SUBSURFACE GEOLOGY OF A PEAT DIKE, A CASE STUDY IN TEMPELDIJK SOUTH, THE NETHERLANDS

DEDI MUNIR
March, 2014

SUPERVISORS:
Dr. H.R.G.K. Hack
MSc. W.H. Bakker

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Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
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SUPERVISORS:
Dr. H.R.G.K. Hack
MSc. W.H. Bakker

THESIS ASSESSMENT BOARD:
Prof. Dr. V.G. Jetten (Chair)
Dr. R. van Beek (External Examiner, Universiteit Utrecht)

ABSTRACT

Peat dikes have functions as flood prevention and water barrier. Stability of peat dikes is related to soil moisture content and pore water pressure in the dikes. As the effect of change of seasons, indication of deficiency may be found, such as seepage and subsidence. This situation can be linked to lithological variations formed in the subsurface. Peat dikes are composed of peat layers or combinations of peat and clay layers and occasionally more silty and sandy layers. Variations in composition and lithology may cause different behavior and condition of peat dikes.

Comprehensive geological and geotechnical study are conducted in this research. Borehole and CPT data are correlated to identify lithological units of the dike. Both CPT and boreholes show different method in classifying layers of lithology. The classification of lithology in boreholes is based on core description while CPT interprets lithology from values of cone resistance, friction sleeve, friction ratio, and pore water pressure. Description of boreholes is needed to validate the interpretation of CPT.

3D geology of Tempeldijk South has been modeled based on available data. Beforehand, data in each location is interpreted. Then, the data are correlated in certain distances to have interpretation of stratigraphy in geological profiles of the study area. The geology of the Tempeldijk South varies in vertical and lateral directions. In lateral directions, lithological variations can be interpreted not only at depth near the surface but also in deeper depths. Different lithological layers at depth near surface are peat layers that have changed horizontally from one to another. Changes of peat to become clay layers can be found in deeper depths. Also in this research, correlation of stratigraphy and resistivity survey results is conducted.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. GENERAL INTRODUCTION

1.1. Background

Peat dikes are typical secondary dikes in The Netherlands. The composition of peat dikes comprises of the natural subsurface lithology consisting of peat layers interbedded with layers of more sandy or more clayey peat materials (Cundill et al., 2013b). The peat dikes act as water barrier for canals and ditches along excavated areas, i.e. "polders" (fig. 1). The lithological variations and moisture content are factors in the stability of a peat dike and its ability to act as water barrier. Because of these factors, the strength of peat dikes may depend on the seasonal variation.
Investigation of surface and subsurface geology and geotechnics of peat dikes is conducted in the RSDYK project for the Dutch Flood Control 2015 program studying the use of remote sensing for dike inspection. One of the test locations for the project is Tempeldijk in Reeuwijk (Hack et al., 2012). The study shows that irregular structures, such as seepage and subsidence can be interpreted as indication of imperfections in the Tempeldijk South (Hack et al., 2008). However, the study also showed some possibly conflicting results. Some resistivity surveys in Tempeldijk-South (Cundill et al., 2013c) show a relative "high" in resistivity values below and in the lower part of the dike, i.e. at the toe side of the dike. Speculatively this can be explained as an upward flow of fresh water or relatively fresher water in an environment containing more saline water. However, the Water Board established that the Tempeldijk polder is becoming more brackish likely due to brackish water influx from the surrounding peat and deeper layers (Rupke & Hack, 2010). Gas bubbles present in the upward water flow may be an explanation as gas bubbles increase the resistivity. To try to establish the exact reason for the possible conflicting results of subsurface investigations comprehensive study of the geological characteristics and stratigraphy of the subsurface in the Tempeldijk study area is done.
This comprehensive geological and geotechnical study interprets the geological condition in the subsurface of the dike based on available data of boreholes, Dutch cone penetration tests (CPT), and resistivity surveys. For the first step of the study, the boreholes are correlated to CPT data in order to define and classify lithological units as well as to record the depth of upper and lower boundaries of the units, and to correlate lithology between locations of boreholes and CPTs. The next step is to correlate these data to stratigraphy of the study area. Then, all data and stratigraphy are processed into a 3D subsurface computer models (Rockworks).

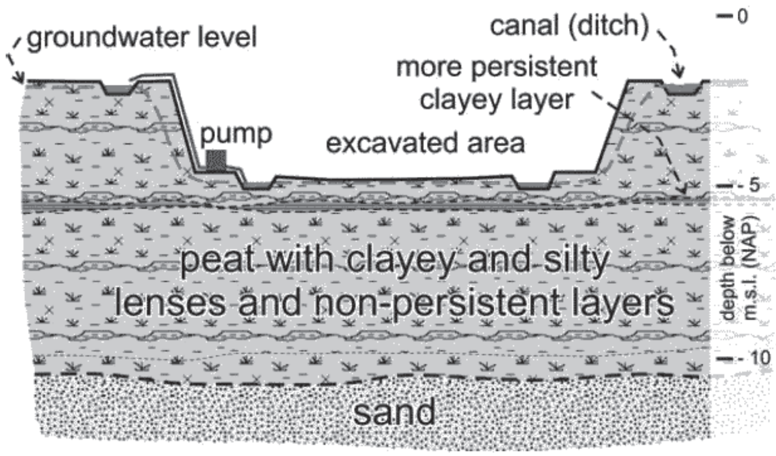


Figure 1 A peat dike with geology (Cundill et al., 2013b)

3D models can represent geological and geotechnical characteristics in three dimensions. The advantages of a 3D computer models over a 2D or 3D hand-made model (i.e. hand-drawn sections and fence diagrams on paper) are the mathematical correctness, the easy handling and visualization of the model (De Mulder et al., 2012). This allows an improved detailed interpretation of the geology.

1.2. Problem statement

The change of relative sea and river levels due to land subsidence and possible climate change has increased the awareness for dike monitoring and stability of dikes. This applies to dikes in The Netherlands as well as other countries in low-level mostly deltaic, areas in the world. The change influences the strength of the dike not only from the outside but also from inside or below by variation in moisture content and pore water pressure. The lowering of the groundwater table for agricultural purposes and residential areas exposed the peat to the surface. The peat may oxidize when it is exposed causing decomposition, consolidation and subsidence of the lands (Hoogland et al., 2012).

Monitoring of peat dikes should be done regularly to detect any indication of imperfection that may trigger failure of peat dikes. Processes of monitoring are normally conducted in different seasons. Moisture content and pore water pressure are factors that are influenced because of variation of seasons. This variation results in excess and shortage of water in the dikes. These changes affect stability and can cause problem in peat dikes. On the other hand, the stability and behavior of the dikes will also depend on lithological and geohydrological variations of the subsurface of the dikes. In August 2003, a peat dike in the village of Wilnes collapsed because of drought. The specific weight of the peat in upper part of the dike had become lower than peat in wet condition since the peat became dry near surface (Van Baars, 2004) due to a long dry period with little rain.

Based on the study from Cundill, et al (2013c), the resistivity surveys show that lower resistivity values with relatively horizontal layering is defined in the eastern part of the study area. These values represent lithological variations in the Tempeldijk South. On the other hand, resistivity of the left (west) part of the study area displays higher resistivity values without horizontal layers. The increasing resistivity in the left part of the section may be caused by upwelling fresh water from deeper layer (chapter 5 (fig. 37)). There are changes interpreted in lateral and horizontal directions of resistivity values that need to be studied together with lithological variations of the Tempeldijk South.

1.3. Main objective

The main objective of the study is to analyze subsurface geological condition in Tempeldijk South, the Netherlands, with the help of computer 3D subsurface models.

1.3.1. Sub objectives

To achieve the main objective of the study, there are five sub objectives that need to be accomplished in the study. The sub objectives are:

- Correlation between borehole and CPT data.
- Analyzing geological structures, characteristics, and lithology in the subsurface of the dike based on CPTs, boreholes, and resistivity measurements.
- Correlation between subsurface data to interpret stratigraphy of the area.
- Model all available data of the Tempeldijk South into a computer 3D geological and geotechnical model.
- Correlation of stratigraphy and resistivity survey results.

1.4. Research questions

There are six research questions in the study:

- How does lithology from borehole description correlate to lithology in CPT interpretation?
- What are geological structures, characteristics, and lithology in the subsurface of the dike interpreted from CPTs, boreholes, and resistivity?
- How many lithological units can be interpreted in stratigraphy of the Tempeldijk South?
- How is the stratigraphy of Tempeldijk South from correlation of subsurface data?
- How does subsurface geology vary three dimensionally?
- How do stratigraphic layers correlate to resistivity values in the Tempeldijk South?

1.5. Structure of thesis

The thesis comprises of five chapters:

Chapter one introduces background, problem statements, objectives, sub objectives, and research questions of the study.

Chapter two reviews the literature on surface and subsurface investigation of dikes, the occurrence of upwelling water, and previous researches done in similar topics.

Chapter three describes the study area Tempeldijk, characteristics of geology and hydrogeology of study area. The chapter also provides information of available data used in the study.

Chapter four defines the methodology of the study comprising of data collection, data interpretation, data processing, and data analyses of the results.

Chapter five displays the results of the data obtained from geology, geophysics, and geotechnical methods. This chapter results in subsurface geological models and resistivity models. Analyses and discussion of the results of geological condition are also explained in this chapter.

2. LITERATURE REVIEW

2.1. Peat dikes

There are two different types of dikes in the Netherlands; primary and secondary dikes. Primary dikes have a total length of about 3,200 km long and secondary or regional dikes have a total length of about 14,000 km (Van Baars, 2004). The division between primary and secondary is based on the purpose and locations. Primary dikes are constructed as primary structures to defend lands against flooding from the sea and main rivers (Knoeff et al., 2008; Pilarczyk, 2007). The areas prevented by the primary dike structures are called dike ring areas (Pilarczyk, 2007). Secondary dikes are built to protect land against floods mainly from canals and ditches (Van Baars, 2004). Secondary dikes may also decrease the effect of flood if primary dikes break (Hack et al., 2008). Many secondary dikes are composed of the natural lithology (fig. 1) of peat and clay. (Knoeff et al., 2008).

Peat consists of remains of organic material (plants, trees, etc.) deposited in an oxygen-poor environment. It is generally soft or spongy with a high compressibility (Grover & Baldock, 2013; Ponziani et al., 2012), and a low specific weight (Van Baars, 2004). Generally, peat contains large amount of water (Grover & Baldock, 2013; Van Baars, 2004). Peat has a higher ability to absorb water than clay under normal conditions (Hack et al., 2008). The condition of peat is affected by the groundwater level (Boelter, 1964; Bragg, 2002). Groundwater influences the growth of peat in its environments and also influence peat lithology after it was formed. One of processes that changes peat materials is a lowering of groundwater level. The lowering process of groundwater level in a polder for agricultural and residence purposes reduces the water content of peat (Boelter, 1964) and escalates the process of oxidation (Hoogland et al., 2012).

Peat can be formed in various environments and conditions. The classification of peat lands or mires has many categories defining characteristic of each environments (fig.2). For example, peat is deposited in an environment influenced by either rainwater or groundwater system. Ombrotrophic peat environment was formed by rain fed having much influence of rain water while rheotrophic mires has been influenced much by groundwater in the process of deposition. Oligotrophic peat is a type of ombrotrophic peat that is poorly fed. Also, there is a type of peat called topogenous peat that depends on surface water in its environments (Thomas, 2013). These conditions are related to peat types interpreted as a member of Nieuwkoop Formations forming geology of the study area. There are four different types of peat in the formation consisting of oligotrophic peat, fen peat, fen wood peat, and lacustrine deposits (Hijma et al., 2009).

