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Prehistoric landscape mapping along the Scheldt by camera- and conductivity CPT-E

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ABSTRACT: Over the past decade, paleolandscape reconstruction was introduced as part of a preventive archaeological evaluation strategy along the Scheldt river, due to the unexpected discovery of well-preserved prehistoric landscapes and sites during construction works in the Antwerp harbor area. Hereby, CPT is an important tool in combination with coring and/or near surface geophysical survey. Applications of CPT range from desktop studies, which determine evaluation strategies, to actual paleolandscape mapping by sedimentological data interpretation. CPT-Es (with added camera and/or electrical conductivity sensors) calibrate and validate geophysical subsurface modelling and soil behavior types are interpreted. Particularly, (electrical conductivity) CPT-C disentangles sedimentological and hydrological variations in electrical conductivity values. On the other hand, camera CPT improves differentiation of organic rich sediments and detection of thin organic soil horizons within homogenous (cover)sands. The usability of CPT is illustrated through recent prehistoric landscape evaluation studies along the Scheldt river.

1 INTRODUCTION

1.1 *Archaeological background*

Over the past decades, well-preserved Late Glacial to Middle Holocene paleolandscapes and prehistoric archaeological sites dating back to the Final Paleolithic to Early Neolithic period have been discovered during harbor infrastructure works to expand the port of Antwerp in the Waasland Scheldt polder region (Crombé, 2005). These remnants of former hunter-gatherer and early farmer-herder habitation were encountered by accident and triggered prompt rescue excavations, which were uncomfortable to both archaeologists and developers. The unexpected nature of these finds was partially caused by the covering sediment sequence, which both protects the sites and impedes detection using traditional archaeological prospection methods, such as test pitting or remote sensing (De Clercq et al., 2012).

Therefore, buried paleolandscape mapping strategies have been developed to reduce costs for subsequent archaeological site detection *sensu stricto* through intensive core sampling (Crombé and Verhegge, 2015). At first, paleolandscape mapping relied primarily on coring (Bats, 2007, De Clercq et al., 2011). However, due to the labor intensity of deep manual coring and the financial burden of mechanical coring, recent research has focused on exploring alternative techniques, such as CPT (Missiaen et al., 2015), in combination with electrical resistance imaging and electromagnetic induction survey (Verhegge et al., 2016a).

1.2 *Geological background*

The prehistoric sites were mainly found on Weichselian Late Pleniglacial and Late Glacial cover sand ridges, river dunes, natural levees and point bars within the fossil Pleistocene floodplain and were gradually buried due to ground water and sea level rise (Figure 1) (Crombé et al., 2011, Crombé et al., 2015).

As such, a primary aim of the prehistoric landscape evaluation is a reconstruction of the topography of the top of the Pleistocene sedimentary sequence. Secondly, it has to be determined to what degree later sedimentation has protected this paleosurface or if erosion has destroyed it as well as the prehistoric sites this paleosurface might contain. Due to sea level rise and surfacing local ground water levels, depressions in the landscape were first covered by Late Atlantic alder carr peat. Peat development was interrupted by a short period of organic rich and clayey supratidal freshwater floodplain sedimentation, after which a sedge fen and birch carr formed. Further acidification resulted in an oligotrophic peat layer (Deforce et al., 2014). From the middle ages onwards, the increased influ-

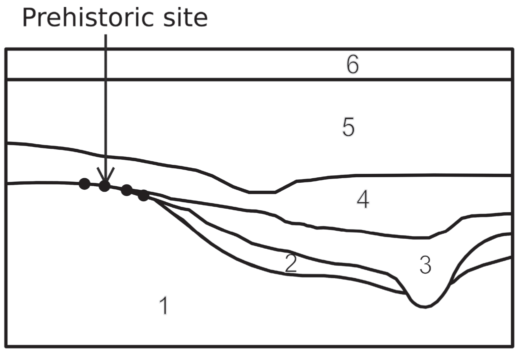

Figure 1. Schematic section of the regional lithostratigraphy and stratigraphic position of Early Mesolithic to Early Neolithic sites in the Waasland Scheldt polders. 1. Weichselian (cover) sand 2. Basal peat layer 3. Organic rich clay intercalation 4. Upper peat layer 5. Clayey to sandy estuarine sediments 6. Top soil.

ence of the sea caused erosion of the prehistoric landscape and covered it with varying sandy to clayey estuarine floodplain sediments as successive embankment attempts gradually claimed the land from the sea (Missiaen et al., 2016 and references therein).

