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Potential of cone penetrating testing for mapping deeply buried palaeolandscapes in the context of archaeological surveys in polder areas

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ABSTRACT

Geoarchaeological mapping of wetlands conventionally involves extensive coring. Especially in wetlands marked by a deep palaeosurface (>3 m deep) this can be very difficult and time-consuming. In this paper we therefore present an alternative approach based on Cone Penetration Testing (CPT) for structured, rapid and cost-effective evaluation of buried palaeolandscapes. Both estuarine and river floodplain environments were investigated, including the water–land transition zone (marsh). The efficiency, reliability and repeatability of the CPT method was tested through the comparison with ground-truth core data. The CPT data generally allowed highly accurate mapping of the palaeotopography of the prehistoric surfaces and the overlying peat sequences. Thin organic-rich clay intercalations within the peat layers could often still be identified. Additional pore pressure, conductivity and seismic velocity data (from CPT-U, CPT-C and S-CPT) did not add much crucial information and their main use seems to lie in the added value for near surface geophysical measurements. The results of this research clearly illustrate the importance of CPT information for mapping of palaeolandscapes in archaeology.

1. Introduction

The potential of wetlands, estuarine and riverine areas for understanding past human exploitation and palaeolandscapes has been demonstrated by many studies (Bell, 2007; Rippon, 2000; Coles, 1987). These areas are often marked by thick peat deposits known to be a rich source of archaeological and palaeoenvironmental information since they often include ecofacts and artefacts that are generally not preserved in other, dryland contexts (Coles, 1987). However, wetlands are also very complex and dynamic environments and understanding the processes of sedimentation and erosion is crucial in order to detect and study archaeological sites (Howard and Macklin, 1999).

Geoarchaeological mapping of wetlands usually involves two main phases (Groenewoudt, 1994; Tol et al., 2004; Bats, 2007; Bats and Crombé, 2007; De Clercq et al., 2011; Crombé and Verhegge, 2015). A first, crucial phase concerns the detailed mapping of the

sealed palaeoenvironment, especially the palaeotopography, and its evolution (i.e. preservation) through time and in relation to the sediment dynamic regime. In a second phase, based on these results, directed archaeological surveys can be carried out on specific locations in view of detecting buried archaeological sites. Previous research in the coastal and riverine wetlands of N Belgium (Crombé, 2002, 2005) and the Netherlands (Peeters, 2007) has shown that most prehistoric occupation sites are situated right below the peat on former higher Pleistocene grounds (river dunes, levees, scroll bars, etc.) and often along open water systems (river channels, creeks), whereas younger settlement sites are usually situated on top of the peat and in the covering clay sediments. Therefore detailed mapping of the peat deposits is crucial in order to reconstruct the palaeorelief and hence to locate potential archaeological zones and levels within this buried landscape.

Until now geoarchaeological and palaeoenvironmental mapping on land has commonly been achieved through manual coring and to a lesser extent by mechanical drilling set in narrow and fixed grids or in transects (Groenewoudt, 1994; Bats, 2007). Manual cores, using 3 cm gouge augers, are effective but very time-consuming, hard work and in the case of deeper layers (below 4–5 m) they are very difficult to obtain and seldom successful. In

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addition manual drilling below groundwater level and/or through certain sediments, such as coarse sands or woody peat, can be seriously hampered by the sediment texture or presence of large organic matter. Mechanical drillings (e.g. Sonic drill, Aqualock, Begemann) on the other hand are less affected by these problems but they are slow and the high costs can be a serious burden (Hissel et al., 2005). Furthermore palaeotopographical modelling by interpolation of palaeosurface depth points often does not allow accurate delineation of geomorphological features, possibly containing archaeological sites, making this sampling strategy prone to errors. Additional methods must therefore be explored which are less expensive, faster and allow accurate correlation between coring points. Recent work in the UK (Bates et al., 2007) has shown the advantages of such a mixed method approach.

In the framework of a recent Flemish research project we have tried to develop an alternative approach that allows structured, rapid and cost-effective evaluation of the buried palaeolandscape in estuarine polder areas, including the water–land transition zone. This approach focuses both on the (combined) use of near surface geophysical methods such as seismic, electrical, and electromagnetic survey (Verhegge et al., 2015, submitted for publication), as well as on geotechnical investigations such as Cone Penetration Testing (CPT). Near surface geophysical methods can be hampered by variations in groundwater salinity in combination with the presence of peat (Orbons, 2011), a clay-rich heterogeneous or contaminated top-soil and the burial depth of the prehistoric landscape. In these cases, CPT investigations may provide an answer. The CPT method has been in use for over 70 years in Belgium (Lousberg et al., 1974) and is commonly recognized as a fast, repeatable and economical method for site investigation, but up to now it has largely been neglected in geoarchaeological research, except for a few occasional studies (e.g. Bates and Stafford, 2013; Roozen et al., 2013; Brandenberg et al., 2009).

2. Aims of the study

The main goal of this study is to assess the potential of the electrical CPT method for the palaeotopographical and palaeoenvironmental reconstruction of deeply buried prehistoric landscapes in estuarine polder areas in Flanders. This does not only regard mapping the depth of possible occupation horizons, which are often related to transitions in the sedimentary environment, but also the nature of the different depositional layers (i.e. lithostratigraphy) (Amorosi and Marchi, 1999). This palaeotopographical and lithostratigraphic information is crucial for subsequent archaeological prospection as it will allow efficient sampling at the correct location and depth of possible archaeological sites locations.

Two study-areas within the Scheldt valley of NW Belgium were chosen as test sites (Fig. 1): (1) the site of Doelpolder Noord located in the Waasland polders in the Lower Scheldt estuary, and (2) the alluvial site of Kerkhove located further upstream in the floodplain of the Middle Scheldt river. In both sites the base and top of the peat are known to be important reference horizons for (pre)historic occupation: the base of the peat reflects the relief of the underlying Pleistocene landscape (an important level for Stone Age sites), whereas the top of the peat is an important indicator related to more recent (early historic) occupation (Crombé, 2002, 2005; Bats et al., 2008). In addition, the Scheldt polders are threatened by the continuous expansion of the Antwerp harbour and imposed nature compensation through coastal realignment. Hence there is an urgent need for a detailed, rapid archaeological and palaeoenvironmental evaluation strategy. Therefore accurate mapping of the peat layers was crucial.

An important focus of this research is on the efficiency, applicability, reliability and repeatability of the applied CPT method. This is a.o. tested through the comparison with various ground-truth data (mainly shallow manual cores but also a few deeper mechanical cores) that were either available from previous (archaeological) investigations or newly obtained at the test site.

3. Shallow geology of the study area

The study area of Doelpolder Noord (Fig. 1) is located in the Lower-Scheldt polders in the NW of Belgium, near the Dutch border. The Tertiary geology here consists of a shelly sand (Formation of Lillo) and is covered by Late Pleistocene fluviatile sand
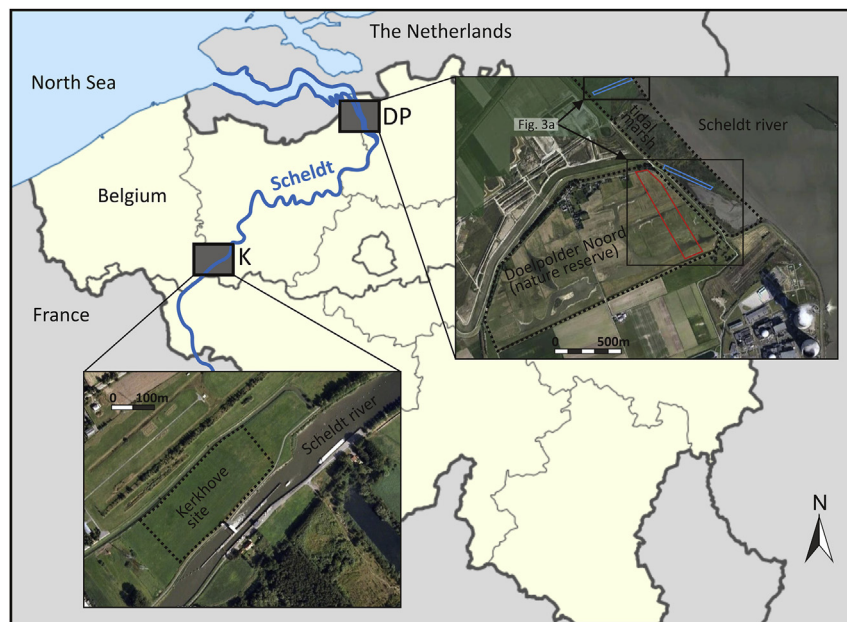
Fig. 1. Overview map of the site locations of Doelpolder Noord (DPN) and Kerkhove (K). The river Scheldt is marked in blue. Colour rectangles indicate the investigated areas in Doelpolder Noord (red: polder; blue: marsh). Aerial images © Agiv. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Bogemans, 1997; Jacobs et al., 2010a,b). These sandy deposits were reworked by wind activity in the Late Pleniglacial and Late Glacial, locally resulting in thick coversand ridges (Bogemans, 1997). In the lower depressions the sand is locally overlain by early Holocene deposits consisting of fluviatile fine sand or sandy clay deposits (Bogemans, 1997). During the Mid Holocene increased marine influence and rising ground water level changed the area into a large swamp, with the earliest basal peat growing from between 8345 and 7785 cal BP (Gilot, 1997). The lower regions were flooded by a peri-marine incursion starting between 6530 cal BP and 6410 cal BP (Verhegge et al., 2014) leading to the interfingering of (organic-rich) clay into the peat deposits (Kiden and Verbruggen, 2001; Kiden, 2006). Recent Bayesian chronological modelling of this (organic-rich) clay facies situates the restart of the peat growth between 6090 and 5770 cal BP (Verhegge et al., 2014). Late Holocene flooding turned the area into a tidal mudflat environment resulting in a thick layer of estuarine deposits consisting of an alternation of sandy and clayey sediments (Kiden and Verbruggen, 2001; Kiden, 2006).