Peat on the surface of the dike has been excavated for fuel purposes. The excavated areas became flooded because groundwater level was located at shallow depths or near the surface. The reclamation of areas for agricultural uses and residential areas took place in the 16^{th} and particularly in the 18^{th} and 19^{th} centuries. To manage the reclaimed areas, the water in excavated areas was pumped and drained through ditches and canal systems. Water management in the Netherlands adjust water level in polders by transporting excess water to main rivers or to the sea (Cundill & Hack, 2013)

Soil moisture of lithology may change according to change of season. Higher pore water pressure may occur because of the effect of upwelling water from deeper layer below the dike. The presence of a water flow from deeper layers may give pressure to the overlying layers. This pressure influences the strength of the layers in the dike. The strength resulted by contact of lithology (layers) may be reduced or changed by the presence of water. Furthermore, the changes in pore water pressure may result in indication of imperfection such as, uplift mechanism, seepage, and leakage of dikes. Those mechanisms can be caused by high pore pressure of an underlying sand layer resulting in the loss of strength of overlying peat and clay layers (Koelewijn et al., 2004)

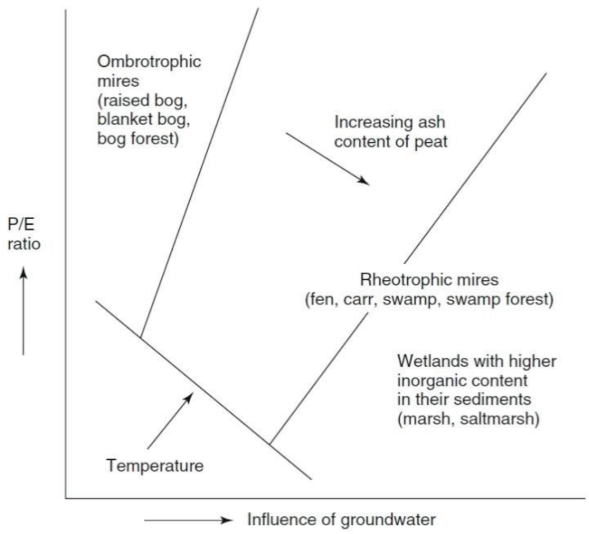


Figure 2 Peat environments in relation to rainwater (precipitation/evaporation) and groundwater (Thomas, 2013)

2.2. Dike monitoring

Dike monitoring is done to evaluate surface and subsurface condition of dikes. The monitoring can be conducted by many activities such as, by conducting dike inspection or by sensor installed in dikes such as piezo and deformation meters. Dike inspection is done regularly to ascertain the functions of the dike as flood prevention and water barrier. Standard practice of dike inspection is visual interpretation at regular intervals (Mériaux & Royet, 2007). The inspection assesses the surface of the dike and subsurface structural imperfections shown at the surface. Structural deficiencies that may commonly occur are seepage and deformation.

Remote sensing has been used for monitoring of dikes (Cundill et al., 2013a), For example, the use of remote sensing in detecting deformation (Groot, 2004) and seepages (Givehchi et al., 2002). The evaluation of dike cover related to soil moisture based on remote sensing on the surface of the dike has also been studied (Cundill et al., 2013b).

2.3. The upwelling water.

The occurrence of upwelling fresh water may take place as the result of reclamation of areas (polders) near lakes. For instance, in the condition of Bethune polder near the Loosdrecht Lake in the area between Amsterdam and Utrecht (De Haan et al., 1993). The hydraulic head of the lake causes upwelling fresh water in the overlying Holocene layer in the polders near the lake. The low elevations of the polders which are below mean sea level may determine the occurrence of upwelling water in those locations. The higher water table of the lake results in more pressure of the upwelling water to overlying layers. Another explanation of upwelling fresh water is that it originates from the upper aquifer. The hydraulic head in the aquifer has higher position than phreatic water level in polder. Seepage or upwelling water can be as discharge of groundwater in ditches, polder, and lakes (De Louw, 2013). In the Reuwijk area, the lakes are located about 3 km to the southeast of the study area. De Haan (1993) found a downward seepage flow of water was found in the lake because of porous peaty materials in the bottom of the Lake. This occurrence influences the water balance of lakes and may result in upwelling water in surrounding areas of the lake.

Fig. 3 displays the regional hydrogeological profile of peat dikes showing the flow path of groundwater and boundary between fresh and brackish/salt groundwater. Many classifications of water are possible defining the content of chloride concentration in the water. The figure defines that the fresh water has <150 mg/l Chloride concentration while brackish/salt water has >150 mg/l Chloride concentration (Oude Essink et al., 2012). Based on other classification, The saline water has ($Cl^- \geq 1000$ mg/L) chloride concentration (Oude Essink et al., 2010).

On the other hand, the intrusion of saline water from upper aquifer located at depth about 11 meters can occur in deep polders (fig. 4), for example, Noordplas Polder in Rotterdam and Haarlemmermeer Polder in Amsterdam. The upwelling saline water in the Holocene layers may show diffuse seepage as the water flows through layers of peat, clay, and loam with relatively low permeability (De Louw et al., 2010). The other upcoming mechanisms of saline water from the upper aquifer are through paleo-channels and as boil seepages. Paleo-channel and boil seepages work as a pathway for the upward flow of saline water (De Louw et al., 2010; De Louw et al., 2013). The boil seepage has conduit structure. It may develop to become cracking if the pressure of water is greater than the weight of the overlying layers. Further, it may grow to become sand boils if it carries sand materials from layers below (De Louw et al., 2013). The process of seepage of the intrusion of saline water are likely similar as the process of the upwelling fresh water.

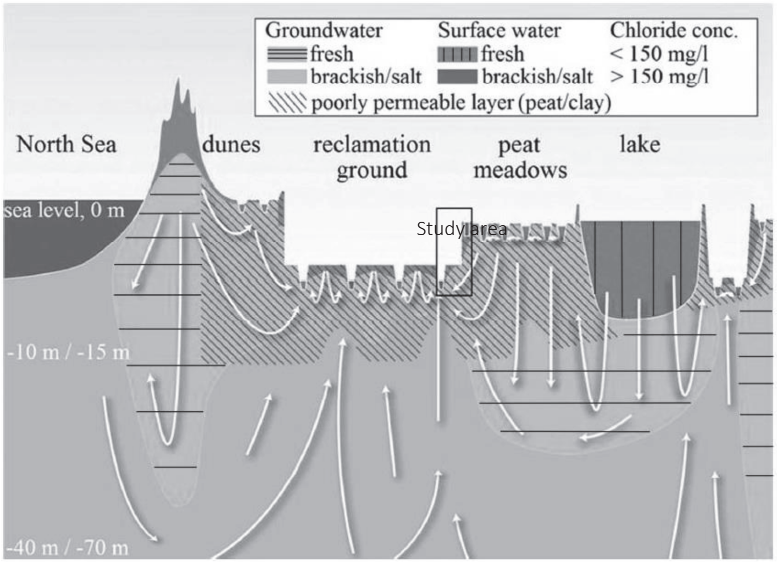


Figure 3 Regional profile of groundwater flow in typical environment of study area (modified after (Oude Essink et al., 2012)) recited in (Cundill et al., 2013c)

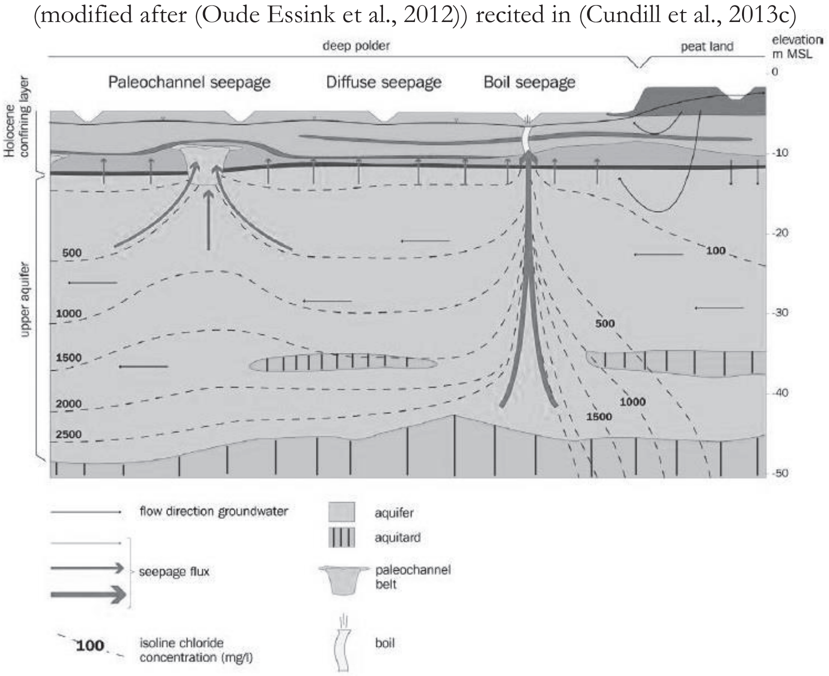


Figure 4 Three mechanisms of upward saline water (after (De Louw et al., 2010))

The occurrence of upwelling water depends on the seasons. Wetter periods causing a high water table may result in higher fluxes of seepages. In dry season periods may stop. Also, geological condition in the area of polders determines the occurrence and pathways of upwelling water of those different processes. These three processes of upwelling saline water cause different results of salinization of surface water.

2.4. 3D Geological Modeling

The use of modeling is to display lithological variations and stratigraphy in three dimensional subsurface. 3D geological models may improve the results of interpretation of the subsurface. The models may provide more information of subsurface than information from 2D data, for instance, on geological maps or in cross sections. The models displays subsurface geology based on available or limited data obtained in the subsurface investigation, such as, boreholes, CPTs, and geophysical methods. The processes in subsurface investigation influence data quality and consequently results of modeling. The interpretation of geology of the results also determines the models. Each model can be applied for different purposes depending on subjects of investigations (De Mulder et al., 2012).

The merits of 3D subsurface geological models have been applied extensively in different geological subjects, for instance, in engineering geology, mineral mining, oil geology, environmental geology, etc. One specific subject will concern more on geology of certain characteristics than other subjects. For example, engineering geology will focus more on geology on top or at shallow depths of an area. Most of lithological units at or near the surface are sedimentary rocks. The condition is different from subjects of mineral and oil geology. The concern will be on geology in relatively deep subsurface. Igneous rocks will be given more attention on mineral exploration subjects than others. In oil geology, sedimentary environment plays huge role. However, there is still situation that the real geological condition or geological objects cannot be fully represented. Sometime, the models cannot be trusted. Reliability of models is not fully trusted and the certainty of models still needs to be assessed. Reliability of models may depend on available data used in the process of modeling. The models can be improved and updated if new data in the location have been obtained (Fufa, 2004).

The reliability of 3D geological models can be interpreted by visual inspections from geologists or geotechnical engineers who have expertise and good knowledge in the study area. The interpretation should be based on geological knowledge from those interpreters. For example, in the west part of the Netherlands, sand formation of marine deposits can be found. It is assumed that the deposit will continuously present on adjacent area of borehole locations. However, the situation may be different if sand from fluvial deposits is interpreted. The sand may not be found in other locations of boreholes because it has lenses structures. The deposit has limited lateral extension which needs to be considered (Hack, 2003). Interpretation of geology based on geo-knowledge can be different from each interpreter. It depends on experience, ability, and it also related to understanding of local geology of those interpreters.

Uncertainty in geological modelling can be related to data quality, data interpretation, and data processing. The interpretation of boreholes in the site should be done by geologist or geotechnical engineers who have knowledge and experience. However, sometime the interpretation cannot be done by geologist if they are not available in well site. The interpretation may result in different description of borehole data, and the data quality may not be fully trusted. The uncertainty based on this condition may take place in data quality which can influence the models. Furthermore, the selection of modelling algorithms in data processing determines the results of the models (Fufa, 2004).