2 METHODOLOGY

2.1 *Lithological and stratigraphic interpretation of CPT-E*

Although CPTs are primarily developed for geotechnical purposes (Robertson and Cabal, 2012), the correlation of the recorded soil mechanical data to the sedimentological variables, such as grain size, makes them suitable for lithostratigraphic mapping of soft alluvial plain deposits (e.g. Amorosi and Marchi, 1999). Particularly electric (piezo-)CPTs allow an easy identification of peat layers by the greater friction ratio- (R_f), often >5% and negative pore pressure values (Lunne et al., 1997). Due to the high vertical data density, even thin peat layers down to about 20 cm are mapped correctly (Lunne et al., 1997). However, the added value of pore pressure data is rather limited in our study region (Missiaen et al., 2015) in contrast to studies in surfacing peat bogs (Long and Boylan, 2012, Long, 2005). Therefore, only CPT-Es are employed and piezocones are not used in this study.

Rapid interpretation of the CPT data in desktop studies is done through comparison with lithostratigraphic knowledge of the region. Furthermore, soil behavior types (SBT) are determined by a Robertson (1990) chart adapted by Fugro GeoServices to the subsoils of the Netherlands with consolidated Holocene peats using an approximated normalization (Koster, 2016). High quality cores (e.g. Begemann core) are used to validate these interpretations and to adjust the SBT chart to the local situation, if necessary. The cores are also used to determine the organic soil types more accurately or to assess if paleosols are present on top of or within the sediments below. Further subsurface modeling and visualization are facilitated through a three dimensional geographic information system using ESRI ArcGIS and Rockware Rockworks software.

2.2 *CPT(-C) and near surface geophysical paleolandscape mapping*

Electrical resistivity imaging (ERI)- and electromagnetic induction (EMI) survey provides a horizontally dense dataset in addition to the vertically dense CPT data. These near surface geophysical data are interpreted, calibrated or validated using two possible CPT applications. On the one hand, regular electric CPTs provide depths of lithological data of layers and depths of their transitions. On the other hand, electrical conductivity (EC) sensors are added to the conus and continuous EC is recorded continuously during penetration to determine if CPT-E and EC variations correlate.

2.3 *Camera-CPT*

A first test was performed with a camera CPT recording images every 1.5 cm during penetration. Subsequently the images were processed to correct the illumination and collated into an image log. This test was aimed as distinguishing similar soil behavior types with differing lithologies by their color. Furthermore, it was aimed at mapping small remnants of eroded or reworked peat layers and organic rich soil horizons with a thickness below the SBT identification limit of regular CPT-E.

2.4 *Study area*

Three possible uses of CPT in prehistoric paleolandscape mapping will be illustrated based on paleolandscape reconstruction results (Figure 2) from the sites of 'Prosperpolder Zuid' (PPZ) (51°19'15"N 4°13'08"E) (Saey et al., 2016) and 'Doelpolder Noord' (DPN) (51°19'57"N 4°14'58"E) (Verhegge et al., 2016a, Missiaen et al., 2015). The adjacent sites are located on the left bank of the Scheldt river, between the port of Antwerp and the national border (Figure 2-inset map).

