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# Cone Penetration Testing: A Sound Method for Urban Archaeological Prospection

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ABSTRACT Cone Penetration Testing (CPT) is a geotechnical *in situ* site investigation method and is widely applied in urbanized areas of the Netherlands. Approximately 20,000 CPTs are conducted in the Netherlands each year. The frequency of such testing, and the presence of archaeological deposits within the subsurface, results in a relatively high probability that archaeological deposits could be encountered during sounding. A significant amount of the results of these CPTs are freely available and are easily accessible in a national database. This combination of frequency and accessibility suggests that CPT could potentially be a very attractive tool for archaeological prospection. However, in practice, the integration of CPT in archaeology is poor. This is largely the result of the lack of a general overview of characteristics concerning the recognition of archaeological deposits in CPT data.

This study explores the potential of CPTs for archaeological prospection in urbanized areas by characterizing archaeological deposits in CPT log data, with a special focus on the historical city centre of Amsterdam. In total, seven CPTs conducted at two archaeological sites in Amsterdam were analysed. A characterization based on the examined CPTs was subsequently used to identify archaeological deposits in 407 CPTs conducted in Amsterdam, deriving from the national database. This resulted in a map depicting the spatial distribution and thickness of archaeological deposits in the city centre of Amsterdam, solely based on CPTs. The map was validated using data from previously published archaeological reports. Copyright © 2015 John Wiley & Sons, Ltd.

*Key words:* Cone Penetration Testing; Amsterdam; archaeological deposits; urban archaeology

## Introduction

Cone Penetration Testing (CPT) is a geotechnical method used to determine the composition of the subsurface and its mechanical properties. It was developed in the Netherlands in the 1930s and was initially used as a tool to measure the penetration resistance of sediments during pile foundation investigations (Keverling Buisman, 1940). In subsequent decades, technical improvements made it possible to use for lithological classification as well (Begemann, 1965).

Almost the entire subsurface of the Netherlands consists of unconsolidated sediments. Knowing the mechanical properties and lithological composition of these sediments is essential for all kinds of construction and engineering projects. The most convenient and economical way to obtain this knowledge is by CPT. Thus, over 20,000 CPTs are conducted in the Netherlands each year. A significant amount of these measurements are stored in Dinoloket, an internet portal providing Dutch geo-data and information, operated by the Geological Survey of the Netherlands (TNO, 2014).

Since CPTs are primarily associated with construction and engineering projects, the majority of soundings are conducted in urbanized areas. In Europe the subsurface of urbanized areas often comprises thick layers of archaeological deposits (e.g. Holden *et al.*, 2009; De Beer *et al.*, 2012). Therefore, when performed in an urban setting, there is a high probability that archaeological layers are being sounded during CPT.

CPT is, strictly-speaking, a geotechnical method. Nevertheless, it has been widely adopted by the international geological community (see e.g. Amorosi and Marchi, 1999; Törnqvist *et al.*, 2000; Schokker and

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Koster, 2004; Lafuerza *et al.*, 2005; Hijma *et al.*, 2009; Sarti *et al.*, 2012). This is not the case in the field of archaeology. Only a few archaeological investigations have made use of CPT soundings and even then it has been primarily to examine the geological context of sites under archaeological investigation, and not necessarily to map archaeological deposits contained within the natural stratigraphy (e.g. Bates *et al.*, 2007; Calabrese *et al.*, 2010; Bates and Stafford, 2013; Missiaen *et al.*, 2015; Vos and Cohen, 2015; Vos *et al.*, 2015). One of the only exceptions to this is a study by Ovandan-Shelley and Manzanilla (1997). They used CPT data to analyse geotechnical characteristics of both archaeological and geological layers situated beneath a cathedral in Mexico City.

Although CPT is a less expensive and more time-efficient method of examining the subsurface than drilling, the poor integration of CPT in archaeology is understandable; CPT only sounds mechanical properties and no direct samples can be taken. Furthermore, no general characteristics have been documented regarding the recognition of archaeological layers in CPT log data. In a study by the Dutch governmental institute for archaeology and heritage (RCE), it was even stated that the identification of archaeological deposits in CPT logs is improbable (Huisman *et al.*, 2011).

This paper aims to explore the potential of CPT as a tool for archaeological prospection, with a special focus on Amsterdam (Figure 1), by: (i) differentiating archaeological from natural deposits in CPT soundings, (ii) characterizing archaeological deposits in soundings, and (iii) using this characterization to produce a map depicting the spatial distribution and thickness of archaeological deposits in the historic centre of Amsterdam.

## Cone Penetration Testing (CPT)

Background information and technicalities on CPT are summarized from Lunne *et al.* (1997). CPT is a so-called *in situ* site investigation method that sounds the subsurface without taking sediment samples. A test consists of the pushing of a cone, attached to a series of rods (Figure 2a), with a constant rate of 2 ± 0.5 cm/s into the subsurface, during which: (i) the resistance the tip of the cone experiences during the penetration or cone resistance $q_c$ (in MPa), and (ii) the friction between the adhesion jacket and the surrounding deposits or sleeve friction $f_s$ (in MPa), are each measured (Figure 2b). These two measurements, in combination with the friction ratio $R_f$ (the ratio between the sleeve friction and cone resistance expressed as a percentage), can be used to gain insight into the composition of the subsurface.

A fundamental difference between defining the composition of the subsurface using CPT and more traditional archaeological analyses such as coring and transect studies, is that, in CPT, the texture and structure of deposits are not directly derived. Instead, with a CPT, the mechanical behaviour of sediments is sounded. Although this mechanical behaviour is primarily caused by lithology and plasticity; post-depositional processes like cementation, current- and past-groundwater levels, and consolidation can also influence the measurements. In areas with a well-known geological composition, such as Amsterdam, CPT almost entirely replaced geotechnical drilling. Many decades of subsurface investigations have enabled engineers to recognize geological units solely by their mechanical behaviour. However, in less examined areas, ground truthing of CPTs is a necessity. This is often conducted by drilling a borehole within decimetres of a CPT site. By comparing the lithological composition of a drilled core with the log data of its corresponding CPT, a site specific framework can be obtained, which can subsequently be used to interpret CPTs conducted in the surrounding area.

To enable the use of CPT in either geology or archaeology, it is advisable to translate the sounded mechanical properties into lithology. Several charts have been developed for this purpose. The most popular in geological studies appears to be the chart of Robertson *et al.* (1986) and its updated version (Robertson, 1990), used in studies of, for example, Amorosi and Marchi (1999), Lafuerza *et al.* (2005), Arel (2012) and Missiaen *et al.* (2015). Others are the charts of Olsen and Farr (1986) used by, for example, Coerts (1996), or Douglas and Olsen (1981) used by, for example, Schokker and Koster (2004), and, in the past, that of Begemann (1965) used by, for example, Krajícek and Kruizinga (1982). In this study, the Robertson (1990) chart was applied to translate the CPT soundings into lithology (Figure 3). By using a popular chart, scientific reproducibility is stimulated.

## Study area

In the context of north-western Europe, Amsterdam is a relatively young city. It was founded in the thirteenth century AD in a coastal wetland, at the intersection of the Amstel River and the former IJ estuary (e.g. De Gans, 2015). The subsurface consists of a ~12 m thick Holocene sequence overlying a Pleistocene basement. For engineering purposes, a CPT in Amsterdam is typically conducted to a depth of 25 m below mean sea level (MSL).