Doelpolder Noord has been evaluated in recent years in the context of nature compensation works. According to an extensive handcoring campaign conducted in 2007 (Klinck et al., 2007), the buried coversand landscape in this area is well preserved. Our study focuses on a 100 m wide and 700 m long transect through the easternmost part, and the adjoining supratidal marsh (only flooded during spring tides) (Fig. 1). The study area contains a micro sand-ridge buried about 2 m deep which is flanked by an 8–9 m deep depression in the Pleistocene sands, and surrounded by an undulating palaeotopography of roughly 5–6 m deep.

The second test site is situated further upstream along the Middle-Scheldt river near Kerkhove (see Fig. 1). In the framework of planned construction works for a lock this site has recently been evaluated through a large number of shallow handcorings (Bats and Crombé, 2007). Similar as in Doelpolder Noord the site at Kerkhove contains a well preserved, palaeotopography marked by an elongated ridge, the top of which is buried at least 3 m deep. This late-Pleistocene natural levee is made up of (locally organic-rich) sandy clay deposits and flanked to the east by a depression 4–5 m deep, probably representing the onset of a palaeochannel of the Scheldt. The natural levee and the flanking depression are covered by a locally thick (>3 m) peat layer (Bats and Crombé, 2007). The overlying deposits consist of alluvial, organic-rich clay. Similar to Doelpolder Noord the peat layer is intercalated with peaty clay and/or organic-rich clay deposits (Bats and Crombé, 2007).

4. Archaeological background

The sites of Doelpolder Noord and Kerkhove are known to be very rich in archaeology. At both sites the late Pleistocene/early Holocene palaeolandscape is well preserved, and the local high topography make attractive locations for prehistoric occupation in the proximity of a river. Furthermore the relative deep burial depth of the palaeolandscape and the wet conditions allow for good conservation of the archaeological remains.

During the last decade various excavations in the direct vicinity of Doelpolder Noord have revealed a number of well-preserved prehistoric settlements, all located on the tops and flanks of the Pleistocene sand ridges (Crombé, 2005). The oldest remains date back to the Final Palaeolithic and Early Mesolithic (Crombé et al., 2011, 2013), when the landscape was still a largely dry environment. A series of sites dating back to the Mesolithic–Neolithic transition (Crombé, 2005; Sergant et al., 2006; Crombé et al., 2009) and attributed to the Swifterbant culture (Crombé et al., 2011), are contemporaneous with a period of increased tidal influence

(Verhegge et al., 2014). So far no direct archaeological evidence of human activity has been found that dates from the Middle Neolithic to the Middle Ages, when the area was a large peat marsh, but archaeological records from nearby locations in the Netherlands suggest that occupation took place even in these wet environments (De Clercq, 2009; De Clercq and Van Dierendonck, 2008).

Archaeological appraisal of the Kerkhove site dates back to the early 20th century when several prehistoric discoveries were made in the area (Claerhout, 1921a,b). Research in the 80's and 90's mainly concentrated on the dry river bank, yielding remains from the Mesolithic to early Medieval times (Crombé, 1985). Recent archaeological corings in 2007–2008 focused on the adjacent floodplain area and yielded numerous findings including lithic artefacts (burnt), animal bone remnants, hazelnut shells, and charcoal fragments (Bats and Crombé, 2007; Bats et al., 2008). The stratigraphic position of these finds suggests that the occupation of the site took place before the gradual inundation and formation of peat. Very little archaeological evidence was found in the overlying peat layer, although a nearby Roman and Merovingian site suggests a larger archaeological potential (Bats et al., 2008).

5. Materials and methods

5.1. General characteristics of CPT methodology

Cone Penetration Testing (CPT) is a geotechnical method to sound the composition of the subsurface. A cone on the end of a series of rods is pushed into the ground and (continuous or intermittent) measurements are made of the resistance of the cone tip (q_c) and the friction on the trailing sleeve (f_s) (Fig. 2). The technique generally allows fast and continuous profiling for subsurface sediment characterization and stratigraphical analysis. It is primarily aimed at fine-grained, relatively soft soils, as penetration can be difficult or restricted in hard layers such as gravel or compact sand (Lunne et al., 1997; Robertson and Cabal, 2012).

Additional sensors can be added to the cone. In piezocone penetrometer tests (CPT-U) also the in-situ pore pressure (u) is recorded, at the cone or just behind (Fig. 2a). Piezocone measurements are more time consuming than regular CPTs but the obtained pore pressure data may add valuable information on the presence of more, or less, permeable material within the soil matrix.

In conductivity (or resistivity) penetrometer tests (CPT-C) the electrical conductivity is also recorded, derived from the impedance between one or more pair(s) of electrodes attached to the sleeve section (Lunne et al., 1997) (Fig. 2b). Since the conductivity is related to various soil properties (e.g. water content, porosity, electrolyte content) this may give valuable information regarding the lithology (e.g. clay and organic matter will increase the conductivity). When working in estuarine environments one must keep into account that changes in salinity will have significant effects on the electrical conductivity. Since resistivity values are often comprised in overlapping ranges, interpretation is not straightforward and additional information will always be needed (Montafia, 2013). In dielectric cones also the electrical permittivity (dielectric constant) is obtained (Hilhorst, 1998). The latter is mainly used for contamination studies.

In seismic cone penetration tests (CPT-S) the sounding is combined with downhole velocity measurements using geophones installed into the cone rod (Fig. 2c–d). CPT-S measurements are often used to determine the soil deformation and bearing capacity (since these are related to the seismic velocities) but in our case we wanted to see if any valuable added information could be obtained regarding the presence of peat. According to Silva and Brandes
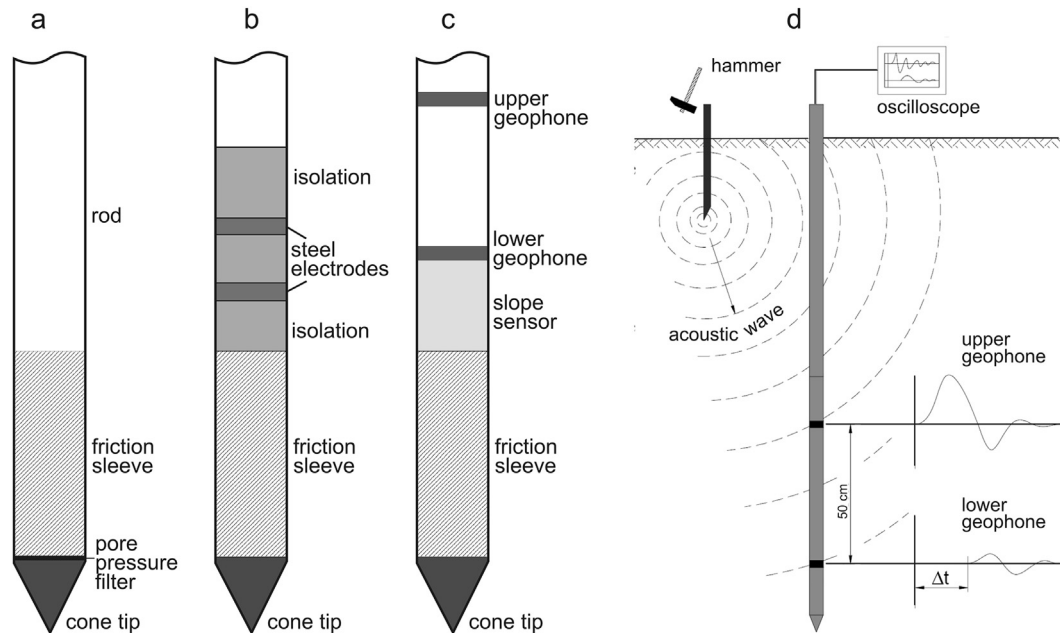
Fig. 2. Schematic diagrams of different CPT cones (a: piezometric cone; b: resistivity cone; c: seismic cone) and principle of seismic CPT measurements (d) (adapted after Lech et al., 2008).