3. STUDY AREA AND DATA SETS

3.1. Study area

The Tempeldijk is located in Reeuwijk, in the area between Amsterdam and Rotterdam, The Netherlands. The area is divided into two parts comprising of Tempeldijk North and Tempeldijk South (fig. 5). The study area for this study is Tempeldijk South. The dike area consists of high elevation (where no peat has been excavated) and low elevation (where peat has been excavated) areas. The location of Tempeldijk is relatively flat with elevation of non-excavated area about 1.6 - 2 m below m.s.l and the level of excavated areas about 5 meters below m.s.l. The dike has length about 1 km with the ditches located in both higher area and in the low (excavated) areas of the dike. The low-elevation area reclaimed as a polder has been used for agriculture lands and residential areas (Hack et al., 2008).

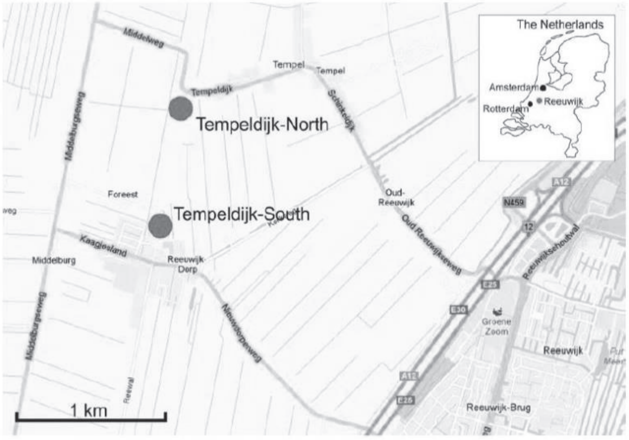


Figure 5 The study area ((Maps, 2012) recited in (Hack et al., 2012)).

3.2. Datasets

Data are available from surface and subsurface investigations for the study in the Tempeldijk. It comprises of boreholes, CPTs, and resistivity measurements. Two boreholes done by Delft continuous soil sampler have been conducted with depths of observation about 11 and 18 meter below m.s.l. The results of the borehole investigation (so-called 'Begeman' or 'Delft Continuous Soil Sampler' boreholes) are a complete core from surface to end of borehole. Tempeldijk South has 17 CPTs with gas and pore water pressure measurements that obtain data to a depth of about 15 m below m.s.l. The resistivity survey in the study area is done with 20 lines with 2 m electrode distance, and 3 meters distance between lines. The penetration depth is about 8 m below terrain surfaces. The observation scale of data in Tempeldijk South is in an area of 25 m x 40 m with 15 m below m.s.l. as depth of observation.

3.3. Geology

This chapter defines geological processes of the Netherlands during Pleistocene and Holocene as well as chronostratigraphy and lithostratigraphy of the study area. Description of the geology based on the literature explains geological condition related to lithology (composition), structures, history, and processes in the study area from regional geological scale to local geology of the dike to comprehend geology in the Tempeldijk South based on available data described beforehand.

3.3.1. The Pleistocene Geology

Geology of the Netherlands was formed in the Period from Pliocene-Pleistocene to the Holocene. Geological processes comprising of transgression and regression cycles commonly occurred during these periods. The situation is related to glacial and interglacial processes. The Pleistocene geology is illustrated

by paleogeography map of the Netherlands in (fig. 6) starting from Upper Pliocene to Weichselian stage. In the Upper Pliocene we can see the influence of transgression during the time by large marine deposit in wide area (fig. 6a). Another deposit that can be illustrated having large area is deposit from rivers from North Germany and Baltic shield. Upper Tiglian map shows the reducing of the North Sea depositional area in the regression phase. The fluvial deposits of rivers of North Germany together with Baltic shield and river Rhine were getting larger (fig. 6b).
Ice during Saliaan glaciation covers vast areas in the northern part of Europe including the northern part of the Netherlands (6d). This glaciation is the process that changed the river sequence of Rhine and Meuse. The process caused high areas in the eastern part of the study area. During this stage, ridges and hills which some of those have over 100 m height were formed by alluvial deposits pushed by ice sheets (Zagwijn, 1989). The map of the Saliaan is illustrated in (Fig. 6d).
The following Eemian interglacial resulted in the melting of the ice and rise of the sea level. Weichselian glaciation occurred as another event of geological process after Eemian interglacial phase. During this time, aeolian deposit formed in terraces outside the main rivers. The occurrence may be caused by snowstorms. In Weichselian glaciation, the end of ice age caused by the melting of inland ice resulted in the rising of sea level worldwide and continued in Holocene. There are three sedimentation zones during this phase, namely, coastal barriers with dunes, tidal flats-salt marshes-brackish lagoons, and peat formation (Ten Cate, 1982).

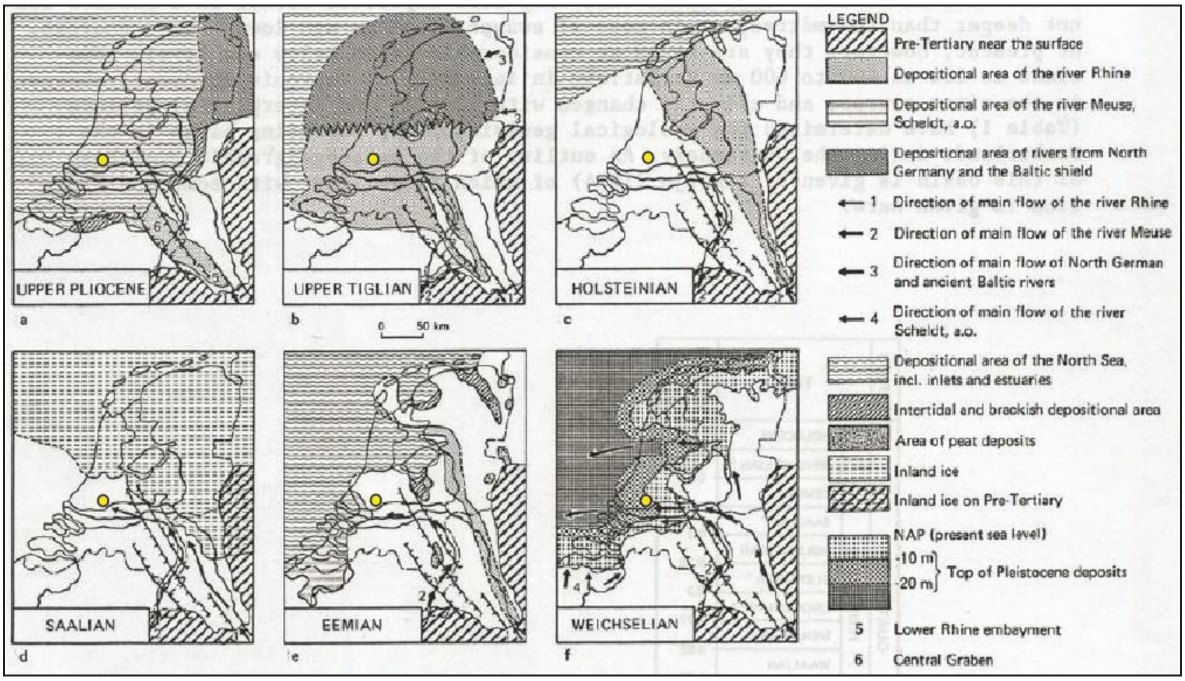


Figure 6 Paleogeography map of the Netherlands during Pleistocene Period (Ten Cate, 1982)

3.3.2. The Holocene Geology

The processes of transgression and regression formed geological characteristics in the Holocene geology of the Netherlands. Based on Bijlsma (1982), in the start of Holocene, sea level increased very rapidly resulting in transgression phase of the sea. The transgression caused the North Sea to enter Dutch area in about 8000 BP. This transgression is related to melting of ice. Because most of the ice had melted, the sea level rise became slow in about 6000 BP. The rise of sea level resulted in higher groundwater table. The high groundwater and quiet places are suitable environment for formation of peat layers. Generally, peat formation can be formed in the environment with relatively high and stagnant water levels.
Sea level decreased in 3700 BP producing less marine deposits in this period. At this time, the elevation of ground water table was still high resulting in extensive formation of peat. After 2000 BP, the marine and

fluvial processes interrupted the peat formation to form interbedded and intercalated layers of peat, sand, and clay. The change of sea level was not only caused by transgression and regression phases but also by tectonic movements. The subsiding of the North Sea Basin had a rate of one or two centimeters per hundred years in the western part of the Netherlands (Bijlsma, 1982).

The evolution of geology of the Netherlands during Holocene Epoch from the 7000 BP to the present is shown in fig. 7. The figure shows lithological variation of the Netherlands comprising of beach barrier, Pleistocene deposits, peat, fluvial deposits, and marine deposits. The study area is illustrated in the figure. From the different time in Holocene, the study area has experienced many processes comprising of Pleistocene, peat, marine and fluvial deposits.

As the results of transgression and regression processes, the evolution of Rhine-Meuse Rivers was taking place during Holocene. The types of river channel had changed during the evolution. The figure shows paleochannel deposits of meandering rivers in Northern and Southern margin and anastomosing river channels (with flood basins in between) in the center of the delta (Berendsen, 2007). The river environment transformed from river channels to estuarine, delta, and tidal rivers. Those paleochannel deposits can be found in surrounding of study area. Paleochannel deposits with ages during Holocene in the Netherlands are illustrated in fig. 8.

3.3.3. Geology of the study area.

3.3.3.1. Regional geology of study area

The regional geology of study area is influenced by evolution processes of the Rhine-Meuse Rivers in Holocene. The chronostratigraphy and lithostratigraphy of the Reeuwijk are shown in (fig. 10). The Chronostratigraphy defines geological time scale and geological processes of formations during the late Pleistocene and Holocene. Lithostratigraphy shows geological formations and relations between those formations in study area. From the figure, it can be described that regional Lithostratigraphy of the study area comprises of various formations of Boxtel, Kreftenheye, Nieuwkoop, Echteld, and Naaldwijk Formations. The bottom formations formed earlier than formations on top of it. Also, parallel relationships between formations can be interpreted formed relatively at the same time.

Table 2 describes the chronostratigraphy and lithostratigraphy in regional geology of the study area. It is defined based on genetic information and variation of member in the formations. A transgression phase formed lithological deposits in the study area from aeolian, river valley, estuarine, deltaic, to marine environments on top of formations.

