the *increase* in penetration resistance (strength) in the peat below the embankment.

The maximum value of the penetration resistance from CiPPT obtained in the top decimeters of the peat both below and outside the embankment is due to the fiber effect in the peat causing a deformation pattern in the peat below and next beside the CiPPT, as the form or contour of a hammock, when the peat starts to be loaded. This is similar to what was identified in previous model tests [7]. When the maximum penetration resistance is reached, the fibers are pulled apart and/or broken, and with further penetration, the hammock shaped deformation pattern diminishes and the penetration resistance decreases. The impact of the hammock type of deformation on penetration resistance is especially clear in peat within the bog, where the effective stresses are essentially zero, and the peat has not been previously loaded. Furthermore, the upper part of the peat within the bog generally contains a higher proportion of longer fibers (not decomposed as much as further down in the peat profile), which also contributes to the higher penetration resistance in the top zone.

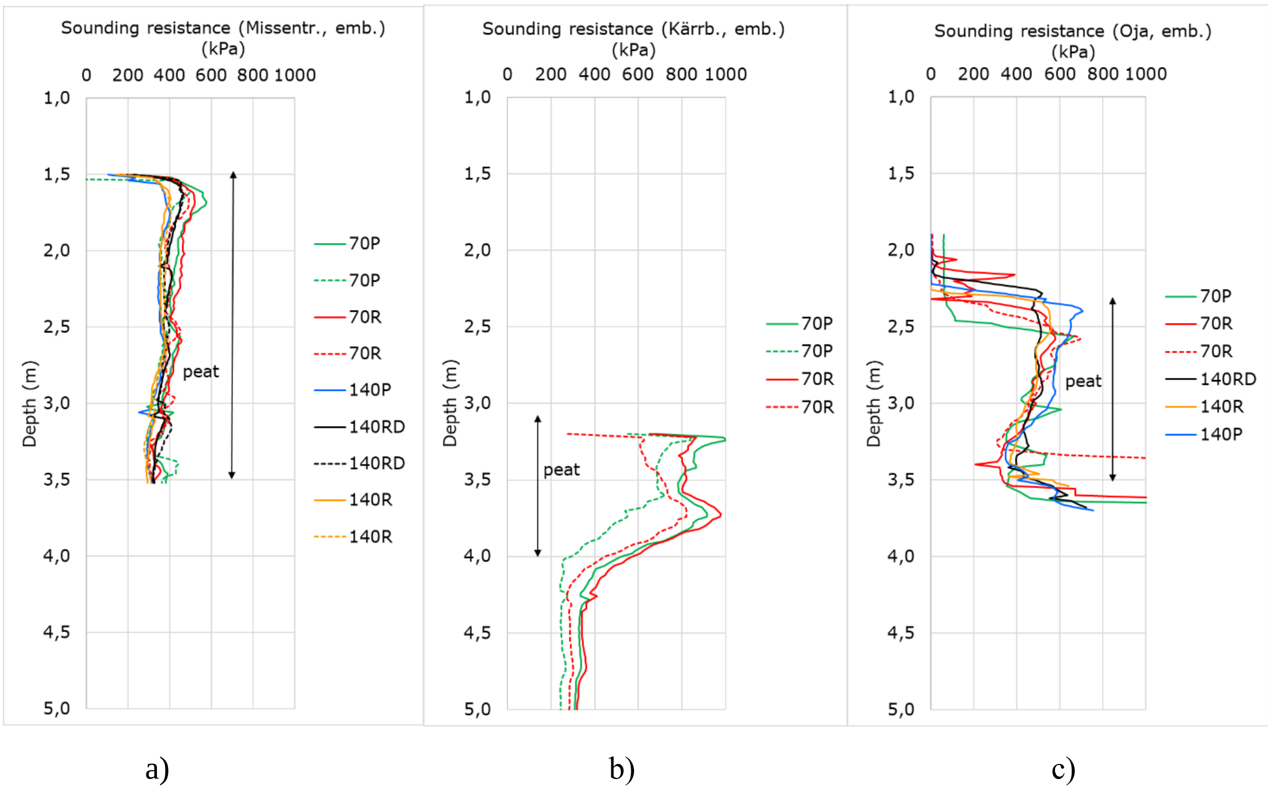


Figure 10. Sounding resistance of different CiPPT in peat below embankment, a) Missenträsk, b) Kärrbäck, and c) Oja. Legends for CiPPT: 70/140 = 70/140 mm diameter, P = pins, R = rough, D = double plate (combined).