(1998) peat will lower the acoustic velocity due to increased compressibility (organic matter absorbs water and causes clay particles to aggregate, creating an open structure that is weak and relatively easy to deform).

5.2. Soil classification and the identification of peat

Both tip resistance and sleeve friction are related to soil type and moisture content, and the ratio of sleeve friction and cone resistance (friction ratio R_f) can be used to classify the soil. The most widely used CPT soil classification (SBT) chart was suggested by Robertson et al. (1986) and an updated, dimensionless (normalized) version (Robertson, 2010). The normalization allows to compensate for the cone resistance dependency on the overburden stress, although for shallow depths (<30 m) this does not prove to be more advantageous (Fellenius and Eslami, 2000).

In the case of a uniform and well understood geology the predictions based on CPT results may be used singly for soil type identification. However this is rarely the case, and in practice CPT data must always be accompanied by data from boreholes, sampling and/or laboratory testing. This is especially the case for areas with variable and heterogenic geology (such as the present study sites) where interpretation of CPT data is not straightforward and ground-truth data are needed in order to verify local correlations (Lunne et al., 1997).

Automatic soil classification of peat for stratigraphic reconnaissance of polder areas is problematic, since most soil charts have difficulty in identifying peat and (organic) clay soils (Long and Boylan, 2012). Indeed how these are classified often depends on how fibrous or how amorphous the peat is (Landva et al., 1983; Long and Boylan, 2012). For instance fibrous peat, which has a higher net cone resistance than amorphous peat, may be classified as mixed silt and clay soil. Therefore, Vos (1982) suggest identifying peat for Dutch (polder) soils merely from the friction ratio (R_f > 5%). Results from comparable areas along the German coast (Lunne et al., 1997) and at Saeftinge, a vast tidal flat north of Doelpolder (Missiaen et al., 2008) largely seem to confirm this approach.

5.3. CPT data acquisition

CPT soundings were carried out in Doelpolder Noord and Kerkhove between 2011 and 2014. In Doelpolder Noord a staggered grid of 41 CPT-E as well as 5 CPT-U, 10 PT-C and 3 CPT-S were obtained in a 90 m wide transect; in addition 12 CPT-E were carried out in the adjoining tidal marsh on the outside of the dyke (Fig. 3a). In Kerkhove in total 12 CPT-E, 13 CPT-C and 5 CPT-U were performed in the same staggered grid as part of the existing hand-corings (Fig. 3b). The location of the non-gridded CPTs was determined by the palaeotopography, the subsurface layering (heterogeneity), available geophysical and ground-truth data, and the accessibility of the terrain.

For the CPTs in Doelpolder Noord (inside the dyke) and Kerkhove a conventional CPT truck was used, in the saltmarsh at Doelpolder Noord, a mobile CPT rig was used that was installed on a small tracked vehicle (Fig. 4a). Working on the marsh proved very risky due to hidden gullies and therefore only a limited number of soundings could be obtained here.

Measurement intervals for all CPTs were 2 cm, allowing a good vertical resolution. Piezocone measurements (CPT-U) involved a pore pressure sensor located just behind the cone. CPT-C measurements were performed with a dielectric cone (Frequency Domain method, 20 MHz) using 2 insulated electrodes (spaced 4 cm apart) located roughly 40 cm behind the cone. The seismic cone was equipped with two geophones (50 cm spacing). A heavy plate and sledge hammer were used to generate the seismic waves. Lateral offset between source (plate) and sensor (cone rod) was 120 cm. Both P (primary) and S (secondary or shear) waves were generated by hitting the beam in different directions (Fig. 4b). Measurements were carried out at depth intervals of 0.5 m. At each depth and for each direction between 4 and 8 hammer blows were recorded and stacked. Sampling frequency was set high enough to allow accurate velocity calculation in view of the small travel path.

5.4. Groundtruth data

In Doelpolder Noord three different ground-truth datasets were available (for location see Fig. 3a): (1) shallow hand cores (over 500
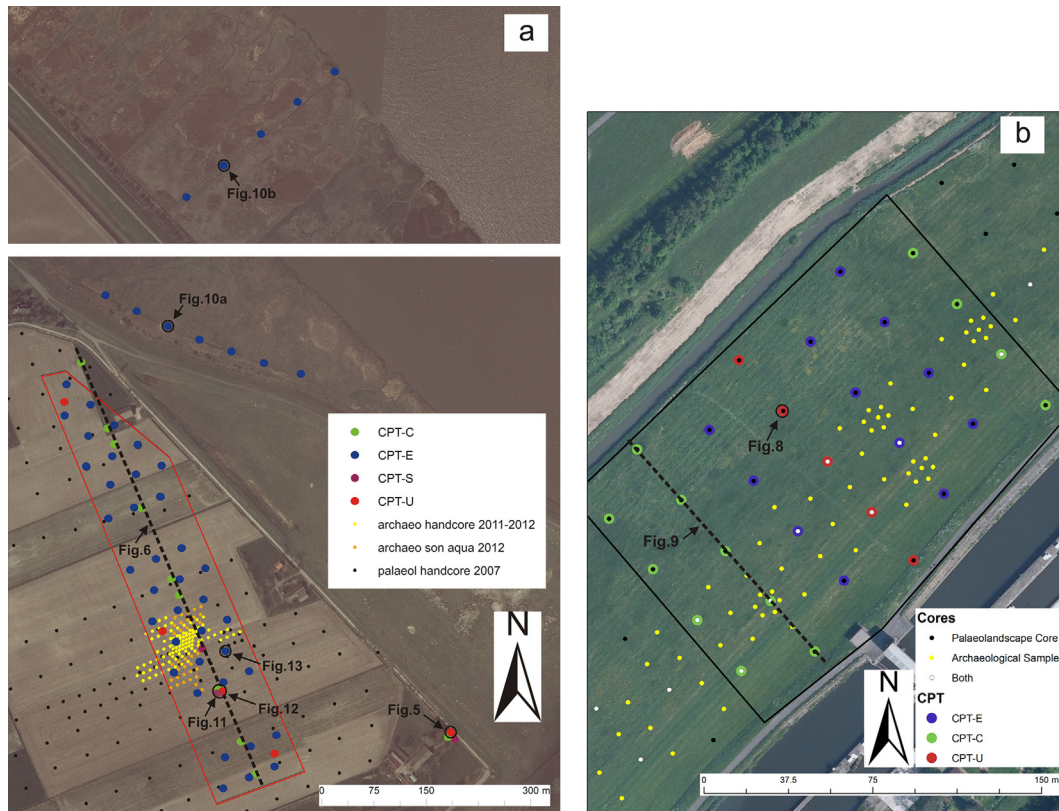
Fig. 3. Overview maps showing CPT and core locations at (a) Doelpolder Noord and (b) Kerkhove. CPTs and cores discussed in the paper are marked. The red line marks the study transect in Doelpolder Noord. Aerial images © Agiv.

cores) obtained in the framework of previous archaeological mapping with concise field descriptions (Klinck et al., 2007). These cores reached up to the basis of the peat; (2) 40 Sonic Aqualock drill cores obtained for archaeological sampling of the top of the coversands with rudimentary field descriptions and photographs; (3) Furthermore, 5 deep mechanical cores with detailed core descriptions and photographs available and reaching well into the Pleistocene sands (max. depth 14 m).

Due to compression of the peat the depth information obtained from the mechanical (Aqualock) cores at Doelpolder Noord was not always fully accurate. In a few cases contamination of samples from overlying layers was also observed. Since mechanical drilling was not possible on the tidal marsh (due to the difficult accessibility of the terrain) instead manual augering was tried out. However this proved to be extremely time consuming (one augering could take multiple hours) and largely unsuccessful since it allowed only to

Fig. 4. (a) CPT measurements with a mobile rig on the marsh adjacent to Doelpolder Noord. (b) Seismic CPT measurements at Doelpolder Noord.

penetrate the upper few metres, well above the depth of the peat sequence.

In Kerkhove a large number of shallow manual augerings, drilled for palaeolandscape mapping (95) and archaeological sampling (141) were available with concise field descriptions as well as a limited number of mechanical corings described and analysed in laboratory conditions (for location see Fig. 3b) (Bats and Crombé, 2007; Bats et al., 2008; MOW, 2010). The cores reached the base of the peat.