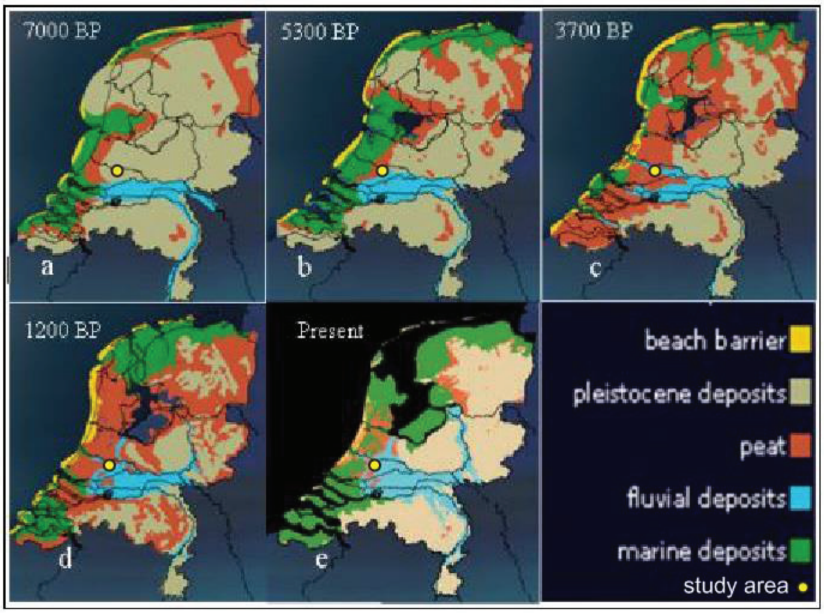


Figure 7 Paleogeography map of the Netherlands during Holocene Period after (De Gans, 2000) recited in (Mahabubur, 2007)

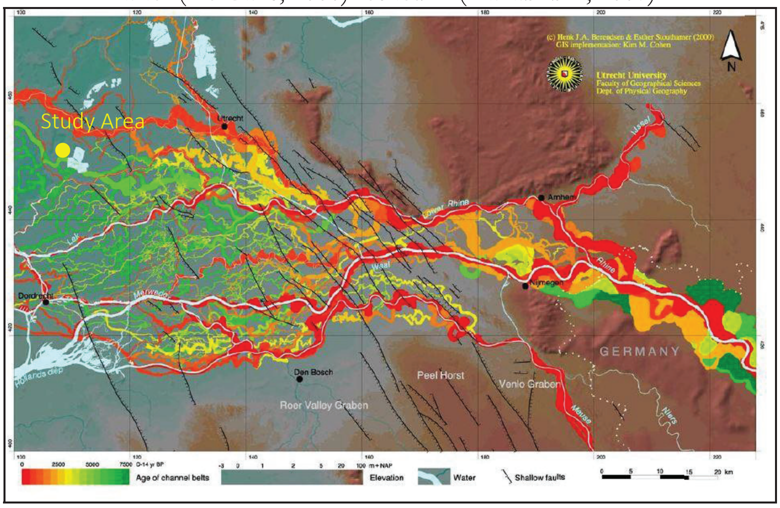


Figure 8 Holocene channel belts with ages in Rhine-Meuse Delta, the Netherlands (Berendsen & Stouthamer, 2001)

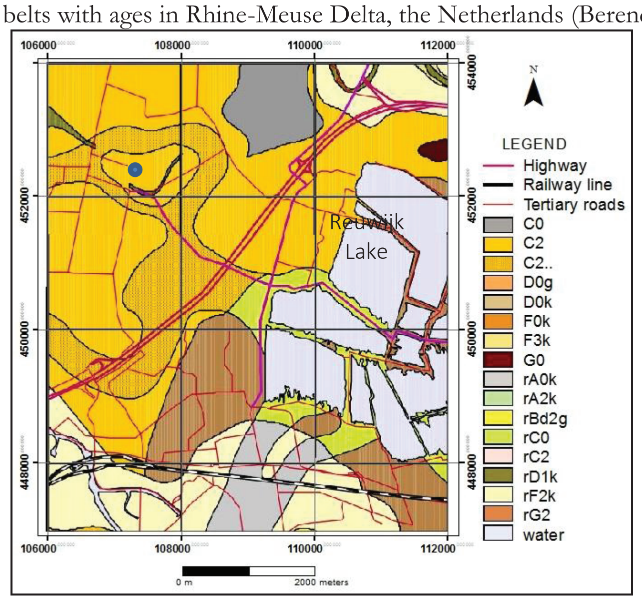


Figure 9 Regional geological map of the study area (after (Bosch & Kok, 1994) in (Amurane, 2003))

Table 1 Legend of geological map (Bosch & Kok, 1994) in (Amurane, 2003)

G0	Holland peat
rC2	Holland peat on an alternation of Gorkum (flood-plain and levee deposits) and Holland peat on Gorkum deposits (channel deposits)
rG2	Holland peat on an alternation of Gorkum deposits (flood-plain and levee deposits) and Holland peat
C2	Holland peat on Callais III Deposits (tidal flat deposits) on an alternation of Holland peat and Gorkum deposits
C2..	Holland peat on Callais III Deposits (tidal flat deposits) on Gorkum deposits (channel deposits)
rC0	Holland peat on Gorkum deposits (channel deposits)
rBd2g	Tiel deposits (channel deposits) on an alternation of Holland peat and Gorkum deposits (flood-plain and levee deposits)
rD0g	Tiel deposits (channel deposits, locally covered by levee deposits)
rA0k	Tiel deposits (flood-plain deposits) on Holland peat on Gorkum deposits (channel deposits)
rD0k	Tiel deposits (flood-plain deposits on channel deposits)
C0	Tiel deposits (flood-plain deposits)
rD1k	Tiel deposits (flood-plain deposits) on Gorkum deposits (flood-plain and levee deposits) on Gorkum deposits (Channel deposits)
rF2k	Tiel deposits (flood-plain deposits) on an alternation of Holland peat and Gorkum deposits (flood-plain and levee deposits)
rA2k	Tiel deposits (flood-plain deposits) on an alternation of Holland peat and Gorkum deposits (flood-plain and levee deposits) on Gorkum deposits (channel deposits)
rF0k	Tiel deposits (flood-plain deposits) on Holland peat
F3k	Tiel deposits (flood-plain deposits) on an alternation of Holland peat and Gorkum deposits (flood-plain and levee deposits)

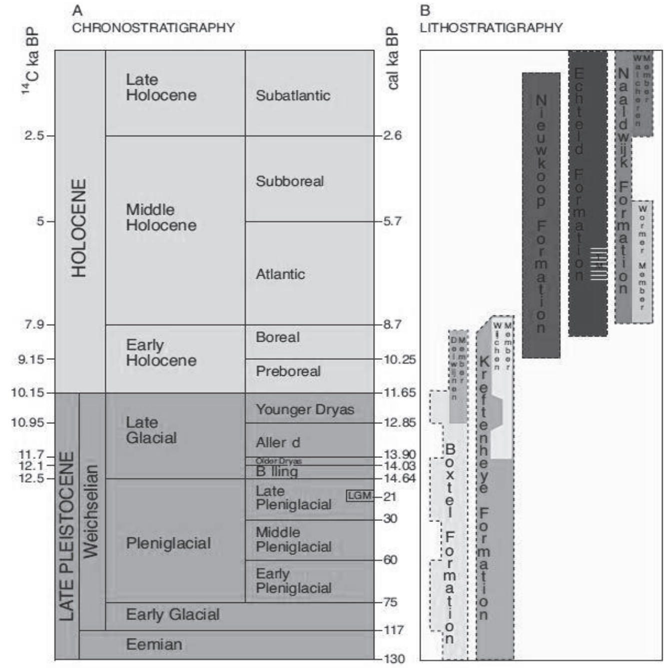


Figure 10 Stratigraphy of the study area (Hijma et al., 2009)

Table 2 Lithostratigraphy in the study area (Hijma et al., 2009)

Formation	Lithogenetic description	Member
Naaldwijk Formation	Shallow marine deposits	Wormer member Mud dominated intertidal flat (clay with silt/very fine sand layers) Sand dominated intertidal flat (sand/silt with clay layers) Tidal channel deposits (predominantly sand)
Nieuwkoop Formation	Autochtenous organic	Oligotrophic peat (sphagnum and Erica) Fen wood peat (mainly alnus and salix) Fen peat (mainly phragmites, carex) Lacustrine deposits (gyttja, detritus)
Echteld Formation	Estuarine-deltaic Rhine Meuse deposits	Flood basin deposits (humic clay) Flood basin deposits (silty clay and clay) Terbregge member upper estuarine flood basin deposits (silty clay with abundant tree debris) Natural levee and crevasse deposits (silty and sandy clay) Channel fill deposits (clastic and organic) Channel belt deposits (sand and gravel) Estimated base of fluvial (channel sand) Fluvial-tidal channel deposits (sand alternating with clay) Bay-head delta deposits (sand and clay)
Kreftenheye/Urk Formation	Valley Rhine Meuse deposits	Channel fill deposits (organic or clastic) Flood basin deposits (silty, sandy clay, clay) Channel deposits (sand and gravel)
Boxtel Formation	Aeolian and local deposits	Sand and silt

3.3.3.2. Geology of the dike

Geology of study area in the Reuwijk consists of different units of lithology formed in the Period from Pleistocene to Quaternary (Holocene). The geological map of Reuwijk area is displayed in (fig. 9). It comprises of lithology formed in marine, perimarine, and fluvial area. The table 2 as a legend of the map explains types of deposits, characteristics, and formations in geological map. According to Berendsen (2007), the explanation of geological map is based on classification by Zagwijn and Van Staalduinen (1975). The subdivision of Lithostratigraphy has not been referred and is changed to a lithostratigraphy by Mulder (2003). The different identifications of formation from those two classifications are illustrated in (fig.11).

The Lithostratigraphy of Westland Formation and Betuwe Formation is replaced by Formations of Naaldwijk, Nieuwkoop, and Echteld. The subdivision of marine, perimarine, and fluvial area is changed to only marine and fluvial area (fig. 10). This new nomenclature introduced in 2000 explains that peat deposits are called Nieuwkoop Formation, Gorkum and Tiel deposits as Etcheld Formation, the marine Calais and Dunkirk as Naaldwijk Walcheren Formation and Naaldwijk Wormer Formation (Berendsen, 2007). The identification needs to be comprehended since both nomenclatures are still being used. The information of geology in this research also applies these references.

Peat formations have vast spread deposited in the regional geology of the study area. The understanding of the peat deposits is important to study geology and characteristics of the peat dike. There are different types of classifications in interpreting peat formation. The classification can be used to describe peat lithology, for example, the description during site investigation. In the study, the interpretation of peat geology from boreholes is defined based on the lithological classification from Dutch soil classification system (Van der Meulen et al., 2007). The interpretation of peat formation from boreholes is based on the interpretation in peat classification systems. It classifies the peat based on the proportion of organic matter content, lutum, silt, and sand. The classification system of peat is displayed in (fig. 12).

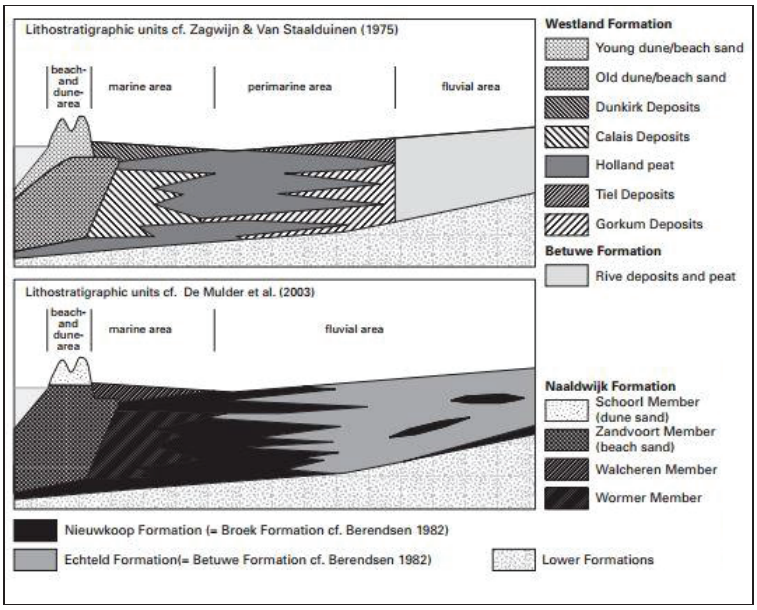


Figure 11 Lithostratigraphic units from different nomenclatures (Berendsen, 2007)

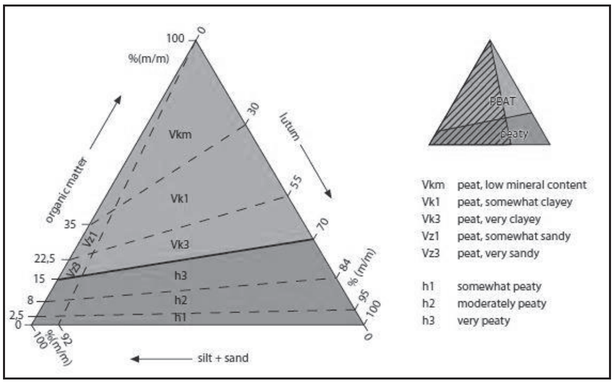


Figure 12 Peat classification systems (Van der Meulen et al., 2007)

3.4. Geohydrology of study area

The hydrogeology of the area depends on the characteristics of lithology and structures. Characteristics of aquifer are influenced by the condition of geology and geomorphology of the area. In The Netherlands, the regional aquifer of fluvial sand with medium grained was formed in Plio-Pleistocene. The thickness of the aquifer is about 25-250 m with the average of permeability from 20 to 50 m/day (De Vries, 2007). Sand aquifer is divided into upper aquifer and lower aquifer. The upper aquifer of Pleistocene sand layer can be found from 9-12 m depth below m.s.l. to a depth of about 60 meters below m.s.l. These upper and lower aquifers are divided by Middle Pleistocene clayey deposits. Moreover, paleochannel deposit can be found in lower part of Holocene layers (De Louw et al., 2010).