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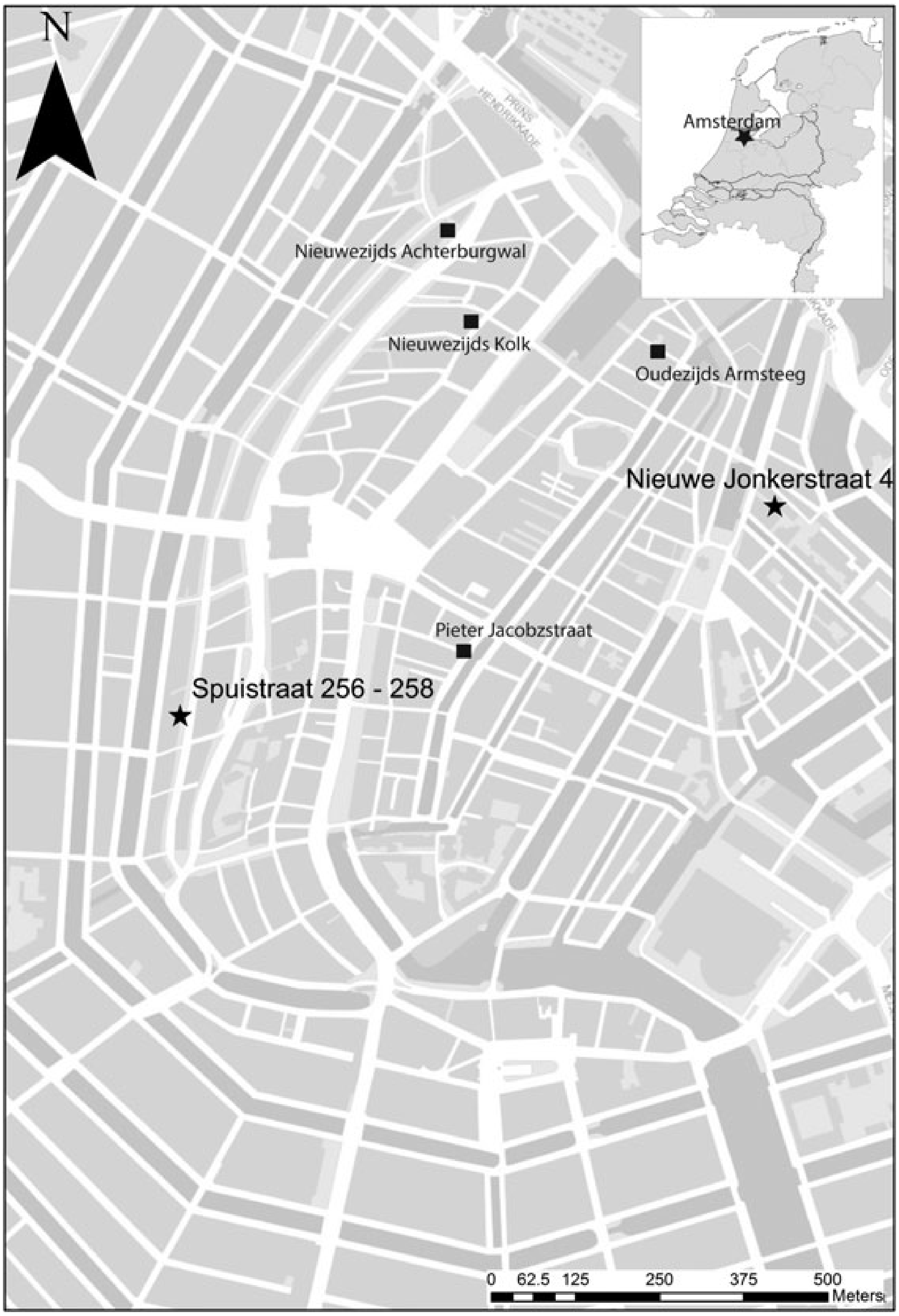

Figure 1. Topographical map depicting the location of Amsterdam and its city centre. Within the city centre, the locations under investigation are indicated. Stars mark the sounded archaeological sites, and squares mark the archaeological sites used for the validation of the archaeological distribution map.

Strong urbanization of Amsterdam during the last 150 years has demanded numerous geological, hydrological, geotechnical, and archaeological investigations. This has yielded a vast amount of subsurface data (Schokker *et al.*, 2015). The first amalgamation of archaeology and CPT in Amsterdam occurred in the 1950s, when CPTs were used to disprove an archaeological statement regarding the foundation of Amsterdam's oldest building, the Oude Kerk (Old Church) (Den Boer, 1955). By the early 1980s, the geological composition of Amsterdam was so well known that geological profiling could be executed solely based on CPTs (Krajícek and Kruizinga, 1982), a procedure that has been repeated during subsequent

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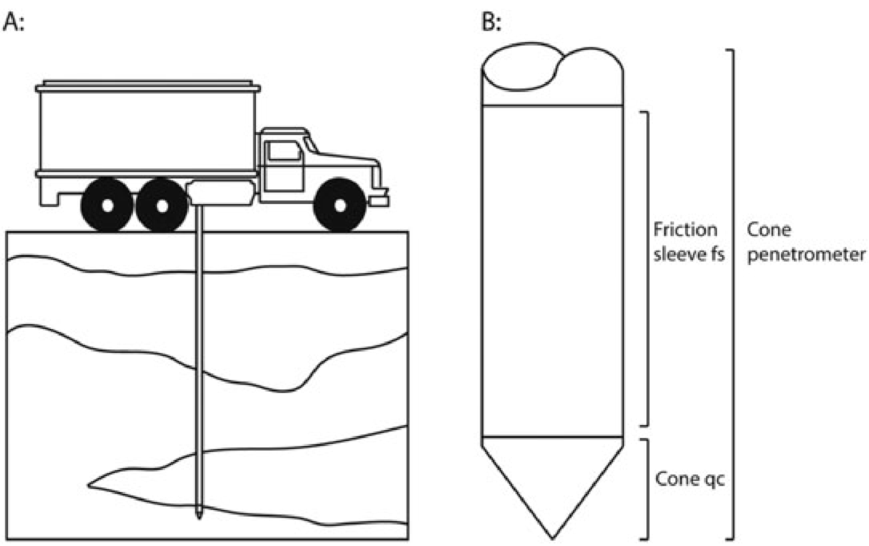

Figure 2. (a) Typical set-up of a cone penetration test, where a heavy truck is being used to push the cone with a constant rate into the subsurface (after Rose *et al*., 1996). (b) Schematic representation of a cone (after Lunne *et al*., 1997); $q_c$ is measured at the cone, $f_s$ at the friction sleeve.

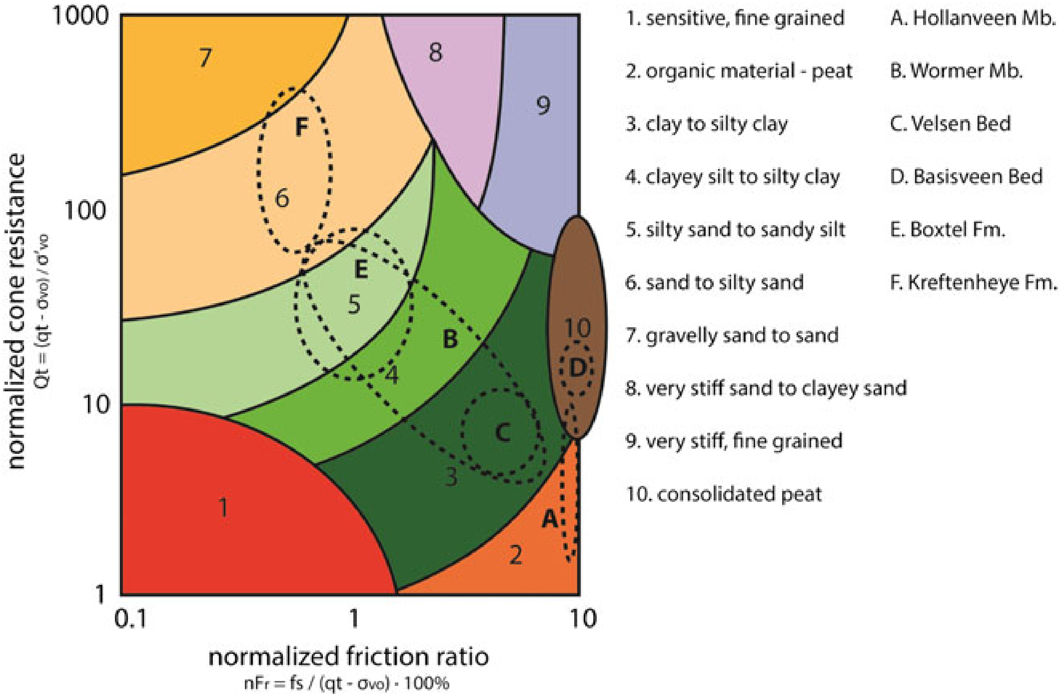

Figure 3. The chart of Robertson (1990). The chart has partly been adjusted for the Dutch subsurface by Fugro GeoServices, since in the Netherlands abundantly present consolidated peat is not a category in the chart. This additional category is defined on the expert judgement of Fugro's engineers, and in practise appears to be working relatively well. During normalization, $q_t$ was substituted by $q_c$, and overburden stress $\sigma_{vo}'$ was set at a constant value of 18 kN/m$^3$. Further details regarding the normalization procedure are provided by Robertson (1990). Within the chart, zones are designated in which lithostratigraphic units, typical for the Amsterdam shallow subsurface, would plot. These values are generalized and estimated from frameworks provide by Vos (1982), Krajícek and Kruizinga (1982) and De Gans and Wassing (2000) (see text for explanation).