6. Results and interpretation

6.1. Doelpolder Noord

Peat layers stood out markedly on all CPT profiles at Doelpolder Noord, with friction ratio values ranging between 4 and 12%. Locally two distinct peat layers (generally the lower peat layer being much thinner) were observed, separated by organic-rich or peaty clay deposits (Figs. 5 and 6). In some cases extremely thin intercalating clay layers (~20 cm thick) could still be identified. The clay intercalations are generally related to a thick peat sequence and often coincide with the lower parts in the palaeotopography. On one occasion intercalating sand was observed within the peat (S13), indicating possible erosion of the ridge. Here the peat sequence was much thinner, and coincided with a higher palaeotopography. In general there was a tendency towards lower cone resistance values for the lower peat layer, which could point towards a less fibrous (more amorphous) peat (Long, 2005).

The transition between peat and the overlying estuarine deposits, and also the underlying Pleistocene sand deposits, was generally very sharp and clear. In the lower parts of the palaeotopography occasionally a thin transition-like layer between the peat and the Pleistocene sand seems to be present on the CPT logs. Neighbouring cores seem to point towards interfingering clay-rich and sand-rich deposits (Fig. 5). Similar features were also observed in the surrounding Waasland polder area (K. Heirman, pers. comm.). The location (close to the Scheldt river) and

palaeotopography (<−2 m TAW) suggest we could be dealing with early Holocene fluviatile deposits from the meandering Scheldt river.

The estuarine sequence overlying the top of the peat is marked by a high vertical and horizontal variability (Kiden, 2006; Kiden and Verbruggen, 2001). Accurate mapping of this variability is an important challenge. However it turned out that the internal stratification of the estuarine sequence, largely made up of sandy deposits but locally also (intercalated with) clay layers, was not always easily resolved on the CPT logs. In some cases the sand and clay layers could be distinguished unambiguously, even for relatively thin intercalations (confirmed by cores), while in other places this was not the case (e.g. Fig. 5). Most likely this was due to the fact that it concerns only minor changes in sand and clay content, but the thickness of the layers (too low to be resolved) may have also played a role.

Fig. 6 shows a transect of CPT profiles across Doelpolder Noord (for location see Fig. 3). On this transect we can clearly distinguish the late Pleistocene coversand-ridge and the different stratigraphical layers (peat, clay, sand) above the coversand.

Fig. 7 shows a map with the interpolated elevations of respectively the top and base of the peat sequence at Doelpolder Noord, based on the individually interpreted CPTs. Despite the differing locations of the datapoints, this model fits within the available coring model and even fills important gaps.

6.2. Kerkhove

The identification of CPT data at Kerkhove was slightly more complicated. In a number of cases the peat stood out relatively well, with friction ratio values ranging here between 6 and 11%. In general the distinction between the peat layer and underlying sandy clay deposits was quite clear, whereas the transition from peat to the overlying organic clay deposits seemed to be more gradual and was not always clearly distinguishable on the CPT logs (Fig. 8). Unlike Doelpolder Noord, the organic clay intercalations within the peat sequence were less apparent on the CPT logs (Fig. 8). This could be due to their thickness (sometimes less than
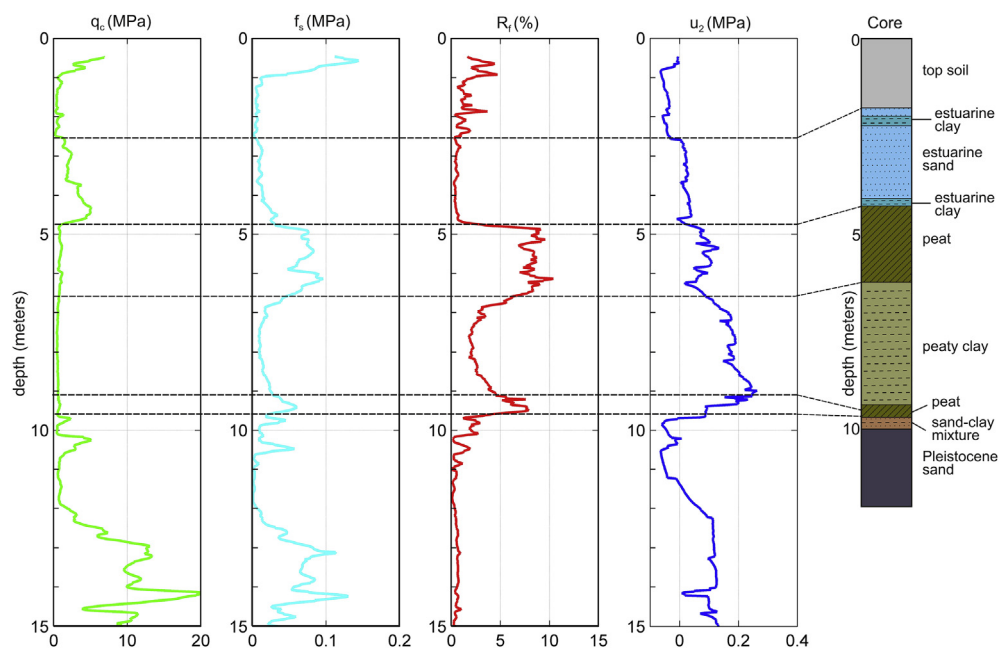

Fig. 5. CPT-U log (piezocone) from Doelpolder Noord and nearby core (U1, core P1). For location see Fig. 3a.
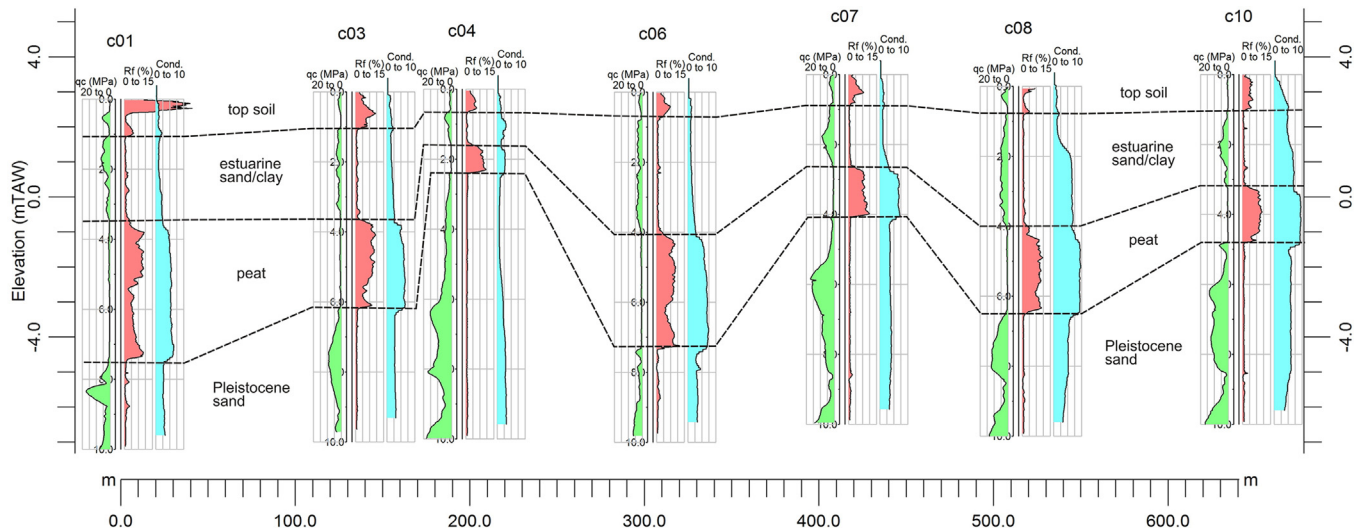
Fig. 6. Transect of CPT-C logs (resistivity CPT) across Doelpolder Noord. For location see Fig. 3a.

20 cm) and/or a reduced difference in lithology (i.e. a more 'uniform' organic sequence of peat and clay deposits). It is not unlikely that the different environment at Kerkhove (fluviatile, freshwater) compared to Doelpolder Noord (estuarine, mainly brackish) and the hydrogenesis (e.g. 'Water rise mire/spring mire' vs. 'Fluvial flood mire', cfr. Meier-Uhlherr et al., 2011) may have played a role here.

The transition between the top layer and the alluvial clay deposits at Kerkhove below stood out well on most data. Variations within the sandy clay river levee sequence could not always be clearly linked to lithological changes (as indicated by the cores), although in some cases a correlation with changing sand or clay content is suggested.

Fig. 9 shows a transect of CPT profiles across Kerkhove (for location see Fig. 3b). The sandy levee and peat sequence stand out relatively well on most logs. Stratification within the peat and the overlying sequence however is not clearly visible.