The overlying layers of the aquifer comprises of Holocene layers of peat, loam, and clay with 6-9 meter thick. The Holocene Formation consisting of peat, loam, and clay has a hydraulic conductivity between 10^{-4} m/d and 10^{-1} m/d while the paleo-channel deposits in lower part of Holocene layers have hydraulic conductivities in the range of 1.0–10.0 m/d (Weerts, 1996) recited in (De Louw et al., 2010). Most of the areas in the western part of the country are below mean sea level. The condition results in the occurrence of diffuse structures of upwelling seepage of fresh and brackish water in polders. The upwelling fresh water seepage (kwel) of groundwater may also originate from Pleistocene aquifer (De Vries, 2007).

Holocene transgression is the process of salinization of the aquifers in The Netherlands. In Holocene, sea level started to rise and flooded surfaces of Pleistocene sand in the west part of the country. The difference in density caused salt water to go under fresh water in the sand. The high permeability of the sand plays role in this occurrence. The process is called free convection. Then, the fresh water in the aquifer was expelled by salt water from below because of the rising salt water. On other locations, the low permeability of layers such as, clay layers obstructed the process of salinization and kept the presence of fresh water. The condition influenced the effects of salinization process and caused different situation of salinization in different locations (Post, 2004). Salinization can also originate from marine deposits containing connate water from dissolved salt deposited during transgression processes. The marine deposits are the fine-grained sands and clays from the Pliocene and Early-Pleistocene (Post, 2004).

Fig. 13 illustrates the depth to interface of fresh and brackish water in The Netherlands. The depths are divided into six classes. The figure also shows the coastlines (transgression lines) in Holocene and in Early Pleistocene.

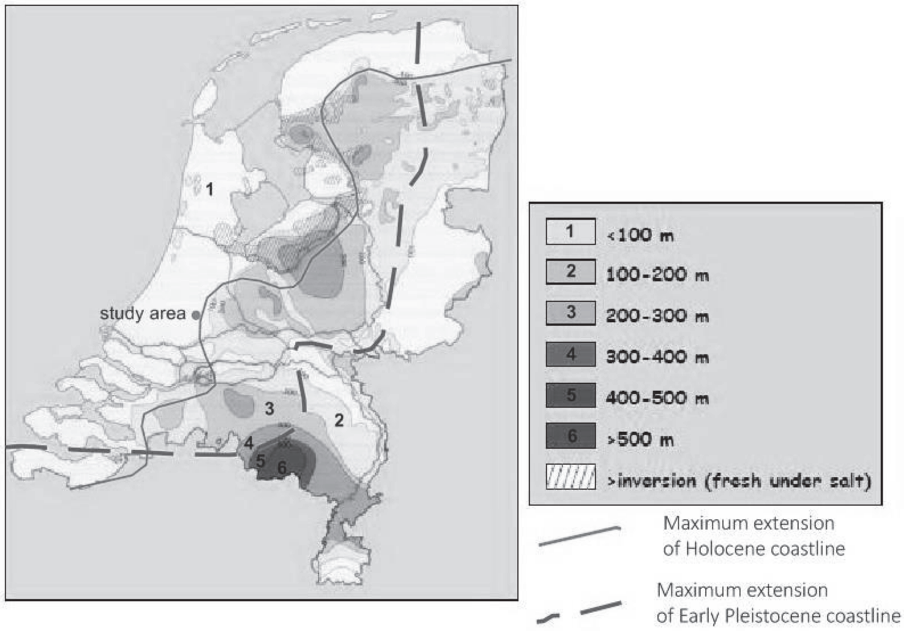


Figure 13 Depth of interface of fresh-brackish groundwater (modified after (De Vries, 2007))

4. METHODS

Methods applied in the study are explained in the following sections:

4.1. Dutch cone penetration tests (CPTs) and boreholes interpretation

One of methods used for obtaining geotechnical characteristics in the study area is Dutch cone penetration tests (CPTs). A CPT is conducted by pushing the cone into the ground at a certain rate of 1 to 2 cm/sec (Rogers, 2006). The method has been applied extensively in The Netherlands because of lithological formations of relatively soft ground materials without obstructions such as crust layers or stones. CPT interpretation is used to characterize lithology and general geology of the study area. ((ASTM, 1994) recited in (Rogers, 2006)).

The CPTs measure geotechnical properties of the ground mass materials such as cone resistance, friction sleeve, and friction ratio, and pore water pressure. For specific aim, the method can be combined with measurements of other properties, such as temperature, seismic wave velocity, resistivity measurements (Robertson & Cabal, 2010). Bearing capacity and settlement of foundations are examples of geotechnical parameters that can be estimated by CPT investigations (Fugro, 2004).

There are various advantages in applying CPT for geotechnical investigation. It can be conducted fast, continuous, and also repeatable (Robertson & Cabal, 2010). The CPT can be applied using mechanical and electrical methods. The mechanical CPT method measures the cone resistance and friction sleeves by a set of inner and outer metal tubes connecting the cone and sleeve in the ground at the end of the CPT rods with a pressure measurement device at surface. The force to insert the cone into the ground mass may be done by hand power or by a hydraulic pump. In an electrical CPT, the cone is replaced by a cone with one or more electrical sensors to measure the various properties. The sensors are connected to a recorder at surface by a cable. On the Reeuwijk site an electrical CPT cone has been used. The CPT equipment can be truck or crawler mounted or be mounted on a sledge semiportable.

The equipment in Reeuwijk was mounted on a crawler truck. The cone is inserted beneath the truck and rods are extended by an employee in the truck. Total weight of the rig is held on hydraulic rams to produce normal force pushing down the cone into the ground at certain rate (Rogers, 2006). The CPT has two load cells to measure force of the cone, sleeve friction. Pressure transducer to measure pore pressure is located usually just behind the cone (fig. 14a). The electrical method of a CPT uses a hydraulic pump system to ensure continuous penetration of the cone into the ground with a certain speed (fig. 14b).

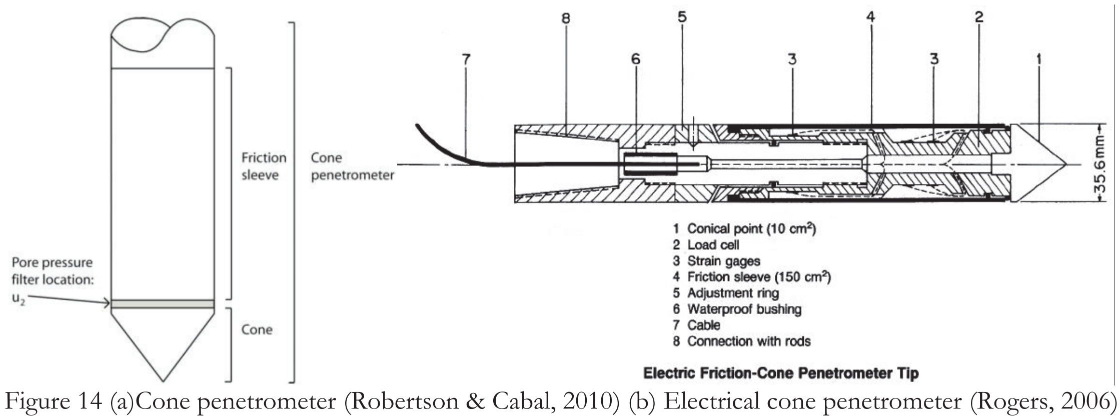


Figure 14 (a)Cone penetrometer (Robertson & Cabal, 2010) (b) Electrical cone penetrometer (Rogers, 2006)

Cone resistance, sleeve friction, and pore water pressure are used to interpret geotechnical characteristics of lithology, for example shear strength of the materials. Undrained shear strength of cohesive and saturated materials can be related to cone resistance values. Another characteristic that is commonly used is friction ratio applied to classify lithological units. It is measured in percentage of sleeve friction per cone resistance (Rogers, 2006).

The values of cone resistance, friction ratio, and pore pressure are used for lithological classification, for example in following (fig. 15). However, this classification of lithology in CPT diagram may need to be adjusted depending on characteristics of each lithology in study area. CPT does not obtain samples of lithology. It may be interpreted that values derived from CPTs in other locations may be different from values in the diagram classification. Therefore, the interpretation should need validation from borehole data to check characteristic of lithology based on values of CPT. Especially, if CPT has not been applied in that geologic environments (Robertson, 2006).

CPTs can differentiate clearly clay and sand formations (fig. 15) (Rogers, 2006). Generally, peat material will have higher friction ratio than sand and clay (Eslami & Fellenius, 2004). The interpretation of peat may need to be carefully done since peat contains fibers (Boylan & Long, 2007). The characteristics result in low shear strength and bearing capacity as interpreted in cone resistance. These low strength and low bearing capacity of peat can also be related to high compressibility of these peat materials. Other values which also can be used in classification of lithological units are pore water pressure. High water pressure indicates lithology as clay unit. This type of soil has low permeability that can generate slow dissipation of water. On the other hand, high permeability of sand can be interpreted by relatively lower pore water pressure (Fugro, 2004).

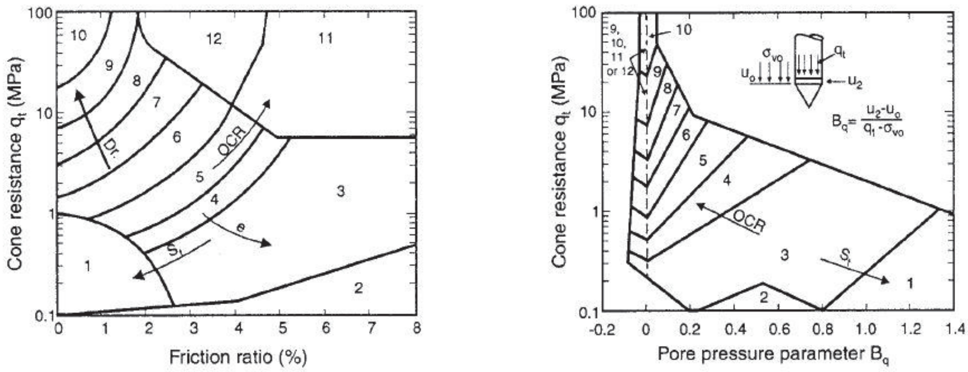


Figure 15 Soil classification from CPT interpretation (Robertson et al., 1986)

Zone 1: sensitive fine grained	Zone 2: organic material
Zone 3: clay	Zone 4: silty clay to clay
Zone 5: clayey silt to silty clay	Zone 6: sandy silt to clayey silt
Zone 7: silty sand to sandy silt	Zone 8: sand to silty sand
Zone 9: sand	Zone 10: gravelly sand to sand
Zone 11: very stiff fine grained	Zone 12: sand to clayey sand
*overconsolidated or cemented	

Pressure correction resulted pore water pressure can influence the results of cone resistance and sleeve friction related to depth (Robertson et al., 1986). The correction is significant mainly for clay or soft soils having very low resistance values and high pore water pressure. The correction is not applied in the study because of CPT values of peat and clay do not show significant difference of pore water pressure and cone resistance. The effect of pore water pressure to cone resistance and friction sleeve can be substantial in deeper depth of CPT observation(Campanella et al., 1982). Overburden stress can also affect results of cone resistance and friction sleeve. The diagram of CPT without correction of pore pressure and overburden stress is based mainly from CPT data obtained at depth less than 30 m. Correction should be made for CPT investigation having greater depth of observation (Robertson et al., 1986). In the study area, peat and clay are located in shallow depths from the surface to about 10 m below m.s.l.