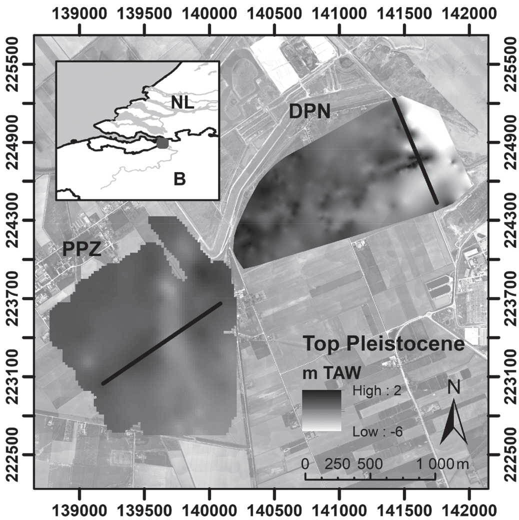

Figure 2. Map of the study areas of PPZ and DPN with an interpolated elevation model of the top of the Pleistocene sediment sequence and locations of the transects on Figure 4 Figure 2and Figure 5. Inset map: the location of the study region close to the border between Belgium and The Netherlands. (Belgian Lambert '72 coordinate system, Belgian reference level-Tweede Algemene Waterpassing).

3 RESULTS

3.1 *CPT in archaeological desktop studies*

Often, CPTs are available from geotechnical studies or from national repositories by the time an archaeological evaluation of a planned construction site is started. During a desk based assessment of the archaeological potential of a study area, CPTs are rarely considered as helpful data. Even if the number of CPTs or their depth is insufficient to map the paleolandscape topography, they provide valuable information to develop a mapping strategy.

A publicly available CPT at PPZ (https://www.dov.vlaanderen.be/data/sondering/2006–046736) indicated a possible burial depth of the Pleistocene sands of 4 and possibly up to 7 m, which excluded efficient manual coring. Furthermore, the presence of clays and shallow groundwater implies the use of electrical near surface geophysical methods instead of ground penetrating radar. A relatively thick peat layer suggests the use of CPT-E is possible but the presence of small and thin variations (e.g. Rf peak at 7 m) warns that high quality cores are necessary for CPT interpretation.

3.2 *CPT as primary paleolandscape mapping tool*

After the desk top study, extensive coring was considered not cost-efficient at PPZ. Therefore, CPT-E was used as principal survey technique in combination with EMI. Figure 3 illustrates that qc and Rf accurately map the main lithostratigraphic variations. However, the SBT interpretation is not able to differentiate between the peat layer and organic rich clayey tidal mudflat sediments.

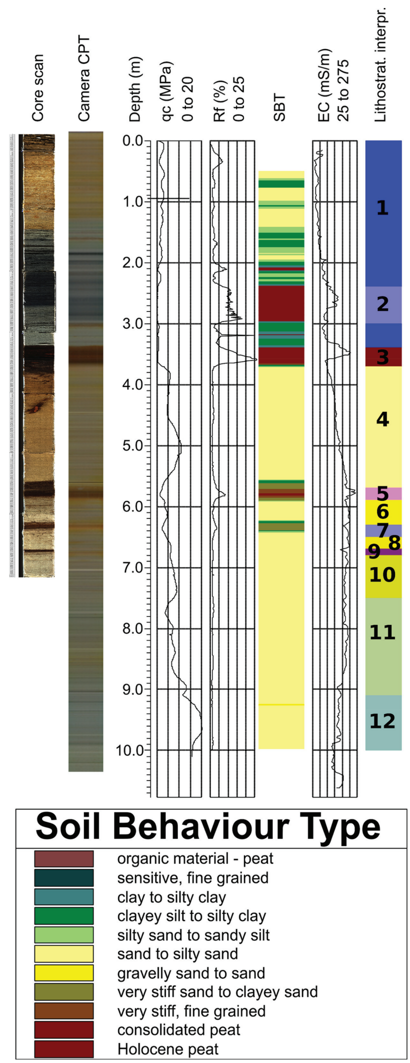

Figure 3. From left to right: Begemann core scan, Camera CPT, CPT-E (qc, Rf, SBT), EC log, Lithostratigraphic interpretation (1. Clayey to sandy estuarine sediments 2. Organic rich clayey tidal mudflat sediments 3. Peat layer 4. Younger Dryas cover sand 5. Upper Allerød soil horizon 6. Upper Allerød cover sand 7. Middle Allerød soil horizon 8. Lower Allerød cover sand 9. Lower Allerød soil horizon 10. Late Pleniglacial/Older Dryas cover sand 11. Weichselian fluvial sediments 12 (Reworked) Tertiary sand with shells.