decades (e.g. De Gans and Wassing, 2000; Koster, 2012; Kranendonk *et al*., 2015). The abundancy of freely available data (see national database Dinoloket: TNO, 2014), encouraged the development of frameworks in which typical Amsterdam CPT values were correlated to known lithostratigraphy (Vos, 1982; Krajícek and Kruizinga, 1982; De Gans and Wassing, 2000; Koster, 2012 applied in Kranendonk *et al*., 2015). These

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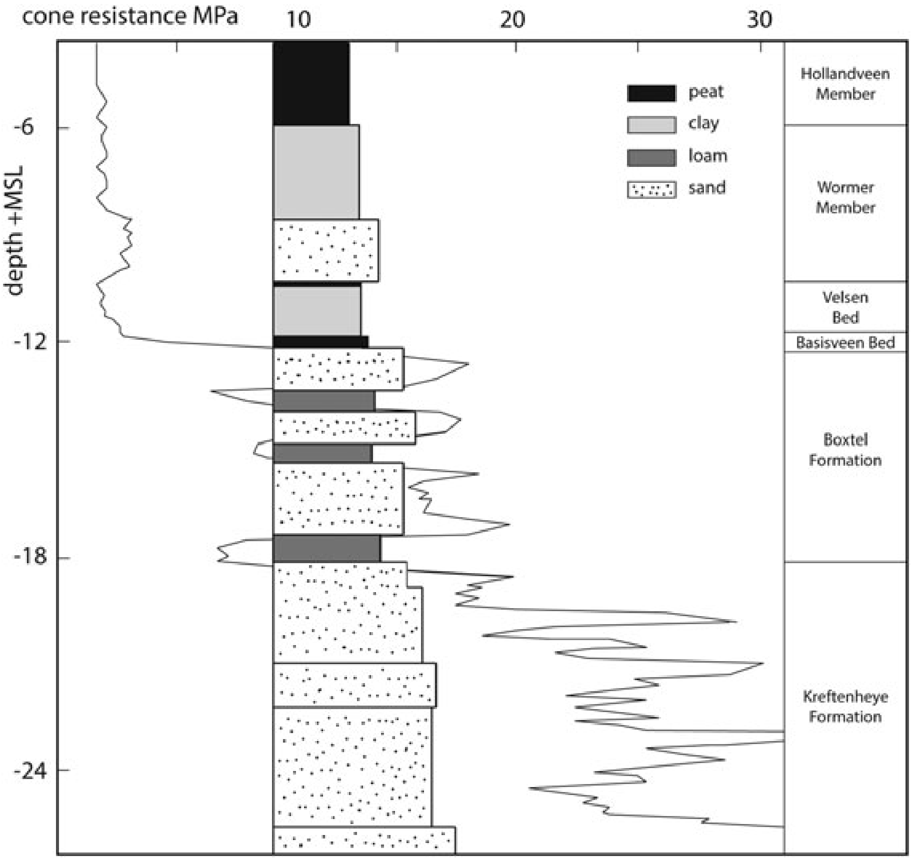

Figure 4. Schematic representation of a typical Amsterdam core log and hypothetical corresponding cone resistance, based on Krajícek and Kruizinga (1982) and De Gans and Wassing (2000). The highest cone resistances are associated with sandy facies. The sand situated at −12 m and deeper belongs to Pleistocene deposits, and is important for engineering purposes, since it acts as a supporting layer for foundations.

frameworks follow certain empirical relations between CPT values and lithostratigraphy; often with use of charts translating mechanical properties into lithology (see references in previous section). These frameworks are essential for interpreting CPTs without having to perform ground truth procedures, catalysing the use of CPT for subsurface investigations (Figure 4).

## *Lithostratigraphic – CPT framework*

Below, the lithostratigraphy of Amsterdam within 25 m MSL is described in conformity with the official nomenclature of the Geological Survey of the Netherlands (De Mulder *et al*. 2003), with corresponding typical cone resistance and sleeve friction values based on empirical frameworks for Amsterdam, provided by Vos (1982), Krajícek and Kruizinga (1982) and De Gans and Wassing (2000), and translation of those CPT values into lithology according to the Robertson (1990) chart (Figure 3).

The lowest deposits consist of medium to very coarse grained fluvial sands of a braided predecessor of the River Rhine (Kreftenheye Formation), and are characterized by the highest cone resistances of the sequence with values ranging from 15 to 30 MPa. Within the Robertson (1990) chart, the lithology of the Kreftenheye Formation will plot within the sand to silty sand and gravelly sand to sand zones. The Kreftenheye Formation is overlain by fine to medium coarse grained aeolian coversands, locally embedded with clays (Boxtel Formation). The sandy facies of the Boxtel Formation typically have cone resistances between 10 and 20 MPa, while its clayey intercalations yield cone resistance values up to 5 MPa. The sandy facies will plot within the sand to silty sand zone, while the clayey facies will plot within the clayey silt to silty clay zone. Both formations were deposited during the Late Pleistocene and range from approximately 25–12 m below MSL. The Holocene sequence commences with a ~20 cm thick basal peat layer (Basisveen Bed). The basal peat of the Basisveen Bed is heavily consolidated; it has a cone resistance between 1 and 2 MPa, and has a very characteristic sleeve friction corresponding with approximately one-tenth of its cone resistance. Within the Robertson (1990) chart, the basal peat will plot within the consolidated peat zone. This peat is overlain by a 2 to 3 m thick organic lagoonal clay (Velsen Bed), which is interbedded with thin sandy layers and often capped by a ~10 cm thick peat layer. The lagoonal deposits of the Velsen Bed typically have lower cone- (<1 MPa) and sleeve friction values (<0.01 MPa) than the underlying basal peat and the sandy facies of the overlying tidal deposits. Due to the alteration of clay with sandy layers and peat, the lines in a CPT graph within the Velsen Bed may, at times, appear erratic. Within the Robertson (1990) chart, the clays will plot within the clay to silty clay zone. Tidal flat deposits (Wormer Member) overlie the lagoonal deposit. They are ~5 m thick and consist of a lower level of very fine to medium fine sandy and an upper level of clayey to humic clayey facies. The sandy facies is ~3 m thick and has a cone resistance up to 5 MPa, the clayey to humic clayey layer is ~2 m thick and has very low cone resistance values (<1 MPa). Within the Robertson (1990) chart, the sandy facies will plot within the sand to silty sand zone, and the clayey facies will plot within the clay to silty clay zone. Peat (Hollandveen Member) forms the end of the natural succession. Its base lies almost uniformly around 5 m below MSL. Similar to the basal peat, it has experienced post-depositional consolidation. However, its cone resistance and sleeve friction yield lower values than the basal peat. Cone resistance is around 1 MPa, with a characteristic sleeve friction of one-tenth of the cone resistance. Therefore, the peat of the Hollandveen Member will plot at the transition between the organic material to peat and the consolidated peat zones.

The peat has been overlain by archaeological deposits. These deposits consist of accumulated layers from different periods of very diverse composition, and could contain archaeological remains of different materials. It is, therefore, impossible to predict precisely how archaeological deposits will mechanically behave during penetration. It is assumed that the oldest part of Amsterdam has the thickest archaeological layers due to a longer period of accumulation. Therefore, a study area was selected in the very centre of Amsterdam, an area that has been under anthropogenic influence since the first centuries of the city's existence.

## Methods

In archaeological prospection, it is important to be able to differentiate between natural and anthropogenic deposits (Bates, 1998). Therefore, particular CPTs were chosen for analysis based on the fact that it was known that they had penetrated through archaeological layers and thus contained log data of both archaeological and natural deposits. In total, seven CPTs conducted at two archaeological sites were selected. The sites and CPTs were selected after comparing the location of CPTs in the database of Fugro GeoServices and archaeological excavation reports of the Archaeological Survey of the Municipality of Amsterdam (BMA: Bureau Monumenten en Archeologie), which are freely available online (BMA, 2014a). This selection criterion returned multiple matches, but only two archaeological reports of excavations in the targeted area contained descriptions of lithological composition of archaeological deposits. Therefore, it was the sites covered by these reports that were seen to be most suitable for cross-analysis with CPT data.