6.3. CPT data on the tidal marsh

The CPT data on the marsh directly adjacent to Doelpolder Noord show largely similar results (Fig. 10a). Again we can clearly observe two peat layers, separated by (supposedly) organic-rich clay deposits (although (deep) core data are lacking on the marsh, the resemblance with the nearby polder data seems to justify this interpretation). The base of the peat is marked by a sharp increase in q_c indicating a transition to sandy deposits. The uppermost metres of the marsh are marked by extremely low tip resistance (between 0 and 0.3 MPa) and sleeve friction (between 0 and 0.02 MPa), suggesting very soft muddy sediments. It is most likely that we are dealing with very recent tidal mudflat deposits. Unfortunately no cores were obtained here that were deep enough to reach the peat layer.

The CPTs on the marsh further north, close to the Dutch border, show different results (Fig. 10b). Here no peat seems to be present. It is not unlikely that peat deposits were once present here but that they were later eroded by (post-)medieval tidal inlets. Again the upper 3—5 m is marked by extreme low resistance and sleeve friction values indicating very soft mud. Below the soft muddy layer the CPT data suggest the presence of sandy estuarine deposits with some possible clay intercalations. Nearby marine seismic data (unpublished) suggest we may be dealing with (post-) medieval

tidal channels. This is also confirmed by corings without peat from a transect in Prosperpolder perpendicular to and in the extension of this CPT transect (ADW, 2010).

6.4. CPT-U

Clay is known to exhibit a higher pore pressure compared to sandy sediments which show a pore pressure close to the hydrostatic pressure (a.o. Eslami and Fellenius, 2004). It was therefore interesting to see whether the pore pressure curves would allow a better definition of the estuarine deposits (i.e. distinction between sand and clay intercalations) overlying the peat at Doelpolder Noord. Unfortunately this proved not to be the case (Fig. 5). This could be due to the relatively subtle changes in lithology (sand/silt/clay content). However, also at Kerkhove local sandy intercalations within the alluvial clay, as witnessed by the shallow cores, could not be traced back on the pore pressure data.

Identification of peat on pore pressure data is not always straightforward, since the pore pressure will strongly depend on the presence of sand or clay in the peat (sand will lower the pore pressure whereas clay will increase it) and the decompositional state of the peat (very fibrous vs. amorphous) (Lunne et al., 1997; Long and Boylan, 2012). The latter suggested that fibrous peat will exhibit lower pore pressures (sometimes negative) compared to an amorphous peat. This pore pressure variability is clear in Fig. 5, where the peat sequence is intercalated by a thick peaty clay/clayey peat layer. The latter is marked by an increased higher pore pressure indicating a more amorphous composition, whereas the actual peat layers show much lower values. The pore pressure data also confirm the more amorphous peat composition of the lower peat layer.

In Kerkhove the pore pressure data sometimes allowed a better distinction between the peat and organic clay deposits than the conventional data (qc/fs/Rf) (Fig. 8). In general here the pore pressure data also indicates a tendency towards an increased decomposed state of the peat towards the bottom.

6.5. CPT-S

Both S-waves and P-waves were clearly observed on the recorded seismograms. Due to their lower velocity the S-waves showed a larger variation (with marked changes in the gradient) than the P-
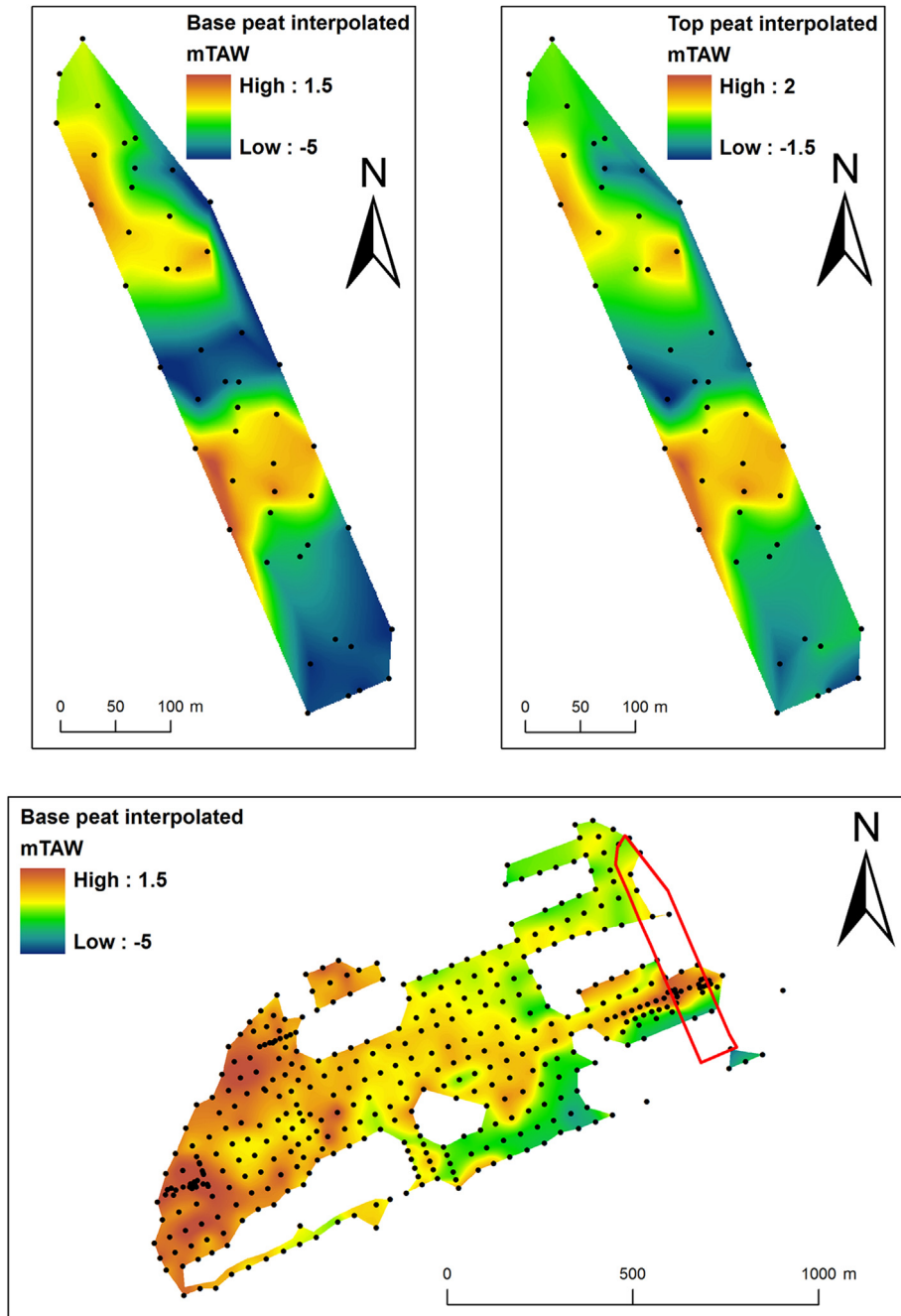
Fig. 7. Top: Elevation maps of the top and base of the peat in the study transect at Doelpolder Noord (for location see Fig. 3), as derived from the CPT data (in m TAW). Black dots indicate the CPT locations. Bottom: Base peat map at Doelpolder Noord derived from 2007 archaeological cores for comparison (in m TAW). Black dots indicate the locations of the archaeological cores. The red area marks the study transect.

waves (Fig. 11a). Identification of the arrival times was carried out with the direct time method, based on visual interpretation. In some cases unambiguous identification of S-waves was not easy. This could in principle be solved easily by comparing two signals from opposite sides of the beam (which will show opposite polarization) but unfortunately such 'opposite signals' were not recorded at Doelpolder. It is highly recommended or future measurements to record 'opposite signals' for identification of S-wave signals in seismic CPTs.