Furthermore, thin organic horizons are identified as very stiff sand to clayey sand and can not be correctly interpreted without validation through coring (Figure 3-left).

Figure 4 shows that transects (or grids) of interpreted CPTs were capable of mapping the post-Pleistocene topography as well as the varying presence of its peat cover. Indeed, even a series of organic Allerød soil horizons within homogeneous sandy sediments, identified in cores, could be mapped through the dropping qc.

The camera CPT log has decreased the interpretative reliance on coring as it differentiated between consolidated peat (Figure 3, layer 3) and unconsolidated and highly organic fine grained saltmarsh deposits (Figure 3, layer 2), which often contain pieces of reworked peat. Secondly, even the relatively thin remnants of largely eroded peat layers can be mapped (Figure 4, layer 3). Furthermore, the camera CPT log increased the capability to map more subtle organic rich sandy Allerød horizons, which do not show qc or Rf variations (e.g. Figure 3, layer 9). In particular, the upper Allerød soil horizon (Figure 4, layer 5) could not be differentiated at the right side of the transect. This horizon consists of leached organic rich sand with a darker color in the cores. Therefore, it could be detected using a camera CPT log.

3.3 *CPT and near surface geophysical paleolandscape mapping*

Figure 5 shows ERI and CPT data at DPN and illustrates that the Rf and EC both increase due to the peat layer. However, the EC also increases above and below the peat layer at the end of the transect, located closer to the dike which embanks the Scheldt estuary. Here, a brackish groundwater lens intrudes into the subsoil via the peat layer.

The high EC due to this saltwater intrusion also renders the low induction number approximation to derive apparent EC($_a$) from the quadrature phase signal of the receiving coil invalid (McNeill, 1980). As such, the EC_a values above about 100 mS/m in Figure 6 deviate from the actual EC, in addition to not correlating to the prehistoric paleolandscape variability (Verhegge et al., 2016a). Nevertheless, the brackish water zone is accurately

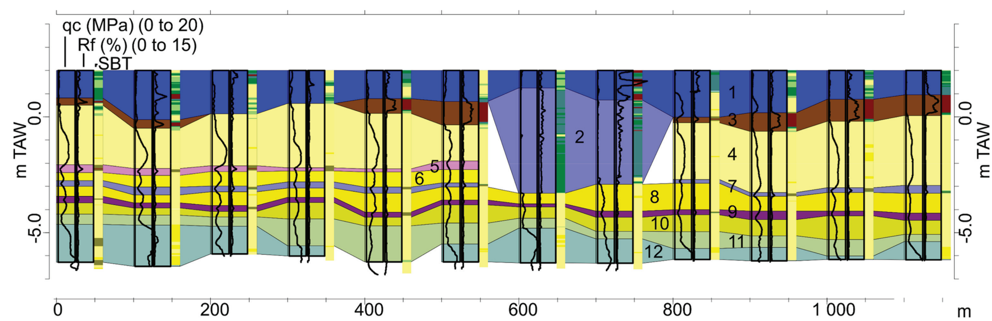

Figure 4. Transect at PPZ with interpreted CPT-Es (qc, Rf, SBT with legend in Figure 3) and interpreted lithostratigraphy Figure 3) (Belgian reference level-Tweede Algemene Waterpassing).