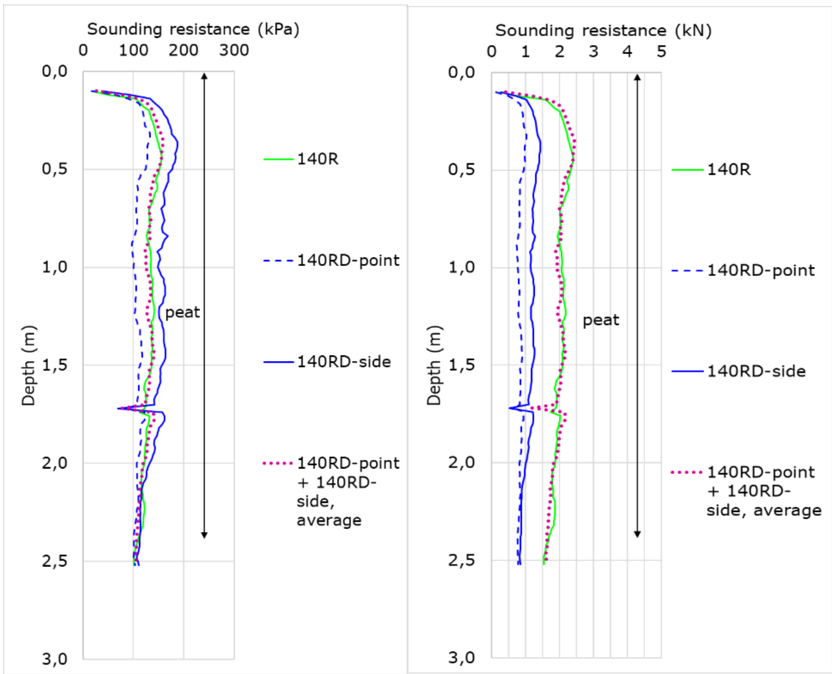
5.3. Double-CiPPT—Penetration resistance in peat

Figures 11a-b show results from the Missenträsk site using double-CiPPT and CiPPT (single plate, 140 mm) from sounding in not loaded peat within the bog beside the embankment. When sounding with double-CiPPT, the outer plate shows higher penetration resistance than the inner plate. When the pressure or force from the outer and inner plates is combined, a penetration resistance is obtained that matches well with that from the single plate sounding. These results verify the functionality of the double-plate CiPPT and confirm the hypothesis that the tensile strength of the peat contributes to the increased penetration resistance during probing with CiPPT.

In Figure 12a, results from sounding with double-CiPPT in peat below the embankment at Missenträsk are presented, and in Figure 12b, sounding in peat within the bog at Kärrbäck is presented.

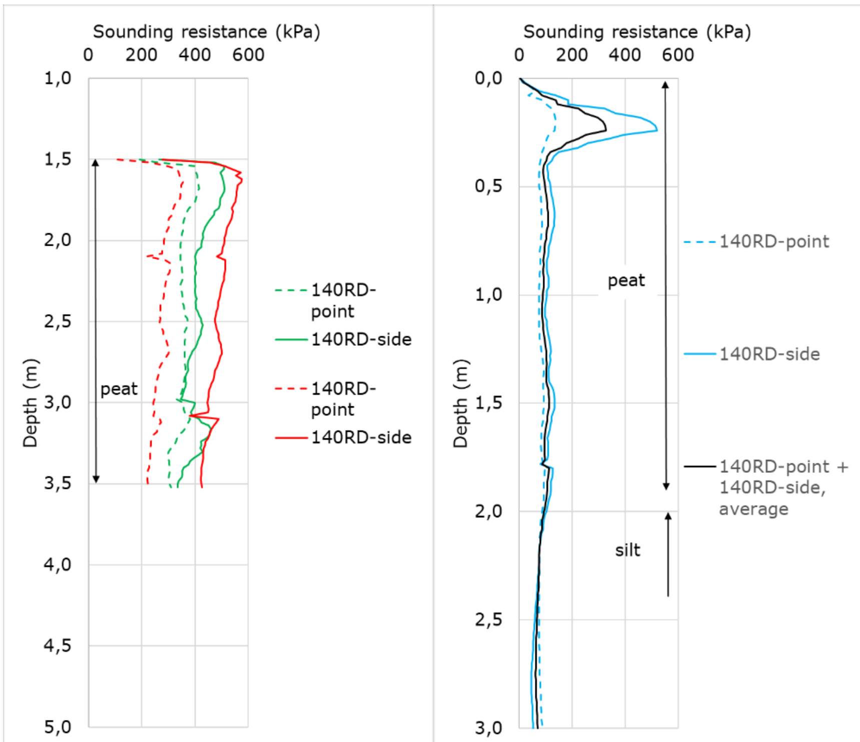
For the variation in side pressure (outer plate) and point pressure (inner plate) with depth for double-CiPPT performed at the three sites, it can be stated that:

- The side pressure decreases in the bog only in the lower part of the peat layer, around 0.5–1.0 meters from the bottom of the peat, and above that, it remains relatively constant (with local variations). This is interpreted as the fiber effect (side pressure) reduces first at greater depths. In the lower part of the peat layer, the side pressure has decreased that much to be the same as the point pressure.



a) b)

Figure 11. Sounding resistance of double CiPPT and single CiPPT in peat on bog at Missenträsk, a) Pressure (kPa) and b) Force (kN). Legends for CiPPT: 140 = 140 mm diameter, R = rough, D = double.



a) b)

Figure 12. Sounding resistance of double CiPPT, a) in peat below embankment at Missenträsk and b) in peat on bog at Kärrbäck. Legends for CiPPT: 140 = 140 mm diameter, R = rough, D = double.

- Point pressure is generally relatively constant with depth for peat within the bog but may decrease at the very bottom of the peat layer (likely due to a higher degree of humification).
- The side pressure decreases slightly or remains constant at certain depth intervals for peat below the embankment.
- Side pressure and point pressure follow approximately the same variation with depth for peat below the embankment, and the difference between them is roughly the same throughout the entire peat layer. This is a clear difference compared to the response when sounding with double-CiPPT in peat within the bog.

When sounding with double-CiPPT in peat within the bog, and continuing into the underlying sulphide silt at Kärrbäck, the side pressure (outer plate) is clearly smaller than the point pressure (inner plate) in all three soundings at Kärrbäck (one sounding is shown in Figure 12b), i.e., the opposite compared to the response in the overlying peat. This shift in pressure distribution in double-CiPPT seems to indicate different deformation and failure mechanisms in silt compared to the overlying peat layer.

5.4. *Impact of surface roughness on CiPPT response*

Generally, no clear differences in penetration resistance were observed between CiPPT with a rough surface and CiPPT with pins, both for not loaded peat within the bog and loaded peat below the embankment, for large and small CiPPT. However, what often differs is that when sounding in the top part of the peat, a slightly higher maximum value of penetration resistance is obtained with pins. This suggests that, during penetration of CiPPT, a larger part of the peat's tensile strength is directly activated when pins are used, i.e., the peat gets stuck in the pins, and the resistance during penetration increases.

5.5. *Impact of size on CiPPT response*

The small CiPPT (70 mm) gives a higher penetration resistance than the large CiPPT (140 mm) in the upper part of the peat within the bog. Sounding in peat below embankment there is a similar difference between the small and large CiPPT below the lowest embankment (Missenträsk), but no actual difference below the middle highest embankment (Oja). Below the highest embankment (Kärrbäck) only sounding with 70 mm CiPPT was possible.

The higher penetration resistance observed for the small CiPPT compared to the large one is due to a larger contribution of fiber tensile strength at the edge of the CiPPT to the total penetration resistance. This is a result of the perimeter-to-area ratio being higher for the smaller CiPPT, leading to a greater contribution to penetration resistance (strength) along the edge (perimeter).

5.6. *Strength—Calibration of CiPPT sounding results and comparison with other in situ methods*

The measured penetration resistance (point pressure, minus the vertical total stress) from CiPPT, T-bar, and CPT was divided by a factor (constant value, denoted N_{kt}) to obtain a corresponding strength value derived from active undrained triaxial tests at 15% axial strain. For CiPPT, a single N_{kt} value was determined for the three test sites. For T-bar and CPT, a separate N_{kt} value was established for each site to achieve the best match with triaxial tests for peat in bogs and under embankments, respectively. Figure 13a-c (peat from bogs) and Figure 14a-c (peat below embankments) present the results of this calibration. These figures also illustrate and enable comparisons of strength variation (and corresponding penetration resistance) with depth across the different in situ methods.