The difference in arrival times between the two geophones allowed to calculate the interval velocity, taking into account the source-sensor offset and assuming that the origin of the source wave is in the middle of the beam. The high P-wave velocities did not allow accurate picking and therefore only S-waves were used. The results for CPT-S4 are shown in Fig. 11b. The sharp drop in V_s, with velocities ranging between 40 and 100 m/s, correlates exactly with the presence of a peat layer at that dept (due to noisy data a reliable velocity estimation for the clay layer just below the peat was not possible). The measurement interval (0.5 m) did not allow to identify thin peat layers (less than a few dm). This may be overcome by decreasing the interval but this would have seriously increased the time to complete the CPT.
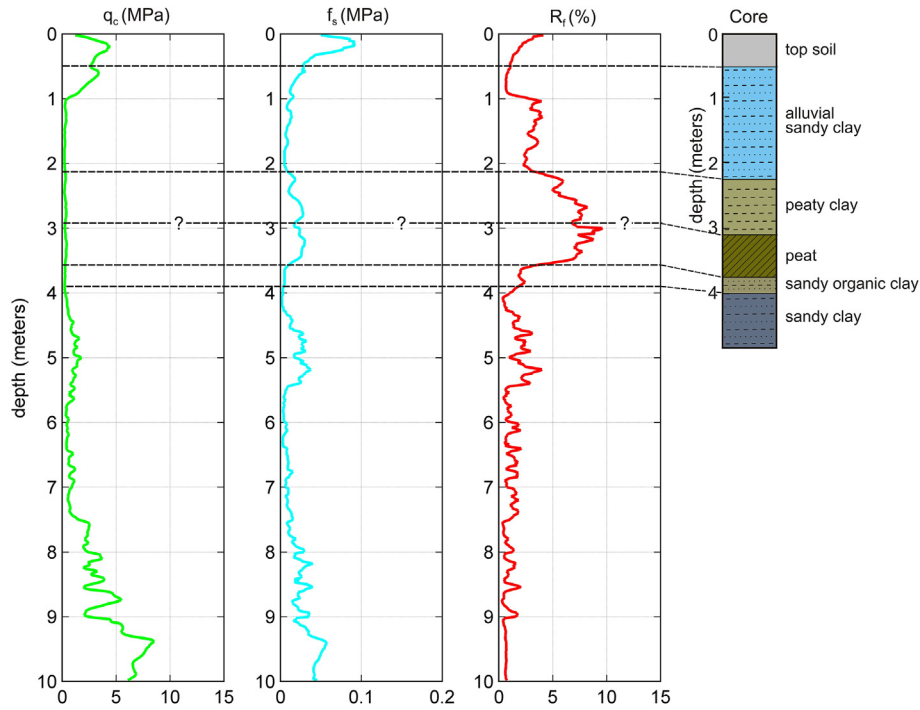
Fig. 8. CPT-U (piezocone) log from Kerkhove and nearby core (B52, core52 + B4). For location see Fig. 3b.

6.6. CPT-C

The conductivity data at Doelpolder Noord clearly show an increase caused by the peat, correlating well with the highest R_f values (Fig. 5). However there seems to be no clear differentiation between other stratigraphic units. Both the average conductivity values of the complete sounding and the peak values caused by the peat alone increase towards the northern edge of the study area, due to the brackish Scheldt water seepage.

In Kerkhove, the clayey textures and peats have a small mechanical/geotechnical contrast. This is also reflected in the conductivity data, which have lower average values per sounding than in Doelpolder Noord but show a more continuous variation (Fig. 8). The top of the peat is not recognizable as a conductivity shift, but continuous increasing values with the depth do indicate a transition to a more conductive substrate.

7. Discussion

7.1. Automatic soil classification

Since both test areas at Doelpolder Noord and Kerkhove are marked by relatively thick peat and organic clay sequences, automatic soil classification was expected to be problematic. Indeed in
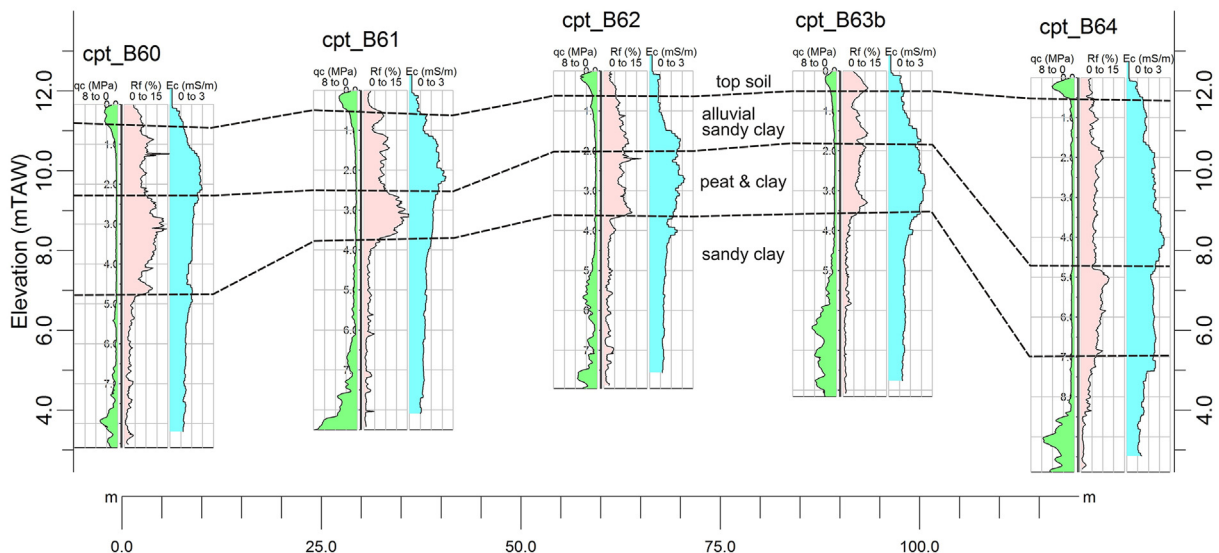

Fig. 9. Transect of CPT-C logs (resistivity CPT) across Kerkhove. For location see Fig. 3b.
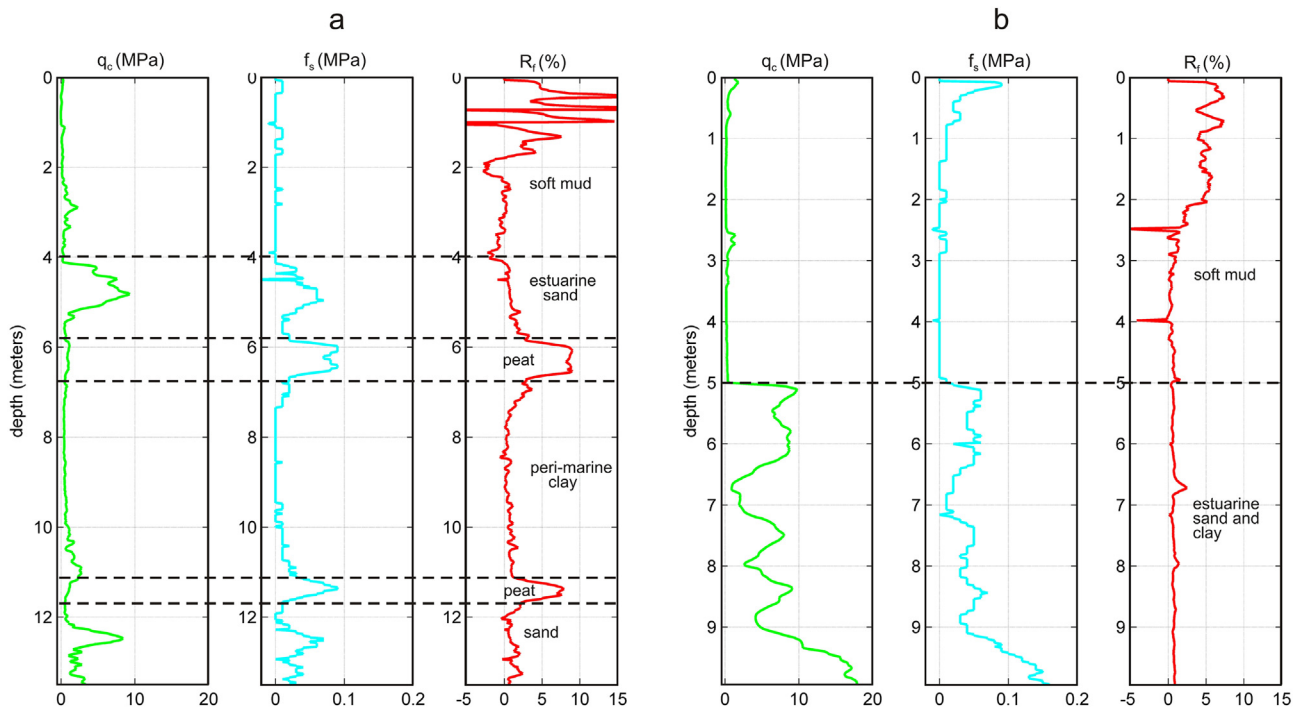
Fig. 10. CPT logs from the tidal marsh adjacent to Doelpolder Noord. For location see Fig. 3a.

most cases the peat and organic-rich clay layers could not be distinguished on the charts (both showing up as clay) (Fig. 12a). It was hoped that normalization and corrected data using pore pressure information would result in a better (i.e. more reliable) soil classification, especially since the correction is believed to be increasingly important with decreasing grain-size (Fellenius and Eslami, 2000; Coutinho and Mayne, 2012). However this was not the case. Due to the very low pore pressure values that were recorded the corrected tip resistance values (q_t) did not differ substantially from the uncorrected data (q_c) (Fig. 12b). The use of soil classification charts was therefore abandoned and interpretation of the CPT data was mainly carried out manually, using the different measured parameters and knowledge of the local geology.