4.2. Resistivity

Resistivity surveys are established methods to determine the lithology and water content (Palacky, 1987), albeit resolution may need to be adjusted to get better interpretation. It can be determined by applying different arrays or adjusting electrode distances in measurements (Loke, 2004). In the interpretation, the geology of study area may be defined by variations of resistivity related to lithological variations, water content, and non-homogeneity of water (fresh and saline water) (Hack et al., 2008). The interpretation of geological formation from resistivity should need the validation from boreholes. Resistivity can be used to analyze groundwater in finding the interface of salt water and fresh water. Fresh water has relatively high resistivity and saline water is defined by apparently low resistivity (fig. 16).

In the resistivity measurements, an electrical current (measured with current meter) is sent through the ground by electrodes. Measuring electrodes are installed in the ground to measure the local surface of potential difference (measured with a volt meter). The measured surface potentials can be related to the flow of the current through the ground. The resistivity distribution is related to subsurface lithology and presence of water (Milsom, 2003).

Different arrays can be applied in the resistivity surveys that can determine the result of the measurements. The arrays used in resistivity survey will depend on the types of structures to be measured and sensitivity of resistivity meter (Hack et al., 2012). Three different arrays that are normally used are Wenner, Schlumberger, and Dipole-dipole. Wenner array results in best interpretation for vertical variation of structures or it is sensitive for horizontal structures. Dipole-dipole array is sensitive for vertical structures while schlumberger array is sensitive for both horizontal and vertical variations (Loke, 2004). Another type of the array that is commonly used is the combination of Wenner-Schlumberger arrays. The pattern of pseudo section data and electrode arrangements of Wenner-Schlumberger arrays are illustrated in fig. 17.

A device of sting R1 (memory earth resistivity meter) measures the resistivity with multi-electrode system. Electrodes are connected by a multi core cable to a switching box and resistance meter. Penetration depth of resistivity depends on the length of line measurement, type of materials, and type of arrays applied in the survey. Electrode space in the survey determines also penetration depth of measurement (Loke, 2004).

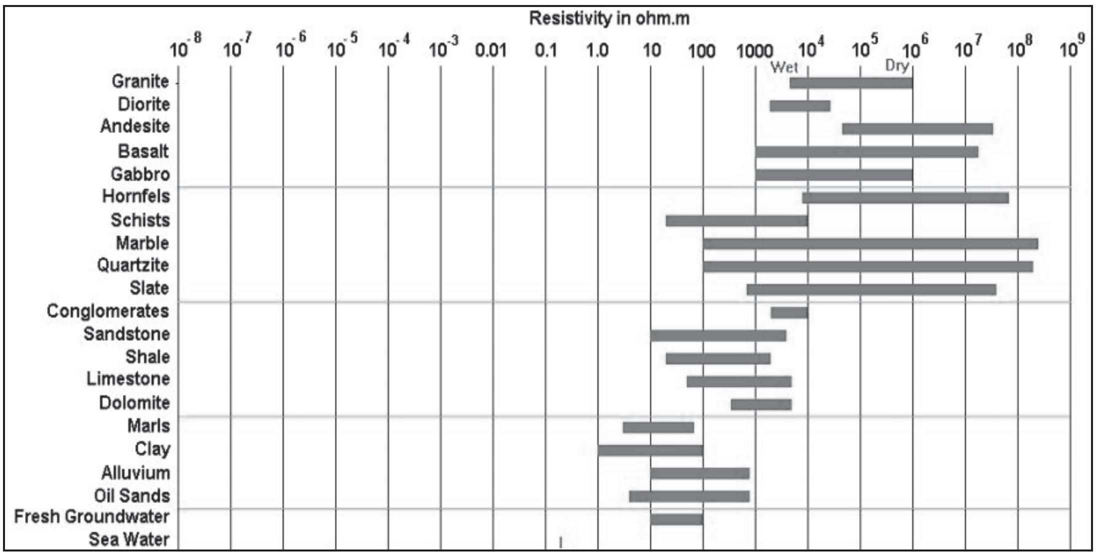


Figure 16 Resistivity values of materials (after (Loke, 2004)

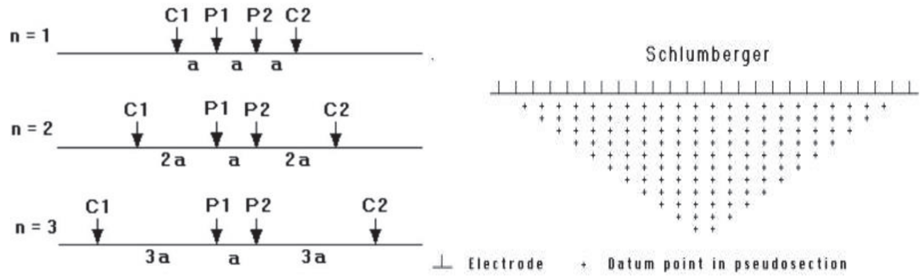


Figure 17 Pattern of pseudosection data and electrode arrangements of Wenner-Schlumberger arrays (Loke, 2004)

4.3. 3D geological modeling

3D subsurface_modeling comprise of subsurface geological and resistivity models. The interpretation of geological modeling is based on analyses of CPT and boreholes. RockWare software is used in processing of subsurface geological modeling comprising of 3D subsurface models, 2D cross section or slices of the models, and fence diagrams. Data processing of resistivity is conducted by earth imager resistivity software. The software processes the resistivity data Tempeldijk South.

4.3.1. RockWorks software

The RockWare or RockWorks is software to analyze, manage, and visualize geological data in 2D and 3D diagrams. It has two main data windows; The Borehole Manager and The RockWorks Utilities (RockWorks, 2010). Model used_in data processing is stratigraphic model and lithological model interpolating grid models for the upper and lower stratigraphic units. Interpretation of the depths of lithological units from boreholes and CPTs is plotted in locations based on coordinates. The model generates a 3-dimensional diagram that displays the stratigraphic layers. Cross section creates a 2D profile diagram and illustrates the models between two points.

The Borehole_Data window is used to input and manage data of borehole locations, geophysical or geochemical measurements, lithologies, stratigraphic contacts, etc. 2D diagrams that can be created from the data are contour maps, geological maps, logs, cross sections, and profiles. In addition to 2D diagrams, there are 3D diagrams that can be produced from data. For example, 3D logs, surfaces, fence diagrams, and solid models. The RockWorks Utilities can be used to process data to create basic gridding and contouring, hydrology and hydrochemistry tools (drawdown & flow diagrams), 2D and 3D feature analysis (rose and stereonet diagrams, lineation maps and densities), and etc. The software only applies The Borehole Manager for this study (RockWorks, 2010).

For 3D stratigraphic_modeling, there are various types of gridding interpolation (algorithms) methods that can be selected in data processing. Inverse distance and kriging are few of methods in gridding options which are available. Other options such as, multiple linear regressions, closest point, and distance to point can be selected in the processing. Moreover, grid size and data size in modeling options are available in processing of 3D subsurface models (Amurane, 2003).

5. RESULTS AND DISCUSSION

5.1. Geology of the dike

Geology of Tempeldijk South is based on borehole and CPT data that have been conducted in the study area (table 3). Two borehole data are obtained by the Delft continuous soil sampler having depths of about 18 meters and 11 meters respectively (table 4 and 5). This soil sampler is a type of triple tube core sampler that can be applied to obtain full (coring) samples of soils in subsurface investigation. Borehole data are used to identify lithological units and to explain the geological characteristics in Tempeldijk South. In this research, interpretation of boreholes uses descriptions of lithology made by Deltares. In addition to borehole description, geology in the study area is also described by interpretation of 17 CPT data. Interpretation of CPT is done after correlation between CPT and borehole data is conducted. Lithological units described from boreholes are defined based on CPT values comprising of cone resistance, friction sleeve, friction ratio, and pore water pressure. Furthermore, interpretation of lithology from the correlation will also be used to determine upper and lower boundary of each lithology.
Based on the correlation between borehole and CPT data, each lithological unit has certain ranges of CPT values. The ranges can be used to distinguish clearly lithological units in CPT. For example, different ranges of values interpreted between sand and clay/peat layers. However, different lithological units can be interpreted having relatively similar ranges of values. This condition can be found in interpretation to differentiate peat and clay units. In addition to similar ranges of values, depths of the upper and lower boundary of lithological units from the two methods can also be defined although several boundaries give different results. These situations need to be considered in interpreting correlations between the CPT and borehole data. Borehole and CPT locations are marked with red and green symbols shown in (fig. 18).

Table 3 Borehole and Dutch cone penetration test data (Hack et al., 2008)

Name	Data	Coordinates				Elevation (m)
		RD (Rijks-Driehoek) The Dutch geographical service		UTM WGS-1984 31U		
		X	Y	Easting	Northing	
BH01 (S04)	Boreholes	107238.38	452370.59	615921.089	5768791.26	-4.58
BH02 (S17)	Boreholes	107267.02	452338.03	615950.779	5768759.67	-2.01
S01	CPT	107226.43	452371.91	615909.104	5768792.19	-5.06
S02	CPT	107230.42	452371.91	615913.091	5768792.32	-4.85
S03	CPT	107234.39	452371.18	615917.083	5768791.72	-4.69
S04	CPT	107238.38	452370.59	615921.089	5768791.26	-4.58
S05	CPT	107242.25	452369.91	615924.979	5768790.71	-4.39
S06	CPT	107246.2	452369.18	615928.95	5768790.11	-4.23
S07	CPT	107250.23	452368.51	615932.999	5768789.57	-4.03
S08	CPT	107254.09	452367.90	615936.877	5768789.09	-3.64
S09	CPT	107241.57	452390.37	615923.627	5768811.13	-4.77
S10	CPT	107240.77	452385.44	615922.99	5768806.18	-4.66
S11	CPT	107240.01	452380.53	615922.392	5768801.25	-4.54
S12	CPT	107239.33	452376.64	615921.84	5768797.34	-4.52
S13	CPT	107237.42	452365.41	615920.3	5768786.06	-4.52
S14	CPT	107236.65	452360.55	615919.69	5768781.17	-4.49
S15	CPT	107235.8	452355.61	615919.003	5768776.21	-4.5
S16	CPT	107234.9	452350.69	615918.266	5768771.26	-4.56
S17	CPT	107267.02	452338.03	615950.779	5768759.67	-2.01

The study area can be included into the unit of (C2.) based on geological map of Bosch and Kok (1994) (fig. 9). The explanation of the unit C2. is the lithological unit comprising of Holland peat on Callais III Deposits (tidal flat deposits) on an alternation of Holland peat and Gorkum deposits. All members of the units are included in Westland formation. The peat units located at or near the surface is interpreted as

Holland peat. The Holland peat unit is identified as Nieuwkoop Formation by the new nomenclature (fig. 10). On the other hand, Callais III and Gorkum deposits indicate different depositional environments of the study area. Callais III deposit which is a product of marine processes is interpreted as Naaldwijk formation of Wormer member. Gorkum deposit is a product of fluvial process included in Echteld formation. From the figure 10, it can be further explained that the relationships of stratigraphy from these three formations are parallel. This stratigraphic relationship explains that the three formations can be formed relatively at the same time in certain locations.