For peat within a bog, the N_{kt} factor was evaluated for all three sites collectively as 15 for CiPPT (Figure 13a-c). With the selected N_{kt} factor, the strength values from CiPPT align well with the active triaxial tests at all three sites. For T-bar, however, the evaluated N_{kt} factor varied significantly between the sites and was 15 in Missenträsk, 29 in Kärrbäck, and 20 in Oja, for peat within the bog.

For CPT, a separate N_{kt} factor was determined for each site: 19 in Missenträsk, 20 in Kärrbäck, and 27 in Oja, for peat within bogs. Thus, CPT showed approximately the same factor at two sites and a significantly higher factor at one site. The factor for CPT was higher than for CiPPT. This corresponds to the penetration resistance for CPT being slightly higher or higher than that for CiPPT at all three sites.

In Figure 13a-c results from field vane shear tests are included and adjusted with a correction factor of 0.5 (which is a standard correction factor used in many countries, a low chosen value due to uncertainties regarding the relevance of the method in fibrous peat (see chapter 1)). The field vane tests qualitatively follow the other sounding methods in terms of strength variation with depth in peat from bogs. With the correction factor of 0.5, the obtained strength values are higher in one site (Missenträsk), slightly higher in another (Oja), and slightly lower in Kärrbäck, compared to CiPPT for peat within bogs. These results are consistent with previous experiences of using field vane tests for strength determination in countries such as the Netherlands, Ireland, and Sweden. That is, field vane testing can approximately capture the variation of strength with depth, but the reliability of absolute strength values varies between sites.

For peat below embankments, the N_{kt} factor was evaluated as 11 for CiPPT and 10 for T-bar, Figure 14a-c. T-bar tests could only be conducted under the embankment at one site. With the selected N_{kt} factor, the strength values (mean of different soundings) from CiPPT align well with the active triaxial tests at all three sites, although they may be slightly underestimated in Kärrbäck. For T-bar, the chosen N_{kt} factor showed good agreement with CiPPT at the one site where it was tested under an embankment.

For CPT, the N_{kt} factor was determined separately for each site, yielding 14 in Missenträsk, 15 in Kärrbäck, and 18 in Oja for peat below embankments. This means that CPT had approximately the same factor at two sites, a higher factor at one site, and an overall higher factor than CiPPT. This suggests that penetration resistance under embankments is similar, slightly higher, or significantly higher when CPT is compared to CiPPT across the three sites.

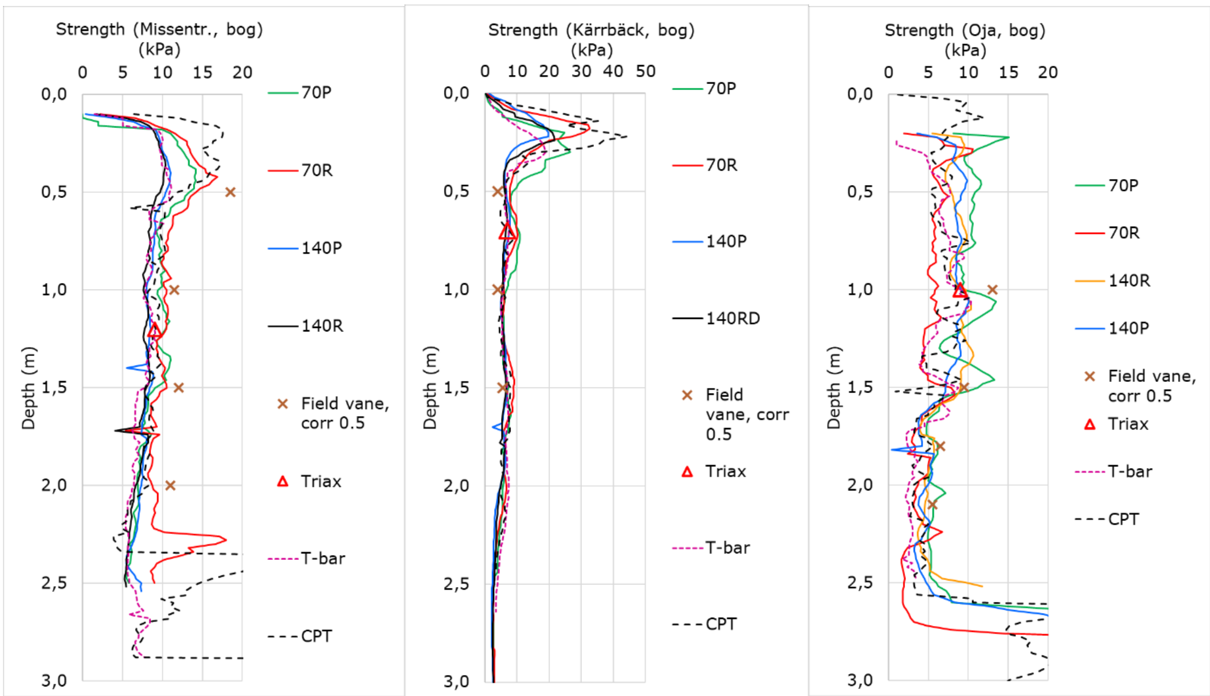
Figure 14a-c for peat below embankments also include results from field vane shear tests, adjusted with a correction factor of 0.5. The field vane tests follow the trends of the other methods at Missenträsk but not at Oja (at Kärrbäck, only one depth was investigated). With the correction factor of 0.5, the obtained strength values under embankments are much lower in Kärrbäck, lower in Missenträsk, and both lower and higher in Oja, compared to CiPPT. For loaded peat below embankments, the strength values from field vane shear tests show greater variation than for peat within bogs.