7.2. Layer thickness and resolution

One of the challenges in this study was the identification of thin layers, especially peat layers but also thin clay intercalations within the peat. Due to the nature of the CPT measurement this is not evident. Since the cone is influenced by the material ahead (and also behind) it will start to sense a change in soil material before it reaches it, and will continue to sense the soil even when it has entered a new material. This means that the tip resistance is actually an average value, taken over a certain zone around the cone tip. According to Lunne et al. (1997) the zone tends to be smaller for soft materials (possibly down to 2 times the cone diameter) but much larger for stiff materials (up to 10 or 20 times the cone diameter). This averaging effect is also the case for the sleeve friction which in fact measures an average value over the total sleeve (13 cm for a 10 cm² cone) and thus may smooth out the effects of very thin layers.

In Doelpolder Noord thin layers of intercalating peat and clay down to 20 cm in thickness could be identified correctly on the CPT logs. No noteworthy difference was observed in resolved layer thickness between 10 cm² and 15 cm² cones. Some software tries to take into account the averaging effect by using an average q_c value, taken over the length of the sleeve, for the calculation of the friction

ratio. This did not seem to have any relevant effect on the results except for producing a faintly smoother R_f curve. Nevertheless it seems advisable to use the original data instead of an averaged value.

It was far more difficult to identify thin clay and sand intercalations in the overlying estuarine deposits. This could be due to the difference in stiffness between the two materials, as suggested by Lunne et al. (1997), which may lead to overestimation of strength in thin clay layers and vice-versa underestimation in thin sand layers. However, as stated before it could also be due to insufficient lithological difference between the sandy and clayey layers. The fact that relatively thick clay-rich intercalations within the sandy estuarine deposits could not always be detected also seems to support the latter.

7.3. Data repeatability and reliability

Overall the CPT data showed a good repeatability. Different CPT logs obtained at approximately the same location (maximum lateral deviation less than 2–3 m) were highly similar, and allowed an identical interpretation. However one remarkable feature stood out with regard to the data obtained at Doelpolder Noord in 2011 and 2013: in general the former showed lower friction ratio values for peat (on average 1.5 times lower). It is known that the CPT sleeve friction is generally less reliable than the cone tip resistance, and the main factors for this include a.o. (1) load cell design and calibration, (2) tolerance in dimensions between cone and sleeve, and (3) surface roughness of the sleeve (Lunne and Andersen, 2007). Since similar cones were used for the various CPT measurements in this study (carried out by the same company and involving the same calibration procedures), a worn sleeve in 2011 may have been the cause for the observed difference, as suggested by the lower sleeve friction values for peat (Fig. 13). Yet the opposite trend observed in the sandy deposits above and below the peat seems to contradict this. Differences were also observed in the tip resistance data from 2011 to 2013. So far no clear explanation has been found for this. All in all, however, the problems in
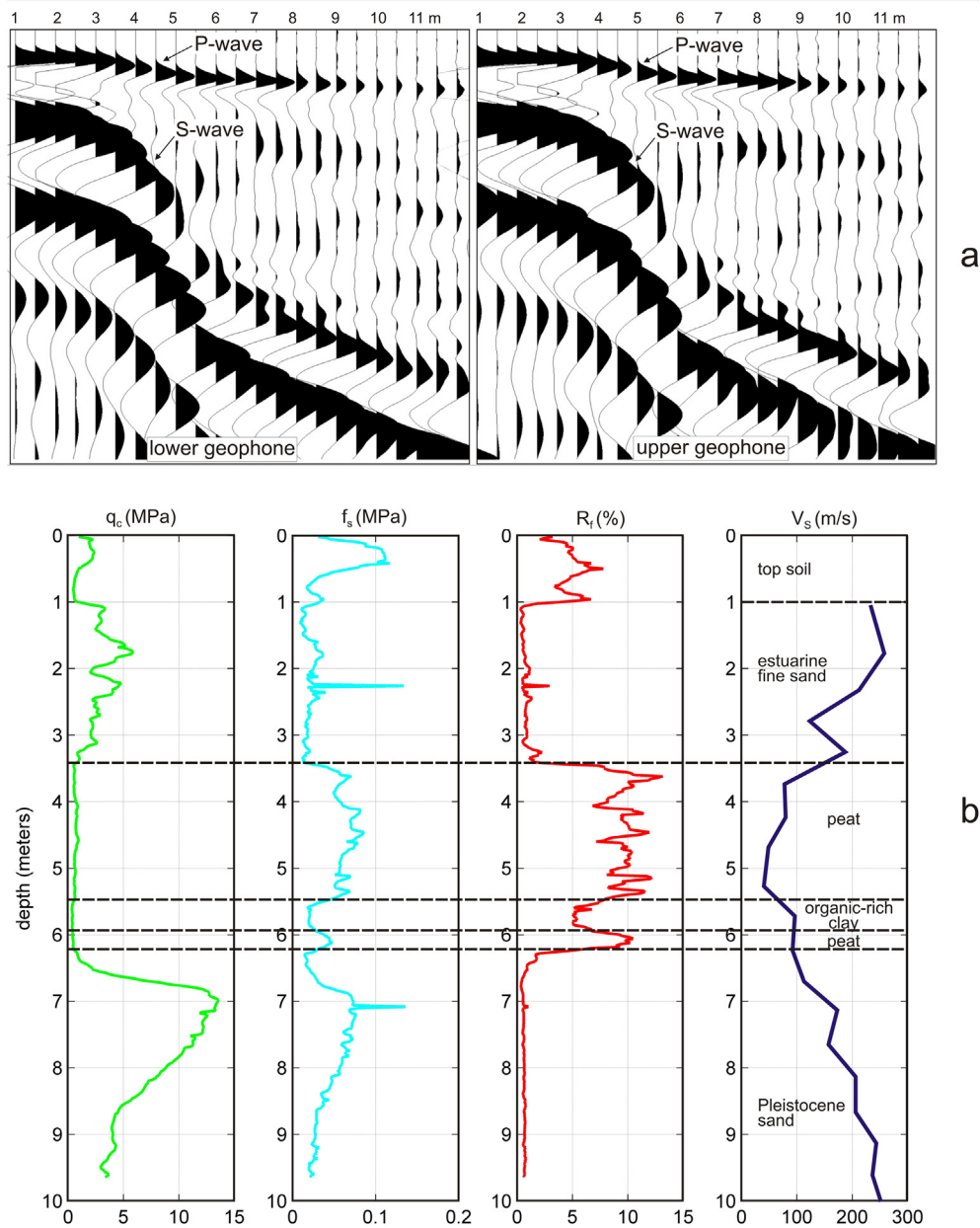
Fig. 11. Results of seismic CPT tests at Doelpolder Noord. (a) Seismograms showing arrivals of P- and S-waves recorded on the upper and lower geophone in the cone rod (source z, receiver x). (b) CPT logs and calculated S-wave velocities. For location see Fig. 3a.

repeatability between the 2011 and 2013 measurements did not affect the interpretation of the data.

The high friction ratio values observed in the upper metres on the tidal marsh (see Fig. 10a and b) could at first sight suggest the presence of peat. However, they are the result of extremely low tip resistance and sleeve friction values (which on the contrary suggesting soft muddy sediments), and it seems therefore likely that the friction ratio values are erroneous since we are operating here at the limit of accuracy. Indeed most standard cones will have difficulty resolving extremely low resistance values (such as measured here) since these are close to the accuracy of the equipment.