Table 4 Description of borehole BH01 (translated from description by Deltares ((appendix 3) in Dutch)

No	Lithology	Description	Depth (m) below NAP		Thickness (m)
			from	to	
1	Peat	very clayey	-4.58	-4.98	0.4
2	Peat	organic material, low mineral content	-4.98	-7.68	2.7
3	Peat	slightly clayey	-7.68	-7.83	0.18
4	Clay	slightly silty, moderately peaty	-7.83	-8.08	0.25
5	Clay	moderately silty, slightly peaty with plant remains	-8.08	-8.33	0.25
6	Clay	moderately silty, moderately peaty	-8.33	-8.48	0.15
7	Peat	organic material, low mineral content	-8.48	-9.38	0.9
8	Clay	moderately silty, slightly peaty with plant debris and some peat layers	-9.38	-9.98	0.6
9	Peat	slightly clayey	-9.98	-10.33	0.35
10	Sand	moderately silty, moderately peaty with grain size = 0.150 mm	-10.33	-10.58	0.25
11	Sand	moderately silty with some plants rest and grain size = 0.150 mm	-10.58	-10.70	0.12
12	Sand	slightly silty with grain size = 0.150 mm	-10.70	-11.13	0.43
13	Sand	moderately silty with pieces of loam with grain size = 0.125 mm	-11.13	-11.93	0.8
14	Sand	slightly silty with some pieces of gravel, single piece of loam with grain size = 0.350 mm	-11.93	-12.56	0.63
15	Sand	very silty with grain size = 0.125 mm	-12.56	-13.33	0.77
16	Sand	slightly silty with grain size = 0.210 mm	-13.33	-13.70	0.37
17	Sand	slightly silty with grain size = 0.250 mm	-13.70	-13.90	0.2
18	Sand	slightly silty with grain size = 0.300 mm	-13.90	-14.83	0.93
19	Sand	slightly silty with grain size = 0.420 mm	-14.83	-15.38	0.55
20	Sand	slightly silty with grain size = 0.175 mm	-15.38	-15.83	0.45
21	Sand	slightly silty with grain size = 0.350 mm	-15.83	-18.48	2.65

Table 5 Description of borehole BH02 (translated from description by Deltares (appendix 5) in Dutch)

No	Lithology	Description	Depth(m) below NAP		Thickness (m)
			from	to	
1	Peat	very clayey with some pieces of debris	-2.01	-2.51	0.5
2	Peat	organic material, low mineral content	-2.51	-2.76	0.25
3	Peat	slightly clayey	-2.76	-3.65	0.89
4	Peat	organic material, low mineral content	-3.65	-4.51	0.86
5	Clay	moderately silty, slightly peaty with some plants rest	-4.51	-5.76	1.25
6	Clay	slightly silty, moderately peaty with some plants rest	-5.76	-7.79	2.03
7	Clay	moderately silty, slightly peaty with some plants rest	-7.79	-8.06	0.27
8	Clay	moderately silty, with shell remains	-8.06	-8.33	0.27
9	Peat	organic material, low mineral content	-8.33	-8.76	0.43
10	Peat	slightly clayey	-8.76	-9.03	0.27
11	Clay	slightly silty, moderately peaty with plant remains	-9.03	-9.27	0.24
12	Clay	moderately silty with plant remains	-9.27	-9.43	0.16
13	Peat	organic material, low mineral content	-9.43	-9.66	0.23
14	Sand	moderately silty, moderately peaty, grain size = 0.150 mm	-9.66	-9.84	0.18
15	Sand	moderately silty, some plants rest, grain size= 0.150 mm	-9.84	-10.06	0.22
16	Sand	slightly silty, some plants rest, grain size = 0.175 mm	-10.06	-10.29	0.23
17	Sand	slightly silty, grain size = 0.125 mm	-10.29	-10.49	0.2
18	Sand	slightly silty, some silt layers, grain size = 0.150 mm	-10.49	-11.09	0.6
19	Loam	slightly sandy	-11.09	-11.16	0.07

The study area is located at the edge of intertidal area (inland) (Berendsen & Stouthamer, 2001). The deposits of the location can be related to Holocene transgression displayed in (fig. 13). The description of boreholes also defines that the study area was located in the area having influences from both fluvial and marine processes. The presence of clay with shell remaining on BH02 at depth about 8 meter below m.s.l. may indicate the influence of marine processes in the study area although freshwater may also produces deposits with fresh water shells. It is likely that marine process influences the clay because grey color of the unit that may indicate iron bounded to sulphide (Fufa, 2004). From stratigraphic profile located near the study area, it is interpreted that deposit at these depth is classified as shallow marine deposit (Hijma et al., 2009). However, the preservation of organic material, such as wood, can identify that fluvial process also influences stratigraphy in the study area.

On the other hand, sand layers in the study area can be categorized into two types. In this research the categorization is made based on interpretation of borehole and CPT data. Adding information from literature study helps identification of the sand layers. From interpretation, the top sand layer having mainly fine sand and silt intercalated with loam are grouped into Boxtel Formation. The formation deposited as aeolian dunes sometimes intercalates with loam layer in several locations. The alternation of fluvio-aeolian deposit is common in lower part of Boxtel formation (Schokker et al., 2007). Borehole BH02 identifies this loam layer at the bottom of borehole, but the layer cannot be found in BH01. The presence of loam is interpreted as piece debris of loam at depth about 12 meters. The presence of this loam layer can also be identified based on CPT interpretation.

The second (lower) sand layer having different structure can be interpreted as the oldest formation of the available data in Tempeldijk. The structure is laminated bedding with coarser grain size that is typical deposits in fluvial environment (appendix 1 and 2). This type of lithology is included in Kreftenheye Formation found at depth about 13 meters below m.s.l. (Hijma et al., 2009). Different grain sizes found on two sand layers are related to depositional processes occurred during depositional time. Fluvial processes by water have more energy to form larger grain size than aeolian processes deposited mainly by wind. However, not every datum of investigation can fully reach this formation. The situation makes that the interpretation of the second sand layer cannot be fully conducted in every location.

5.1.1. Correlation between boreholes and CPT

The correlation between the data from the CPT and boreholes is required to comprehend the geological setting of the study area. From description of the borehole BH01 and BH02, lithological units in Tempeldijk South consist of peat, clay, and sand layers with varying thicknesses. The description of boreholes gives characteristics of each layer. For example, different peat layers can be interpreted having different compositions in BH01. One of peat layers can be described as peat with low mineral content at depth -4.98 m (table 4). On the other hand, variations of the layers can be found where a peat layer at depth -7.68 m comprises of clay as its composition. Differences in composition also occur in the clay layers containing peat and silt in certain amount (table 4).

Unlike peat and clay layers, characteristics of sand layers are not only shown by differences in the composition but also by differences in the average grain size and sedimentary structures of the sand units (table 4 and 5). In addition to those layers, interbedded layers of peat, clay, and loam layers may also be present in particular locations. The description of lithology with the upper and lower boundaries listed in the table 4 and 5 is plotted into the CPT logs S-04 and S-17. The correlation is done to determine the characteristics of each lithology based on CPT values. The results of the plotting can be seen in appendices 6 and 8.

The correlation is used as a validation of the lithological units that will be interpreted in CPT of S04 and S17. Further in this study, the CPT data will be correlated with stratigraphy of the study area. The interpolation shows the significance of borehole validation of CPT. In this study, the classification and identification of lithological names are based on the description of boreholes interpreted by Deltares. For the interpretation of lithology in CPT, the lithology is classified by the values plotted in CPT diagrams.

Diagram that is applied in the correlation is a diagram from Robertson (1986) showing characterization of lithology based on cone resistance and friction ratio values.

Based on borehole description, classification of S-04 and S-17 into CPT diagram is conducted The CPTs are located adjacent to BH01 and BH02 respectively, so the CPT data can be correlated directly to boreholes. Before the classification, the values of cone resistance and friction ratio of each unit are determined in each graph of CPT. These values are averaged to obtain one single value of cone resistance and friction ratio of each lithological unit. The graphs of cone resistance and friction ratio can be seen in (fig. 19).

The cone resistance and friction ratio values of CPT in S-04 are plotted into diagram of Robertson (1986). The values of each unit comprising of peat, clay, and sand layers are resulted based on the description of borehole BH01. The CPT diagram of Robertson shows that the correlation between borehole and CPT does not fully fit in characterizing these lithological layers. The identification of CPT values of peat and clay layers in Robertson diagram is illustrated in (fig. 20). There is difficulty in distinguishing between peat and clay layers. No peat layer has been identified as zone (2) which is organic material in CPT diagram. Every peat and clay layer is classified into the zone (3) which is clay unit of CPT diagram. There is only a clay layer that is plotted in zone of sensitive fine-grained. For interpretation of sand layers, the borehole description can be classified into three different types of classes based on CPT Robertson diagram. The classes of 6, 7, and 8 in CPT Robertson diagram comprise of sandy silt to clayey silt, silty sand to sandy silt, and sand to silty sand.

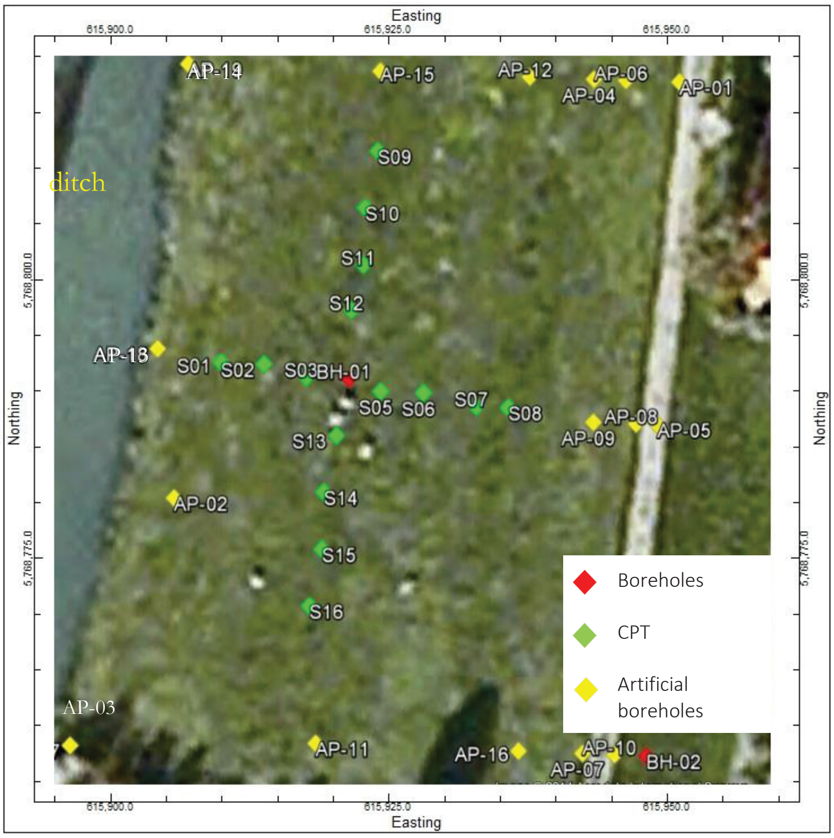


Figure 18 Boreholes and CPT locations with artificial boreholes used in 3D modeling (Maps, 2012)