The obtained N_{kt} values for CiPPT for peat within bogs and below embankments indicate that different correction factors are required for natural not loaded peat and loaded peat, respectively. However, the N_{kt} factor does not appear to vary for peat under embankments regardless of the magnitude of weight of the embankment and, therefore, regardless of the magnitude of the penetration resistance.

This far, no correction has been applied to the CiPPT point pressure for measured pore pressure, partly because such a correction would only adjust strength values by a maximum of 0–2 kPa in bogs and up to 5 kPa below embankments. Furthermore, there is some variability in pore pressure response across the different sites, though it often follows a similar depth variation pattern as point pressure and especially for peat in bogs. There was also a general difference with higher generated pore pressures with the CiPPT than with the CPT. Further development of CiPPT (and other field methods) result interpretation needs to include drainage conditions and to determine if and how pore pressure should be analysed and accounted for. Comparison of strength (and penetration resistance) between different field sounding methods indicate that T-bar, CPT, and field vane shear tests roughly and generally provide similar variations in strength with depth as CiPPT, for both peat within bogs and below embankments. All these methods can thus roughly or more accurately measure variations in peat strength with depth.

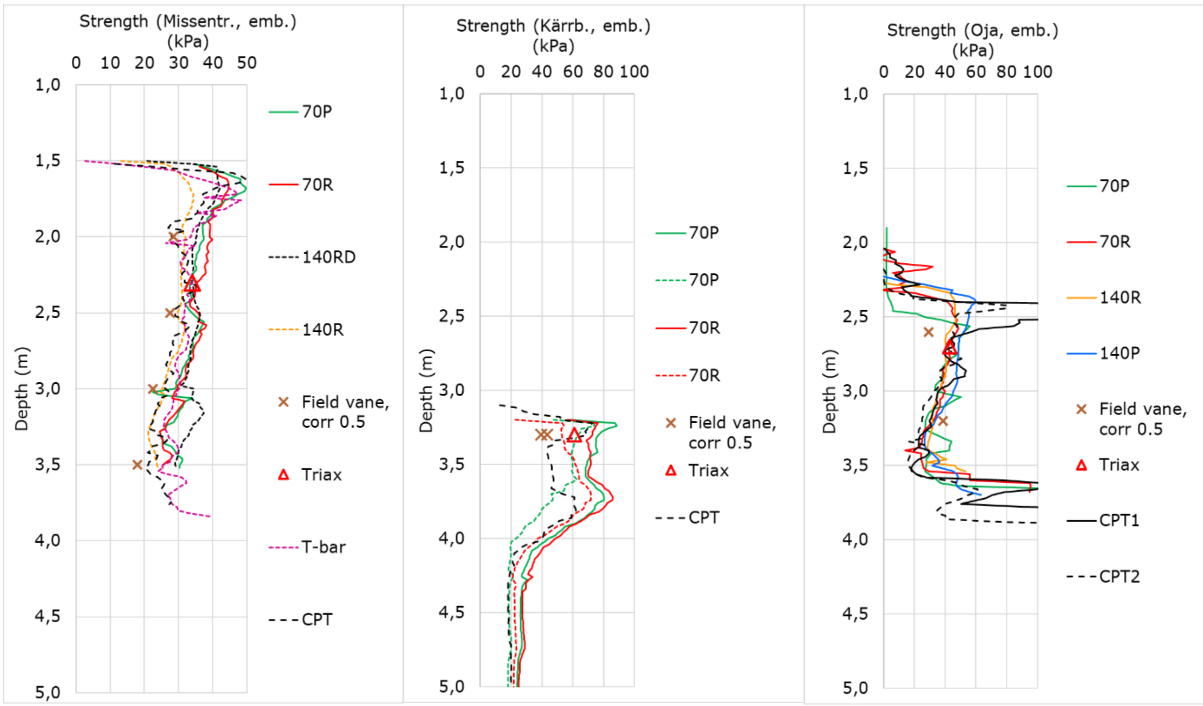
However, regarding the prediction of numerical strength values at different sites, CiPPT provides the best overall agreement with the reference strength, particularly for peat below embankments.