8. Conclusions and recommendations

The results of this study show that CPT measurements are a reliable and accurate tool in determining the soil stratigraphy and palaeotopography of covered prehistoric landscapes. Especially in wetlands marked by a deep palaeosurface and thick peat (and clay) sequence the CPT method may well be more efficient than coring and may provide a cost-efficient calibration tool for surface geophysical data or even a replacement when circumstances impede reliable results. As CPTs are frequently used within other disciplines (e.g. geology, construction, etc.) applying it for geo-archaeological purposes does not demand further technical refinement, except for the interpretation of CPT logs. This is ideally carried out manually, as our case-studies have shown that automated calculation of soil stratigraphy is often incorrect, especially when distinguishing peat and clay layers, and should be used with caution, if at all. Therefore we do not recommend relying on this software in polder areas. However, manual interpretation of CPT logs demands a good knowledge of the local geology and geotechnical background, which can be obtained by means of a limited number of sampling cores from nearby locations.
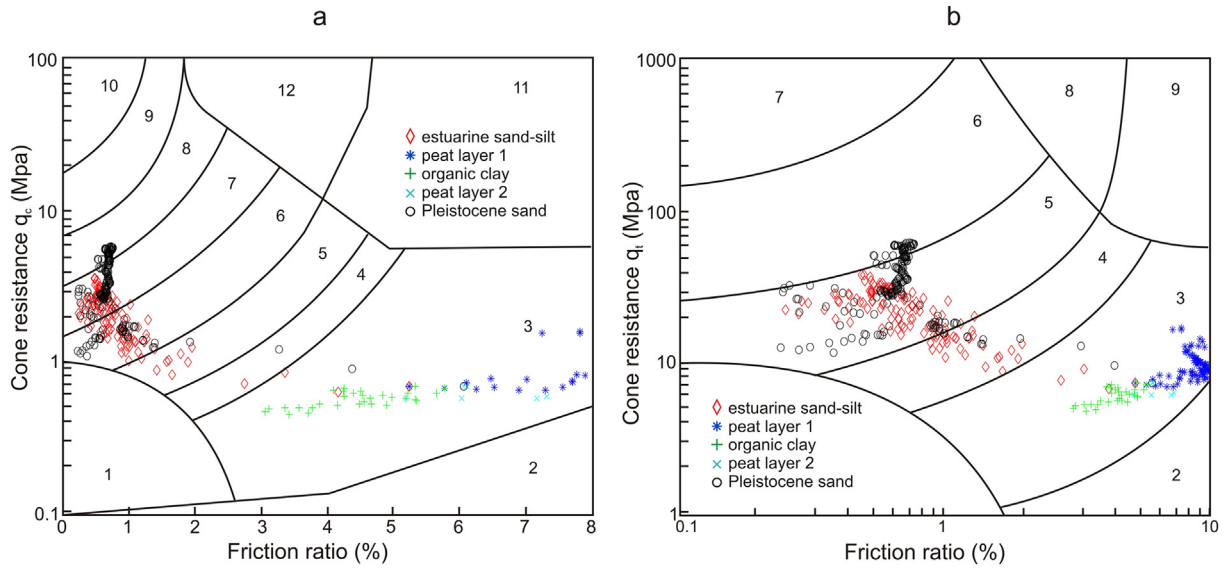
Fig. 12. (a) Soil classification chart using uncorrected q_c data (CPT-U3; for location see Fig. 3a) (1: sensitive fine grained; 2: organic material; 3: clay; 4: silty clay to clay; 5: clayey silt to silty clay; 6: sandy silt to clayey silt; 7: silty sand to sandy silt; 8: sand to silty sand; 9: sand; 10: gravelly sand to sand; 11: very stiff fine grained*; 12: sand to clayey sand*. (b) Normalized soil classification chart using corrected q_t data (CPT-U3) (1: sensitive fine grained; 2: clay−organic soil; 3: clays; 4: silt mixtures; 5: sand mixtures; 6: sands; 7: dense to gravelly sand; 8: stiff to clayey sand*; 9: stiff fine grained*. (*overconsolidated or cemented) (after Robertson, 2010).

In this paper both estuarine (Doelpolder Noord) and alluvial (Kerkhove) polder environments were investigated. Overall the CPT data allowed highly accurate mapping of the palaeotopography of the prehistoric surface (a late-Pleistocene sandy ridge/levee) and the thickness of the overlying peat sequence. Comparison with

available coring or geophysical models at both sites showed a good correlation. At the estuarine site of Doelpolder Noord thin inter-calating (organic-rich) clay layers within, or just below, the peat sequence could still be identified. This was much less the case for the alluvial site of Kerkhove, possibly due to a lack of lithological
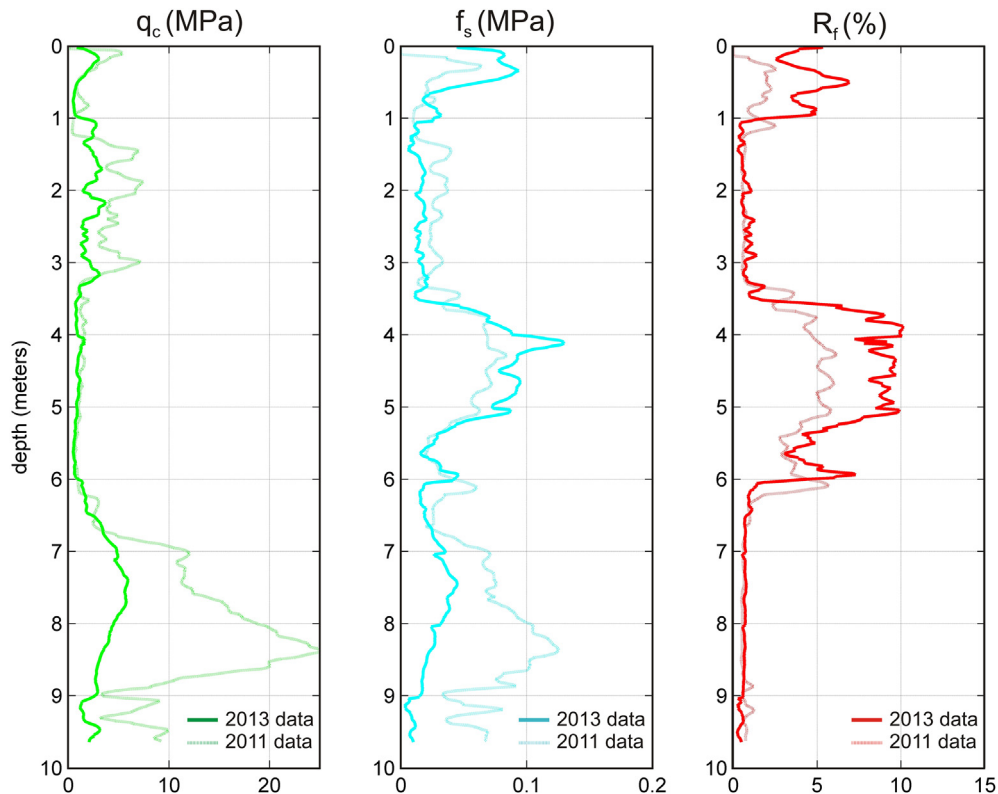
Fig. 13. Comparison between CPT logs obtained in 2011 and 2013 at the same location in Doelpolder Noord (S8-RCPT3). For location see Fig. 3a.

difference. The latter was most likely also the case for the recent estuarine sand and clay deposits at Doelpolder Noord which were seldom distinguished.

The use of a lightweight, mobile rig allowed to obtain CPT data on the tidal marsh. Also here the buried palaeosurface and peat sequence were clearly identified. However some caution must be taken with the identification of the (often very thick) soft muddy top layer, typical for marsh environments. The extremely low tip resistance of these soft sediments may result in high friction ratio values which could wrongly suggest the presence of peat.

Piezometric CPT data did not add significant information compared to conventional CPTs. At most the pore pressure data seemed to suggest a less or more fibrous state of the peat, although this needs to be taken with caution. Given the extra effort required to perform piezometric CPT measurements, their use is not recommended for archaeological palaeolandscape studies. Also additional conductivity data generally did not add much crucial information regarding the peat layer(s) or buried palaeosurface, although in some cases subtle changes in lithology (e.g. increase in sand or clay content) may be detected. The main use of conductivity CPTs seems to lie in their added value for surface geophysical measurements (calibration and interpretation of EMI and/or ERT data) (Verhegge et al., 2015), submitted for publication.

The velocity information obtained from simple seismic CPT measurements showed a remarkably good correlation with the CPT logs and nearby cores regarding the presence of peat. The resolution (i.e. minimum thickness of the identified peat layer) and reliability of the seismic CPT method will however largely depend on the acquisition parameters (seismic wave generation, beam hit direction, measurement and geophone interval, etc.). In general a higher accuracy will require more effort and more time, and therefore seriously affect the cost-efficiency.

The collection of (conventional) electric CPTs is generally quicker than the collection of sediment cores (on average 15 soundings of 10 m deep were obtained in 8 h time). Overall the time benefit will be greater for increasing depth (it is estimated that for depths >3 m CPTs are likely to be more advantageous than coring). CPTs also only involve a limited technical staff in the field, whereas drillings are labour intensive (especially hand augering) and demand an additional specialist to interpret the stratigraphy of the cores in the field. If cores are transported to the laboratory, e.g. in plastic tubes, there are additional costs of transport and opening of the tubes. Finally the depth accuracy of CPTs is often greater than for corings, especially in wetlands since peat has the tendency to expand after coring, resulting in erroneous depth measurements of the subsurface layers.

A major disadvantage of CPTs (and geophysical survey methods) however is that they do not provide data about the preservation of the different lithostratigraphical levels, which is important for assessing the quality of the prehistoric sites potentially present within these sediments. Information about possible erosion, truncation and/or bioturbation of sediment levels can only be achieved through coring. Conventional coring will therefore still be needed, but the palaeotopographical and lithostratigraphic information obtained from CPT data will allow a much more efficient (i.e. less) coring and sampling strategy.

Acknowledgements

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