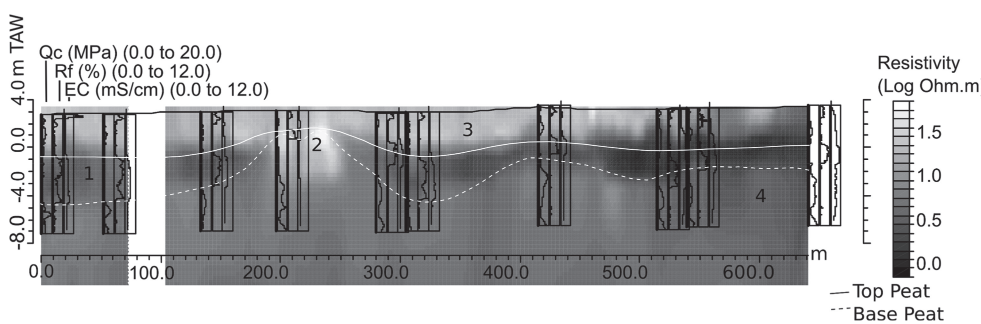

Figure 5. CPT-C transect and electrical resistivity section at DPN, which was inverted using a CPT derived forward model for the top and base of the peat layer. 1. Middle Holocene peat in depression 2. Late Weichselian dune 3. (Post-) Medieval estuarine floodplain sediments 4. Increased EC outside peat layer, due to brackish groundwater lens from the Scheldt river (after Verhegge et al., 2016a figure 2) (Belgian reference level-Tweede Algemene Waterpassing.

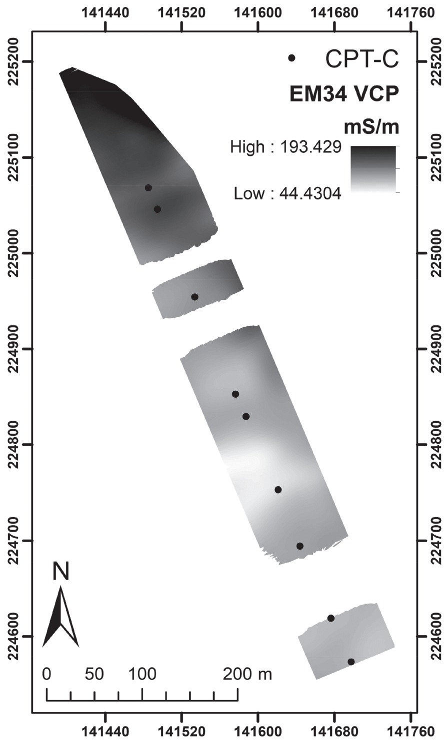

Figure 6. Interpolated EM34 VCP survey data with locations of CPT-Cs in Figure 5 (after Verhegge et al., 2016a Figure 4a) (Belgian Lambert '72 coordinate system).

delineated by the EMI data. Therefore, CPTs are preferred to ERI or EMI for paleolandscape mapping in brackish or saltwater environments (Verhegge et al., 2016a).

However, if no brackish groundwater is present, a geophysical modelling approach using EMI survey with multiple coil pairs and CPTs as calibration data has proven successful to reconstruct the basis of the Holocene peat layer (Saey et al., 2016, Verhegge et al., 2016b).

The EC log on Figure 3 shows that the upper Allerød peaty soil horizon causes a small EC peak. However, the middle and lower Allerød soil horizons consist of organic rich sand and cause a small EC drop. Unfortunately, these variations are too small for near surface geophysical detection using ERI or EMI.

4 DISCUSSION AND CONCLUSION

This paper has demonstrated the value of CPT for archaeological prospection of prehistoric landscapes buried below peat layers and embanked estuarine floodplain sediments. As such, CPT has started to be included in archaeological practice in the study region.

The conversion of CPT-E data to SBTs is particularly useful for ease of communication with archaeologists but possible errors have to be checked using coring. The visualization of CPTs in sections and on maps with lithostratigraphic interpretation is also important to this purpose. Nevertheless, some important limitations of CPT-E were observed, such as the interpretation of horizons <20 cm or the similarity between organic rich unconsolidated clays and peat.

The first camera CPT results provide a solution for these issues. Importantly, the camera CPT log is acquired, processed and visually interpreted straightforwardly. However, further research is necessary to improve the camera CPT results. This should focus on color calibration and analysis to fulfill the additional quantitative potential of colors for SBT interpretation.

While the EC depth log records both lithological as hydrological EC variations (e.g. salt- or freshwater), the CPT-E data can be used to distinguish soil texture from saltwater variations. As such, combined CPT-E and EC logging provides an important tool to interpret and model the major lithological and hydrological variations in both ERI and EMI near surface geophysical data in (embanked) estuarine floodplains. An actual integration of the *in situ* measured EC values in the modelling procedure of the near surface ERI and EMI data could improve results even further. The causes for the differentiation between the EC responses of the Allerød soil horizons require further research as well.

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