Based on this dataset from three field sites, CiPPT is the field method that delivers the most consistent and reliable results among the tested methods in describing both the variation and size of strength with depth in not loaded peat in bogs and loaded peat below embankments. However, additional studies at more sites with different conditions and peat characteristics and using various field methods are necessary to expand the experimental dataset.



a) b) c)

Figure 13. Strength from CiPPT, T-bar, CPT, field vane tests, and a triaxial test in peat within bog, a) Missenträsk, b) Kärrbäck, and c) Oja. Legends for CiPPT: 70/140 = 70/140 mm diameter, P = pins, R = rough, D = double.



a) b) c)

Figure 14. Strength from CiPPT, T-bar, CPT, field vane tests and triaxial test in peat below embankment, a) Missenträsk, b) Kärrbäck, and c) Oja. Legends for CiPPT: 70/140 = 70/140 mm diameter, P = pins, R = rough, and D = double.

6. Conclusions

We present a newly developed and tested method, CiPPT (Circular Probe Penetration Test), and its variants, for sounding and strength determination in peat. We include investigations at three field sites in low- and medium- humified peat.

From the results, the following conclusions are drawn:

- CiPPT, when connected to a conventional CPT measurement system where the CPT probe is replaced with the CiPPT probe, functions well in measuring point pressure and pore pressure.
- CiPPT is a method for measuring variations with depth of penetration resistance and strength in peat.
- With double CiPPT, which has an inner and outer plate measuring penetration resistance, the influence of peat fibers and tensile strength can be studied. This experimental setup helps explain the behaviour and the variation of penetration resistance with depth when sounding in peat within bogs and below embankments.
- A certain effect of the scale factor between the small (70 mm diameter) and large (140 mm diameter) CiPPT is observed on the measured penetration resistance, though mainly in the upper part of the peat layer. This is linked to the influence of fiber tensile strength and the perimeter-to-area ratio of the two CiPPT variants.
- There is no significant difference in penetration resistance between CiPPT with pins and CiPPT with a rough surface.
- With the proposed correction factors for measured penetration resistance, CiPPT reliably

reproduces the selected reference strength at the three test sites, both for not loaded peat within bogs and loaded peat below embankments. The correction factor for CiPPT-soundings has been evaluated as 15 for peat within bogs and 11 for peat below embankments, for a reference strength assessed from active undrained triaxial tests at 15% axial strain.

- Compared to the other in situ methods used in the study, T-bar, CPT, and field vane tests, CiPPT provides more reliable results regarding the description of strength variation and size in peat, both within bogs and below embankments.
- With the production CiPPT, i.e., the small CiPPT, the strength under existing railway embankments in operation can be studied through pre-drilling followed by sounding. This can serve, for example, as a basis for stability calculations of the current conditions or for a future load increase on the railway.
- The experimental data is limited to three test sites and a restricted number of trials with CiPPT and the other field methods. Therefore, further investigations at other locations are needed to verify the generality of the results and comparisons between different field methods. Furthermore, the possible effects on the results of conducting tests different than according to standard procedures, e.g., the penetration rate in situ, including drainage conditions, should be investigated. Further development of CiPPT result interpretation will determine if and how pore pressure should be analyzed and accounted for.

Author contributions

All of the authors belong to the peat research group at the Swedish Geotechnical Institute, and have contributed widely to the development of the new method CiPPT and to the paper. M. Andersson was mainly responsible for conducting the field work. D. Rudebeck focused on the theoretical parts of the work. F. Burman mainly designed the CiPPT. M. Holmén focused on the laboratory work. B. Vesterberg was the main author of the paper and prepared the figures

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Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflict of interest.

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