The archaeological sites are located at Spuistraat 256–258 (Gawronski and Veerkamp, 2010), and at Nieuwe Jonkerstraat 4 (Gawronski *et al.*, 2010) (Figure 1). The sites were excavated by the BMA in 2007 and 2008, respectively. The lithology of the sites has been

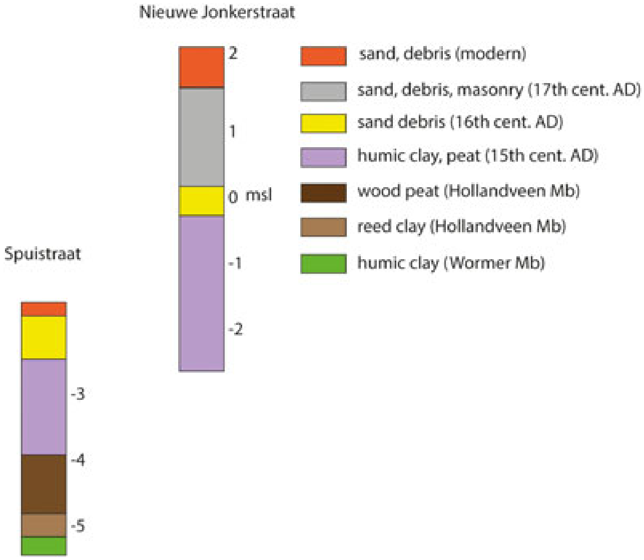

Figure 5. Profile showing the natural and anthropogenic deposits at the Spuistraat and Nieuwe Jonkerstraat sites, encountered during archaeological excavation. Spuistraat: the lowest natural deposits consist of clayey tidal flat deposits (Wormer Member), underlying reedpeat and woodpeat (Hollandveen Member). The anthropogenic deposits consist of clayey, peaty and organic layers deriving from the pre-urbanization period (< AD 1425). The sandy deposits belong to a period after the city expansion (Gawronski & Veerkamp, 2010). Nieuwe Jonkerstraat: The underlying natural deposits have not been encountered during the excavation. The lowest archaeological deposits are correlated to the period prior to AD 1585, when the area was an industrial estate and consist mainly of clayey and organic material. The sandy debris deposits derive from the period after late sixteenth century city expansion (Gawronski *et al.*, 2010).

described by archaeologists of the BMA by examining transects of the excavation pits.

The CPTs at both sites were conducted by Fugro GeoServices. There were two soundings taken at the Spuistraat 256–258 site in 2004 and five taken at the Nieuwe Jonkerstraat 4 site in 2006. The pushing equipment used was a 22.8 tonne heavy truck with a penetration capacity of 20 tons. The cone type used was a Fugro standard cone with a diameter of 3.6 cm, a cross-sectional area of 15 $cm^2$ and a cone apex of 60°. All seven CPTs were predrilled prior to sounding. This is a mandatory procedure to prevent damage to subsurface infrastructures. The predrilled cores were described in the field and added to the CPT graphs.

The lithological descriptions and interpretations of the archaeological sites are derived from the excavation reports of Gawronski and Veerkamp (2010) and Gawronski *et al*. (2010), and are summarized as follows (Figure 5). At Spuistraat 256–258 the pit was excavated to 5 m below MSL. The natural deposits consist of a 1 m thick reed-, wood- and moss-peat layer (Hollandveen Member), which is situated on top of clayish sandy tidal deposits (Wormer Member). The lowest archaeological deposit starts ~3.2 m below MSL and consists of a very humic 60 cm thick clay layer which is partly covered with very compact clayey peat and straw of approximately 5 to 10 cm thick, and is overlain by 60 cm of clay. Locally, situated on top of the clay is a greasy ~20 cm thick manure layer. The layer on top of this consists of an approximately 10 to 50 cm thick clay sequence embedded with small pieces of debris, manure, and pottery fragments. Some small patches of humic clay and loose peat are located in the top of this layer. Throughout this entire clayey/organic sequence, some small ditches are present, filled with clay, sandy clay, wood, and manure. Situated on top of these clayey and organic layers are two sandy and one peat and debris containing sandy layers, with remains of foundations consisting of bricks and wood with an infill of sandy or peaty material. The sandy deposits are ~50 cm thick.

The entire sequence is associated with the city expansion of the fifteenth and sixteenth centuries. First the clayey and organic layers were dumped on the natural peat deposit to make the terrain suitable for construction. During this phase, the terrain was most likely also used as a garbage disposal site. The more sandy layers derive from the period of construction, when coarse material was put into place in order to make it more suitable for construction.

At Nieuwe Jonkerstraat 4 the bottom of the excavation is situated at 2.7 m below MSL and the natural deposits were not reached in the pit. The composition of the lowest encountered archaeological deposits comprises an approximately 2 m thick humic clayey to peaty sequence, intercalated with three levels of shell layers at, respectively, 1.1, 0.9 and 0.6 m below MSL. The sequence has almost no internal layering and its top is situated around 20 cm below MSL. On top of this are situated several phases of foundations, consisting of bricks, tiles, and wood in a matrix of sand, humic sand, and debris.

The thick peaty and clayey layers have been correlated to a period when this area was located just outside the urbanized part of Amsterdam and was in use as an industrial area. The oldest deposits can be dated to approximately AD 1500, but since the bottom of the anthropogenic deposits was not encountered, older material may be situated deeper in the subsurface. The peaty and clayey layers were brought up during phases when the surface became too soggy. The shell layers were probably deposited to provide more stability. The area eventually became urbanized in AD 1585. The sandy debris layer containing several phases of foundations dates from this period onwards.

## *Interpretation of CPTs*

The soundings were interpreted based on the presented lithostratigraphy – CPT framework, the automatic classification from the Robertson (1990) chart, and descriptions of the anthropogenic layers of the sites made during the excavations. Subsequently, the archaeological layers were further analysed to determine general CPT characteristics of archaeological deposits. Once obtained, these general mechanical characteristics and their observed differences when compared with the natural deposits were eventually used to determine the thickness of archaeological deposits in CPTs extracted from the national database (TNO, 2014). The determined thicknesses were interpolated to produce a map depicting the distribution and thickness of archaeological deposits in the historical city centre of Amsterdam.

## *Mapping*

The extracted data from the national database (Figure 6) consists of scanned CPT graphs rather than the original log data. Analysing the CPTs with the inhouse developed software was therefore not an option. Instead, all CPTs were analysed visually, based on the lithostratigraphy – CPT correlation framework presented in the previous section, without the use of the Robertson (1990) chart.

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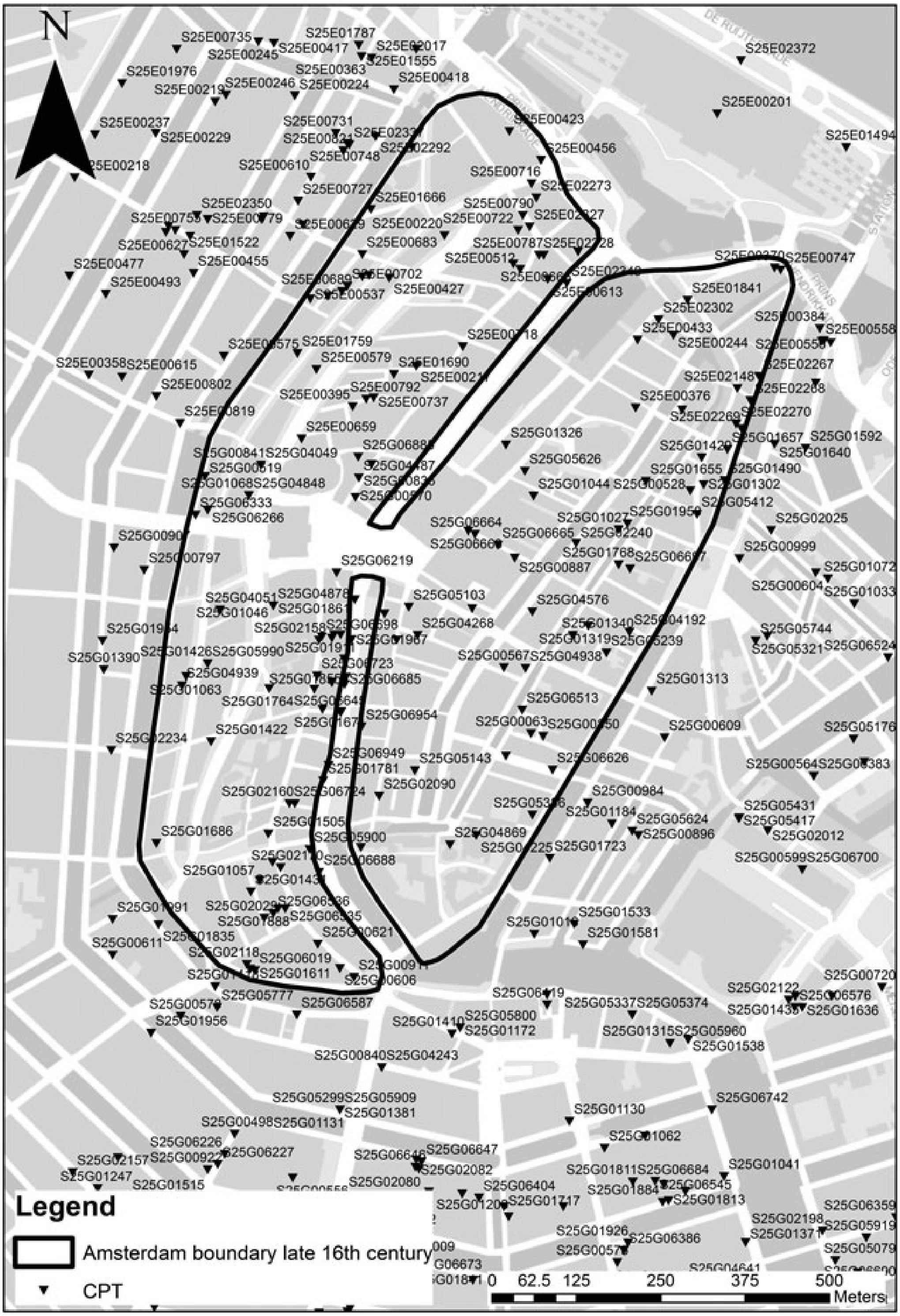

Figure 6. Map depicting 407 CPTs downloaded from the national database (TNO, 2014). All displayed CPTs were visually analysed and used in the interpolation.

The boundary between the natural and anthropogenic deposits was determined by the upward transition of the upper-most natural deposit (i.e. the top of the peat of the Hollandveen Member), with its cone resistance of ~1 MPa and typical sleeve friction of approximately one-tenth of that value, to CPT values departing from these

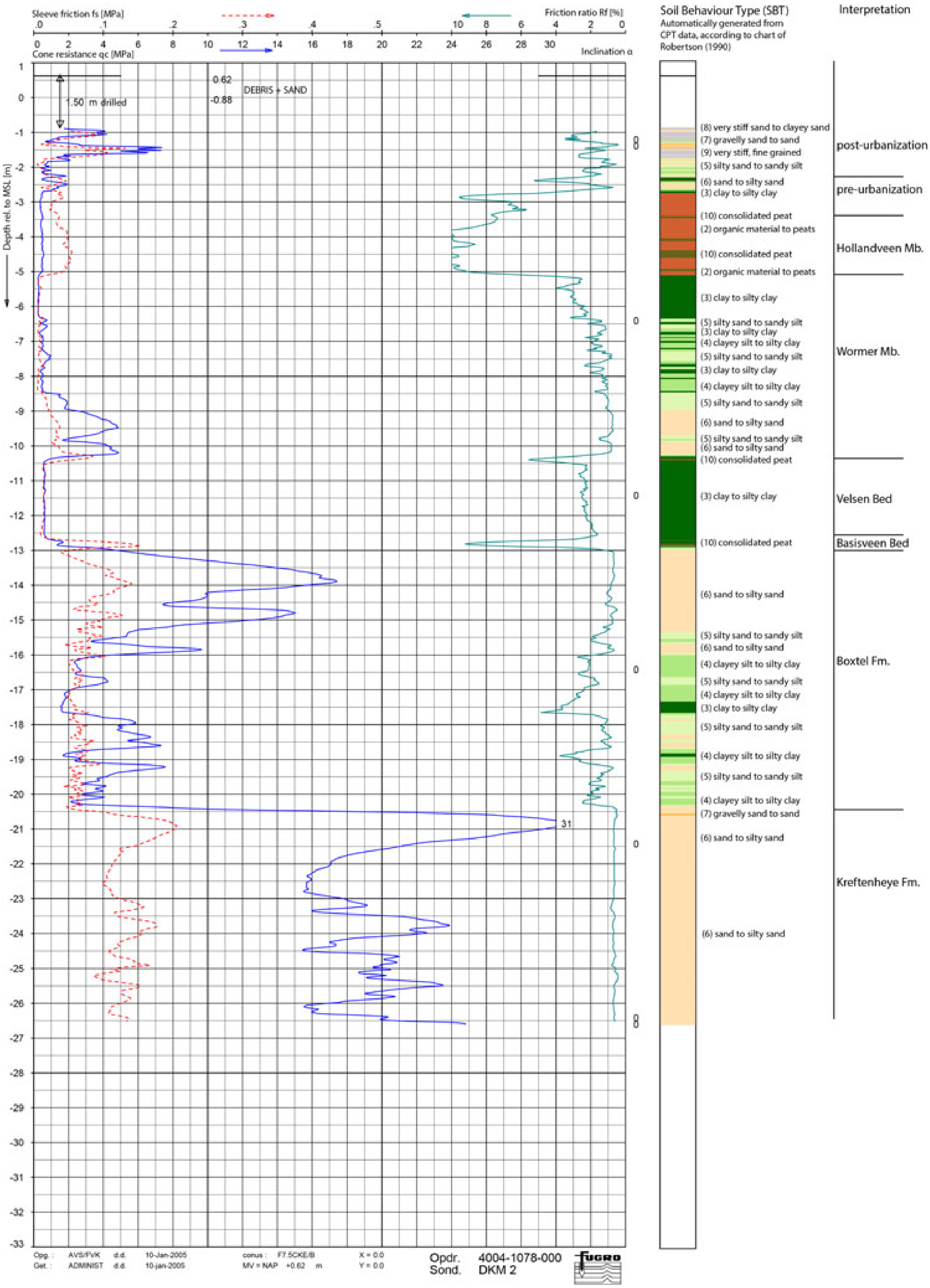

Figure 7. Plot of one of the CPTs conducted at the Spuistraat 256–258 site, with archaeological and geological interpretation.

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expected values. The thicknesses obtained per CPT location were subsequently interpolated using inverse distance weighting, and smoothed with a 100 m × 100 m window.

To validate the interpolated thickness of archaeological deposits in the study area at positions without direct CPT data, a check was performed comparing documented thickness of archaeological deposits at certain locations, with values obtained by interpolation at those locations. In total, 75 excavation reports of the BMA were consulted from their freely accessible online archive to ascertain the documented thickness of archaeological deposits (BMA, 2014a). In total, four reports met the requirement of documented thickness of archaeological deposits within the interpolated area (Gawronski and Jayasena, 2009, 2010, 2011; Gawronski and Veerkamp, 2013). The locations of these excavations are depicted in Figure 1.

## Results

At Spuistraat 256–258 (Figure 7) the surface was measured at 0.6 m above MSL. The deposits, ranging from approximately 10 to 25 m below MSL, were translated into sand to silty sand, and have been interpreted as the Pleistocene Kreftenheye Formation. Its upper boundary was determined at the transition of a cone resistance of ~30 MPa to lower values, corresponding to an overlying 5 m thick alternation of sand to silty sand and clay to silty clay layers and an ~2.5 m thick sand to silty sand deposit. This heterogeneous sequence has been interpreted as the Pleistocene Boxtel Formation. Its upper part was determined by the very characteristic basal peat, with the cone resistance to sleeve friction ratio of ~0.1. The Holocene sequence, therefore, starts with an ~10 cm thick consolidated peat layer, which was interpreted as the Basisveen Bed, followed by an ~2 m thick clay to silty clay layer underlying an ~10 cm thick consolidated peat layer. This clay and peat association, in combination with its position underlying a sandy deposit, led to the interpretation of this sequence as the Velsen Bed. On top of this lies a deposit composed of ~1 m sand to silty sand, ~2 m of thin clay to silty clay and silty sand to sandy silt layers, and an ~1 m clay to silty clay layer. It ends around 5 m below MSL and has been interpreted as the Wormer Member. The Wormer Member is overlain by layers of consolidated peat and organic material to peat, recognizable by its typical cone resistance to sleeve friction ratio of ~0.1. The peat has been interpreted as the Hollandveen Member. The top of the Hollandveen Member is located around 2.8 m below MSL. The upper part of the peat marks the end of the natural sequence and was determined by the transition of a cone resistance to sleeve friction ratio of ~0.1, to deviating lower ratios.

The curves of the overlying deposits as represented on the CPT graphs are very erratic. In this anthropogenic part of the Amsterdam subsurface sequence, the existing framework was not applicable. According to the Robertson (1990) chart, the compositions of the layers directly on top of the Hollandveen Member consist of clay to silty clay, sand to silty sand, silty sand to sandy silt, very stiff fine grained, gravelly sand to sand, and very stiff sand to clayey sand. This strong trend of increasing coarseness conforms to the lithological description of the archaeological deposits. The lowest clayey deposits are interpreted as belonging to the pre-urbanization phase. The classification of the coarser overlying deposits corresponds with the phase of city expansion.

At Nieuwe Jonkerstraat 4 (Figure 8) the surface was measured at 1.7 m above MSL. From approximately 25 to 12 m below MSL the composition was translated into sand to silty sand, interbedded with thin, up to decimetres thick, layers of clay to silty clay, clayey silt to silty clay, and silty sand to sandy silt layer. These deposits were interpreted as the Pleistocene Kreftenheye and Boxtel Formations. Similar to the Spuistraat site, the boundary between the two Pleistocene Formations is based on the onset of fine grained intercalations within the sand, visible by lower cone resistance and sleeve friction values commencing around 18 m below MSL. The Holocene sequence starts around 12 m below MSL. The distinctive basal peat is absent. However, the presence of a 2 m thick clay to silty clay layer overlain by a thin consolidated peat layer, led to the interpretation of this as the lagoonal Velsen Bed, which alternates in the lowest ~1.5 m between clayey silt to silty clay and silty sand to sandy silt. This alternation makes the Velsen Bed appear erratic in the CPT graph, which is typical for this deposit. The Velsen Bed is overlain by an ~2 m thick deposit of alternating clayey silt to silty clay, silty sand to sandy silt and sand to silty sand, which is subsequently overlain by ~1.5 m of clay to silty clay. These two sequences are interpreted as the Wormer Member. An ~1 m thick consolidated peat layer lies over the Wormer Member, and has been interpreted as the Hollandveen Member. It has the typical cone resistance to sleeve friction ratio of ~0.1. The top of the peat, and therefore the top of the natural sequence, is situated at ~4.5 m below MSL, and was determined by a steep decrease of this ratio.

Directly on top of the peat lies an ~2 m thick anthropogenic deposit consisting, according to the Robertson

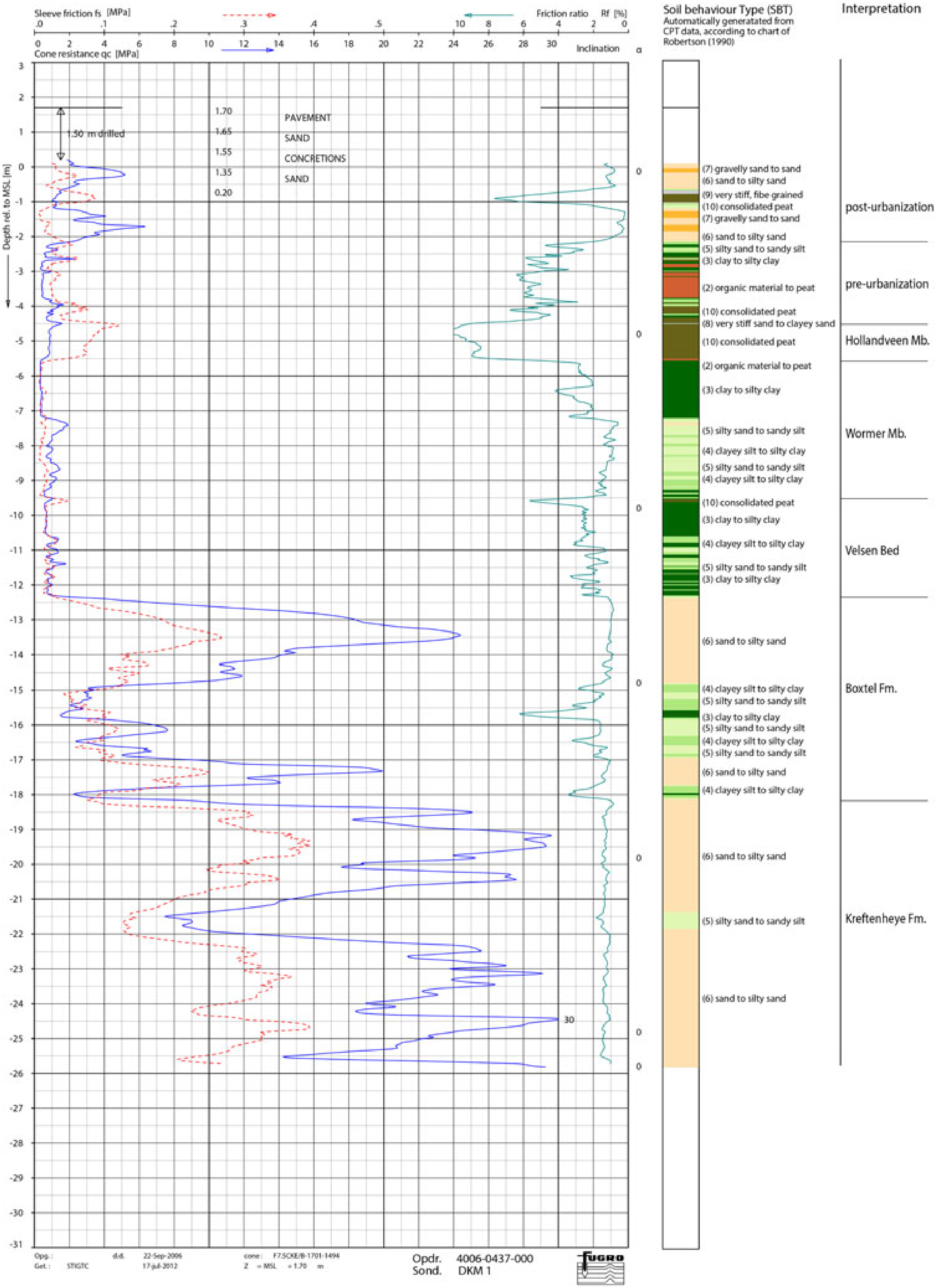

Figure 8. Plot of one of the CPTs conducted at the Nieuwe Jonkerstraat 4 site, with archaeological and geological interpretation.

(1990) chart, of an alternation of very stiff sand to clayey sand, consolidated peat, organic material to peat, clay to silty clay, silty sand to sandy silt, gravelly sand to sand. Similar to the Spuistraat site, the curves of the CPT graphs appear to be very erratic. This organic, peaty to clayey part of this sequence corresponds with the lithological description of the lowest archaeological layers, and has been interpreted as pre-city expansion deposits. The coarser sandy uppermost layer, corresponds with the lithological description of the highest archaeological stratigraphy, and has been interpreted as deposited during actual urbanization.

## *Characterization of archaeological deposits*

Generally speaking, all seven CPTs show the same trends regarding the composition of the subsurface. The archaeological deposits can be identified based on the very distinctive decrease in ratio between the cone resistance and the sleeve friction, which indicates the transition between the uppermost natural peaty deposit of the Hollandveen Member and lowest archaeological deposits. Additionally, the lithological translations of the soundings from the archaeological deposits overlying the peat were comparable to those described in the archaeological excavation reports.

Based on the classification chart of Robertson (1990), within the archaeological deposits, some noticeable characteristics of the archaeological layers are discernable: (i) rapid alternation of layers with a different lithological composition; (ii) very diverse lithological composition; (iii) the presence of overconsolidated layers. When put into a framework similar to that which was used to determine the lithostratigraphical composition, it could be stated that the CPT curves of archaeological sequences appear to be strongly erratic, with rapid alternations of high and low cone resistance and sleeve friction values.

Based on the dataset of seven CPTs, on average, natural layers change in classification every 30 cm. Archaeological layers, however, change in classification on average every 10 cm. The lithological classifications of the archaeological deposits are very diverse and cover the entire range of Robertson's chart; natural deposits belonging to a certain deposit do not show this pattern. Overconsolidated clastic (not peat) deposits are not associated with Holocene sequences in the Netherlands. The youngest overconsolidated deposits in the Netherlands were formed during the penultimate glaciation, under influence of high overburden pressure caused by the Fennoscandia ice sheet. However, especially in the upper archaeological layers, sediments exhibiting this behaviour are relatively abundant.

Figure 9. Distribution map of the thickness of archaeological deposits in the historic centre of Amsterdam. The thickest archaeological deposits are situated around the edges of the selected area. The extent of the historic city centre was estimated with the AD 1544 map of Cornelis Anthonisz. (BMA, 2014b).

Table 1. The four archaeological sites.

| Location | Modeled thickness (m) | Actual thickness (m) | Difference (m) |
|---|---|---|---|
| Nieuwezijds Achterburgwal | 3.42 | 3.55 | −0.13 |
| Oudezijds Armsteeg | 3.06 | 4.00 | −0.94 |
| Pieter Jacobzstraat | 2.60 | 2.30 | 0.30 |
| Nieuwezijds Kolk | 3.10 | 3.50 | −0.40 |

## *Thickness of archaeological deposits map*

The map based on the earlier described characteristics shows that the lower boundary of archaeological layers is typically situated between 2.5 to 3.5 m below MSL (Figure 9). Validation of the four archaeological sites shows deviations of the lower boundary in the range of several decimetres (Table 1).

## Discussion

Although the method of identifying archaeological deposits in CPT log data could appear to be very site- and subsurface-dependent, the results show that it has potential. The key aspect of this method is similar to other archaeological prospection techniques: differentiating anthropogenic anomalies from natural deposits (Bates, 1998). In the case-study presented, this was made possible by using the empirical framework of linking lithostratigraphy to CPT values, the translation of those CPT values into lithology with the Robertson (1990) chart, and the lithological descriptions in the archaeological excavation reports. Such a framework is essential. However, if it is not available, ground truthing by coring is an advisable alternative (e.g. Missiaen *et al*., 2015).

The three characteristics of archaeological deposits identified in CPT logs, when translated with the Robertson (1990) chart – characteristics that do not occur in the natural deposits – are observed at both sites. Two of those characteristics, the rapid alternation of layers and the very diverse composition of those layers, can also be observed in the CPT published by Ovandan-Shelley and Manzanilla (1997) of a site in Mexico City. Although the CPT conducted in Mexico City has not been translated into lithology, the archaeological deposits in their graph appear to be very erratic when compared to the natural sequence, a trend which is also apparent from the findings in Amsterdam. The similarities in characteristics show promise. Therefore they could be a first step to a more general characterization of archaeological deposits through analysis of CPT log data. In the case of Amsterdam, human behaviour is the most obvious explanation for the rapid alteration of thin layers with a wide variety of lithological composition (when translated by Robertson, 1990). Sods, peat, waste, manure, organic remains, clay, etc. have all been dumped on the outskirts of the city and, during periods of urbanization, sands have been brought up to stabilize the area, i.e. to transform it from soggy fields to an area suitable for construction. This resulted in a very heterogeneous sequence relative to the natural deposits, with very diverse mechanical properties. An explanation of the overconsolidated or cemented layers requires some speculation. At present, the best theory is that those values are caused by the presence of debris (i.e. wood and other hard remains in subsurface), which was most likely pulverized during the cone penetration, leading to high sounded values. An alternate explanation could be that the CPT values were affected by unsaturated zones within the subsurface. A lack of groundwater tends to influence CPT values, making them very difficult to interpret (Lunne *et al*., 1997).

The results presented and discussed earlier are heavily dependent upon the selected classification chart. The use of the Robertson (1990) chart appears to yield promising results. Not only were the sounded archaeological deposits translated into lithology similar to the real observations, also the geological units were easily identified using the automatically generated classification, albeit with support of the existing framework. Some downsides to using the Robertson chart are the assumptions regarding the pore water pressures and effective stresses parameters; but even accounting for these assumptions the produced classification conformed to prior expectations. However, a classification chart with more lithological classes and less complex normalization procedures could be a necessity to more successfully – or more generally – integrate CPT in archaeological prospection.

Using the characterization of archaeological deposits in Amsterdam, a map depicting the distribution and thickness of archaeological layers was produced. Even without automatic classification of the CPT values into lithology, the erratic nature of archaeological deposits in CPT graphs relative to natural deposits and the strong decrease in ratio between the cone resistance and sleeve friction enabled the identification of the lower boundary of the archaeological deposits, or the upper boundary of the natural deposits.

## Conclusions

Archaeological deposits were identified in CPTs by:

(i) Translating the cone resistance, the sleeve friction, and friction ratio of the soundings into lithology using the Robertson (1990) chart.
(ii) Comparing the obtained lithology with geology and lithological descriptions of archaeological excavations.
(iii) Determining the upper boundary of the natural sequence by an empirical framework correlating local lithostratigraphy to CPT values.

Archaeological deposits are characterized in CPT log data by (according to the Robertson chart):

(i) Rapid alternation of layers with a different lithology.
(ii) Very diverse lithology.
(iii) The presence of overconsolidated layers.

These processes of identification and characterization enabled the composition of a map depicting the spatial distribution and thickness of archaeological deposits in the historic centre of Amsterdam, through the application of insights on CPTs extracted from the national database.

This study shows the potential of using CPT as a technique for archaeological prospection, especially in urbanized areas. Since this is one of the first studies completely devoted to this topic, it is clear that much more research needs to be conducted before this method can become as generally accepted as other more traditional archaeological prospection methods. The purpose of this study, however, was to exhibit the potential of CPT and to encourage its further study as a relatively non-invasive method of archaeological prospection.

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## References

Amorosi A, Marchi N. 1999. High-resolution sequence stratigraphy from piezocone tests: an example from the Late Quaternary deposits of the southeastern Po Plain. *Sedimentary Geology* **128**: 67–81. DOI:10.106/S0037-0738(99)00062-7.

Arel E. 2012. Predicting the spatial distribution of soil profile in Adapazari/ Turkey by artificial neural networks using CPT data. *Computers & Geosciences* **43**: 90–100. DOI:10.1016/j.cageo.2012.01.021.

Bates MR. 1998. Locating and evaluating archaeology below the alluvium: the role of sub-surface stratigraphical modelling. *Lithics* **19**: 4–18.

Bates MR, Bates CR, Whittaker JE. 2007. Mixed method approaches to the investigation and mapping of buried Quaternary deposits: examples from southern England. *Archaeological Prospection* **14**: 104–129. DOI:10.1002/arp.303.

Bates MR, Stafford E. 2013. *Thames Holocene: A geoarchaeological approach to the investigation of the river floodplain for High Speed 1, 1994–2004*. Wessex Archaeology: Salisbury.

Begemann HKSPh. 1965. *The Friction Jacket Cone as an Aid in Determining the Soil Profile*. *Proceedings of the 6th International Conference on Soil Mechanics and Foundation Engineering*, Montreal 2; 17–20.

Bureau Monumenten en Archeologie (BMA). 2014a. *Online archaeological reports library of the Archaeological Survey of the municipality of Amsterdam*. http://www.amsterdam.nl/kunstencultuur/monumenten/publicaties-0/amsterdamse/

Bureau Monumenten en Archeologie (BMA). 2014b. *Collection of georeferenced historical maps of the city centre of Amsterdam*. http://maps.amsterdam.nl/archeologie

Calabrese L, Di Cocco I, Centineo MC. 2010. Hydrographic evolution and palaeographic reconstruction of the southeastern Po Plain (Italy) during the last 4,000 years: an example of integration between stratigraphy and archaeology. *Geology of the Adriatic Area GeoActa special publication* **3**: 103–108.

Coerts A. 1996. *Analysis of Static Cone Penetration Test Data for Subsurface Modelling, a Methodology*, PhD Dissertation. Utrecht University. NGS 210.

De Beer J, Price SJ, Ford JR. 2012. 3D modelling of geological and anthropogenic deposits at the World Heritage Site of Bryggen in Bergen, Norway. *Quaternary International* **251**: 107–116. DOI:10.1016/j.quaint.2011.06.015.

De Gans W. 2015. The geology of the Amstel River in Amsterdam (Netherlands): man versus nature. *Netherlands Journal of Geosciences* in press. DOI:10.1017/njg.2014.41.

De Gans W, Wassing BBT. 2000. Geology and related geotechnical aspects of the underground of Amsterdam. *Zeitschrift Deutschen Geologischen Gesellschaft* **155**: 9–20.

De Mulder EFJ, Geluk MC, Ritsema IL, Westerhoff WE, Wong TE. 2003. *De ondergrond van Nederland*. Wolters Noordhoff: Groningen/Houten.

Den Boer JFM. 1955. Van heien en heipalen en het probleem van de Amsterdamse bodem. *Jaarboek van het Genootschap Amstelodamum* **47**: 27–47.

Douglas BJ, Olsen RS. 1981. *Soil Classification using Electric Cone Penetrometer*. Symposium on Cone Penetration Testing and Experience, Geotechnical Engineering Division, ASCE, St Louis; 209–227

Gawronski J, Jayasena R. 2009. *Noordoosthoek van eem 13$^{de}$-eeuws verdedigingswerk*, Amsterdamse Archeologische Rapporten 37. Municipality of Amsterdam: Amsterdam.

Gawronski J, Jayasena R. 2010. *Bewoning tussen Nes en stadswal*, Amsterdamse Archeologische Rapporten 49. Municipality of Amsterdam: Amsterdam.

Gawronski J, Jayasena R. 2011. *Wonen achter de Oudezijds Voorburgwal*, Amsterdamse Archeologische Rapporten 60. Municipality of Amsterdam: Amsterdam.

Gawronski J, Vanoverbeke R, Jayasena R. 2010. *Kelderwoningen en een beerput in de Lastage*, Amsterdamse Archeologische Rapporten 44. Municipality of Amsterdam: Amsterdam.

Gawronski J, Veerkamp J. 2010. *Spuistraat*, Amsterdamse Archeologische Rapporten 47. Municipality of Amsterdam: Amsterdam.

Gawronski J, Veerkamp J. 2013. *Archeologische begeleiding Spuistraat 3A/ Nieuwezijds Voorburgwal 16*, Amsterdamse Archeologische Rapporten 73. Municipality of Amsterdam: Amsterdam.

Hijma MP, Cohen KM, Hoffmann G, Van der Spek AJF, Stouthamer E. 2009. From river valley to estuary: the evolution of the Rhine mouth in the early to middle Holocene (western Netherlands, Rhine-Meuse delta). *Netherlands Journal of Geosciences – Geologie en Mijnbouw* **88**(1): 13–53. DOI:10.1017/S0016774600000986.

Holden J, Howard AJ, West J, Maxfield E, Panter I, Oxley J. 2009. A critical review of hydrological data collection for assessing preservation risk for urban waterlogged archaeology: a case study from the City of York, UK. *Journal of Environmental Management* **90**(11): 3197–3204. DOI:10.1016/j.jenvman.2009.04.015.

Huisman DJ *et al.* 2011. *De invloed van bouwwerkzaamheden op archeologische vindplaatsen*. Rijksdienst voor het Cultureel Erfgoed: Amersfoort.

Keverling Buisman AS. 1940. *Grondmechanica*. Uitgeverij Waltman: Delft.

Koster K. 2012. *A Geo-archaeological and Historical Geographical Approach to Examine 18th and 19th Century Pile Driving in Amsterdam*, IGBA-report 2012, MSc Thesis.

Krajícek PVFS, Kruizinga J. 1982. *CPT's, an Excellent Aid to Determine Soil Parameters and Deviations in the Soil Profile of the Proposed Motorway-river Crossing near Amsterdam*, Penetration Testing 2. Proceedings of the Second European Symposium on Penetration Testing, Amsterdam, 24–27 May 1982, Verruijt A, Beringen FL, De Leeuw EH (eds); 651–654.

Kranendonk P, Kluiving SJ, Troelstra SR. 2015. Chrono- and archaeostratigraphy and development of the River Amstel: results of the North/South underground line excavations, Amsterdam, the Netherlands. *Netherlands Journal of Geosciences* in press. DOI:10.1017/njg.2014.38.

Lafuerza S, Canals M, Casamor JL, Devincenzi JM. 2005. Characterization of deltaic sediment bodies based on in situ CPT/CPTU profiles: a case study on the Llobregat delta plain, Barcelona, Spain. *Marine Geology* **222–223**: 497–510. DOI:10.1016/j.margeo.2005.06.043.

Lunne T, Robertson PK, Powell JJM. 1997. *Cone Penetration Testing in geotechnical practice*. Blackie Academic: New York.

Missiaen T, Verhegge J, Heirman K, Crombé P. 2015. Potential of cone penetration testing for mapping deeply buried palaeolandscapes in the context of archaeological surveys in polder areas. *Journal of Archaeological Science* **55**: 174–187. DOI:10.1016/j.jas.2015.01.003.

Olsen RS, Farr JV. 1986. *Site Characterization using the Cone Penetration Test*. Proceedings of the ASCE Specialty Conference In Situ'86: Use of In Situ Tests in Geotechnical Engineering; 854–868.

Ovandan-Shelley E, Manzanilla L. 1997. An archaeological interpretation of geotechnical soundings under the Metropolitan cathedral, Mexico City. *Archaeometry* **39**: 221–235. DOI:10.1111/j.1475-4754.1997.tb00801.x.

Robertson PK. 1990. Soil classification using the cone penetration test. *Canadian Geotechnical Journal* **27**: 151–158. DOI:10.1139/t90-014.

Robertson PK, Campanella RG, Gillespie D, Greig J. 1986. *Use of Piezometer Cone Data*. Proceedings In Situ'86 ASCE specialty conference, Blacksburg, VA.

Rose C *et al.* 1996. *Cone Penetrometer. Innovative Technology Summary Report*, DOE/EM-0309. US Department of Energy: Washington, DC.

Sarti G, Rossi V, Amorosi A. 2012. Influence of Holocene stratigraphic architecture on ground surface settlements: A case study from the City of Pisa (Tuscany, Italy). *Sedimentary Geology* **281**: 75–87. DOI:10.1016/j.sedgeo.2012.08.008.

Schokker J, Koster EA. 2004. Sedimentology and facies distribution of Pleistocene cold-climate aeolian and fluvial deposits in Roer Valley Graben (southeastern Netherlands). *Permafrost and Periglacial Processes* **15**(1): 1–20. DOI:10.1002/ppp.477.

Schokker J, Bakker MAJ, Dubelaar CW, Dambrink RM, Harting R. 2015. 3D subsurface modelling reveals the shallow geology of Amsterdam. *Netherlands Journal of Geosciences* in press. DOI:10.1017/njg.2015.22.

Törnqvist TE, Wallinga J, Murray AS, De Wolf H, Cleveringa P, De Gans W. 2000. Response of the Rhine-Meuse system (west-central Netherlands) to the last Quaternary glacio-eustatic cycles: a first assessment. *Global Planetary Change* **27**: 89–111. DOI:10.1016/S0921-8181(01)00072-8.

TNO. 2014. *Dinoloket internet portal for Dutch geodata and information*. https://www.dinoloket.nl/

Vos JD. 1982. *The practical use of CPT in soil profiling*, Penetration Testing 2. Proceedings of the Second European Symposium on Penetration Testing, Amsterdam, 24–27 May 1982, Verruijt A, Beringen FL, De Leeuw EH (eds); 933–939

Vos PC, Bunnik FPM, Cohen KM, Cremer H. 2015. A staged geogenetic approach to underwater archaeological prospection in the Port of Rotterdam (Yangtzehaven, Maasvlakte, the Netherlands): a geological and palaeoenvironmental case study for local mapping of Mesolithic lowland landscapes. *Quaternary International* **367**: 4–31. DOI:10.1016/j.quaint.2014.11.056.

Vos PC, Cohen KM. 2015. *Landscape genesis and palaeogeography.* In *Interdisciplinary archaeological research programme Maasvlakte 2, Rotterdam*, Moree JM, Sier MM (eds). *BOORrapporten* **566**.