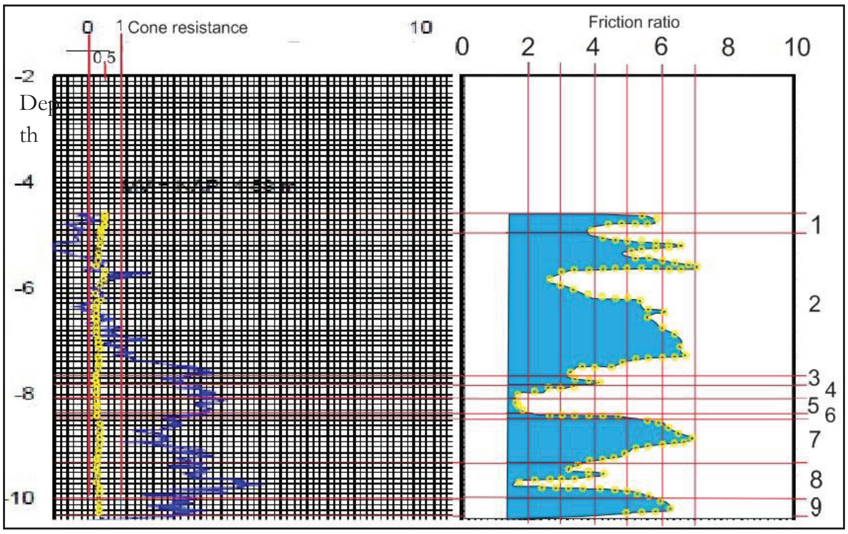
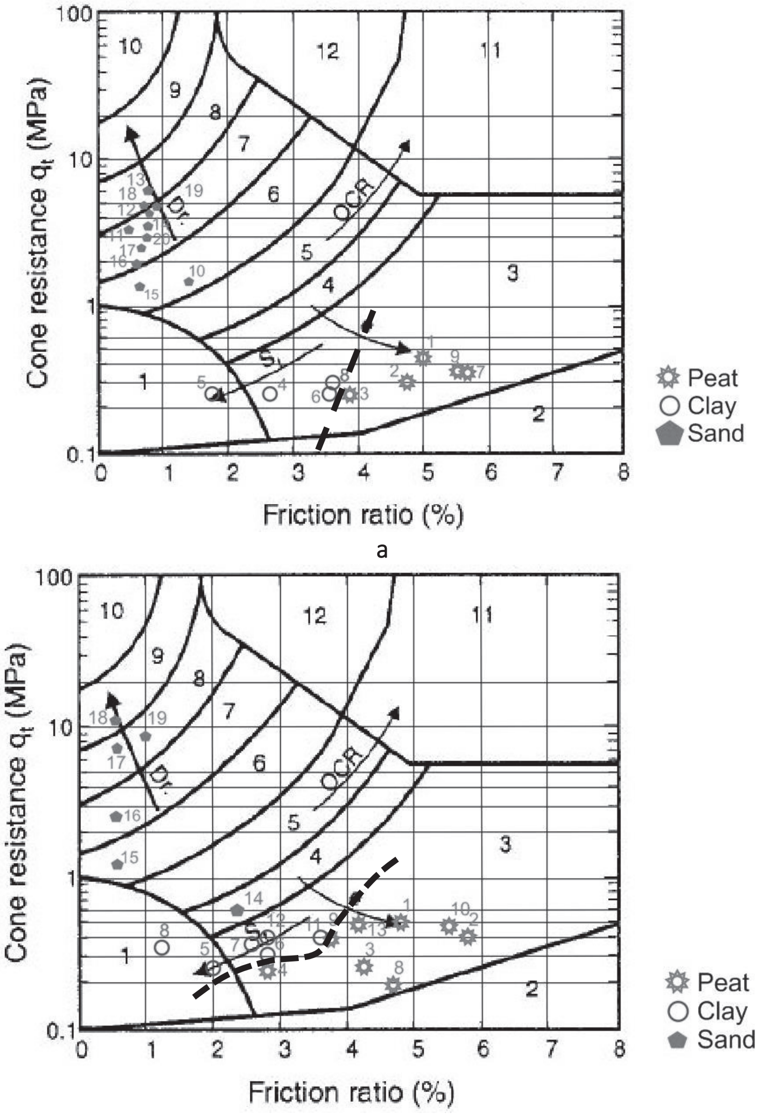


Figure 19 Cone resistance and friction ratio (average) values (S04 CPT) of peat and clay layers for CPT diagram (Numbers on the right side represent lithological units from borehole description)

On the other hand, a similar situation occurs in the correlation between BH02 and S17. Most of peat and clay layers are classified into zone clay. Two units of clay layers are fall in the category of fine-grained sensitive zone. However, interpretation of sand layers can be classified into four different classes of 6, 7, 8, and 9 classes of CPT diagram consisting of sandy silt to clayey silt, silty sand to sandy silt, and sand to silty sand. From both figures, we can see the dashed lines indicating the approximate boundary between the peat and clay layers as the results of the description of boreholes.



Zone 1: sensitive fine grained
Zone 2: organic material
Zone 3: clay
Zone 4: silty clay to clay
Zone 5: clayey silt to silty clay
Zone 6: sandy silt to clayey silt
Zone 7: silty sand to sandy silt
Zone 8: sand to silty sand
Zone 9: sand
Zone 10: gravelly sand to sand
Zone 11: very stiff fine grainedZone 12: sand to clayey sand
*overconsolidated or cemented

Figure 20 Correlation of lithological (a) borehole BH01 and CPT S04 and
(b) borehole BH02 and CPT S17 in CPT diagram of Robertson (1986).
(Numbers beside symbols of lithological units represent lithological units from borehole description)

Previously, the correlation of both methods indicates a discrepancy in the identification of lithological units. Another difference that can be found in the correlation of both methods is related to the thickness of the layer. Borehole data describes the thickness of the lithological units that may be difficult to be distinguished from the CPT. This condition is applied especially to lithological layer that has relatively thin thickness. CPT may not be able to distinguish the difference in lithological composition especially on a similar type of soils. For example, lithological clay layer at a depth of about 8 meters in borehole BH01 is classified into three different units with each thickness of 0.25 m, 0.25 m, and 0.15 m respectively. However, all three units are difficult to be differentiated from the CPT log either by cone resistance or friction ratio values (fig. 21).

The description of the lithology from boreholes is plotted directly on the CPT logs. It can be seen that the S-04 location has 21 lithological units. Further interpretation is done by classifying those lithological units based on CPT. The interpretation classifies that the lithological units can be distinguished into 12 units consisting of variations in peat, clay, and sand layers. Interpretation of CPT is performed to facilitate the interpolation of CPT data and to assist the description of stratigraphy in the study area.

The difference in the number of units derived from the boreholes and CPT methods is caused by the presence of layers that cannot be distinguished from all methods, for example clay layers explained beforehand. In addition to clay layers, sand layers are also classified into different number of classes from borehole and CPT interpretation. Borehole describes 12 different layers of sand while CPT classification groups sand layers into 2 types.

The new classification is not only done as generalization of the existing layers, but also as classification of lithology into more detail. For example, a peat layer with the upper boundary located at a depth of about 5 meters with a thickness of 2.7 meters. The layer can be divided into three classes of peat in CPT graph S-04. Comparison between the classification of BH01 and S04 is illustrated in figure 21. The left part of the figure shows the correlation based on borehole description while the right part of the figure displays the interpretation CPT. Moreover, the correlation indicate similarities and differences in the depth of the upper and lower boundary of lithological units. Some interpretations of depths of units in boreholes and CPT will be adjusted by interpreting from borehole photo and CPT results.

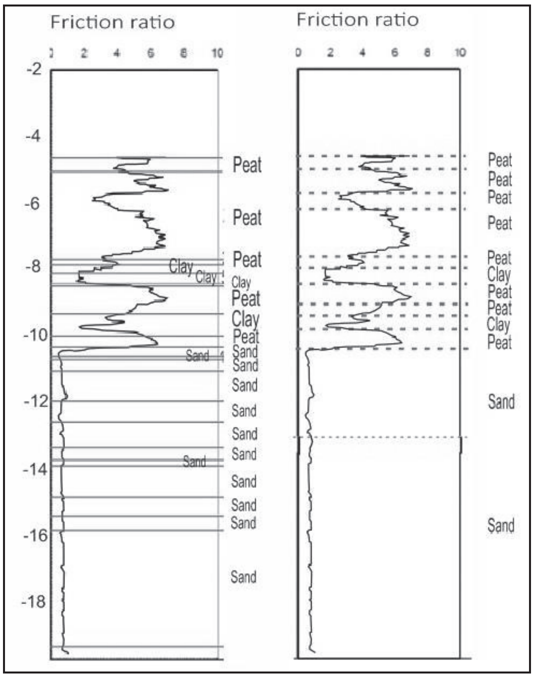


Figure 21 CPT interpretations of S04

Table 6 Interpretation of lithological units of CPT S04

No	Lithology from CPT and borehole	Description of CPT	Depth (m) from	Depth (m) to	Thickness (m)
1	Peat	clayey	-4.58	-4.98	0.40
2	Peat	organic material, low mineral content	-4.98	-5.70	0.72
3	Peat	clayey, silty	-5.70	-6.15	0.45
4	Peat	organic material, low mineral content	-6.15	-7.65	1.50
5	Peat	very clayey	-7.65	-7.95	0.30
6	Clay	slightly peaty	-7.95	-8.42	0.47
7	Peat	organic material, low mineral content	-8.42	-9.02	0.60
8	Peat	Slightly clayey	-9.02	-9.38	0.36
9	Clay	moderately peaty	-9.38	-9.81	0.43
10	Peat	slightly clayey	-9.81	-10.40	0.54
11	Sand	moderately silty	-10.40	-13.30	2.90
12	Sand	slightly silty	-13.30	-19.30	6.00

The same as data of S-04 and BH01, correlation between BH02 and S17 is also conducted. The interpretation of borehole indicates that 19 lithological units can be described comprising also of peat, clay, and sand layers in the left part of (fig. 22). The data is illustrated in table 5 above. A similar situation as correlation of S04 and BH01 can be interpreted on this correlation. A peat layer described from borehole can be divided into two different types which are interpreted to have different composition based on friction ratio values. This layer is found at depth of about 3 meters below m.s.l. The other explanation is in the different depths of upper and lower boundaries of each unit. It is interpreted that similarities of upper and lower levels of the units can be interpreted in several lithological layers. However, some differences exist in other boundary of the units. Classification of CPT shows that 17 units of lithology can be grouped. The 17 lithological units are illustrated in the right part of the figure and listed in table 7.

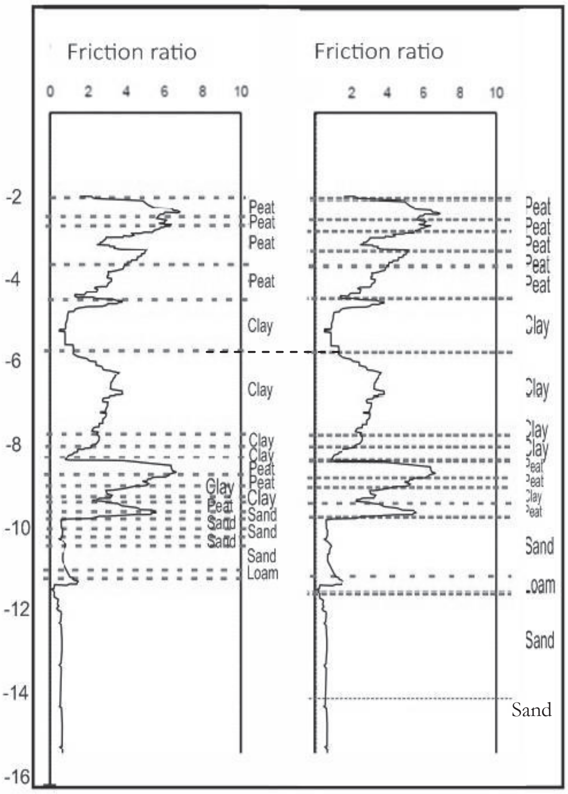


Figure 22 CPT interpretations of S17

Table 7 Interpretation of lithological units of CPT S17

No	Lithology from CPT and borehole	Description of CPT	Depth (m) from	Depth (m) to	Thickness (m)
1	Peat	clayey	-2.01	-2.51	0.50
2	Peat	organic material, low mineral content	-2.51	-2.80	0.29
3	Peat	Clayey	-2.80	-3.30	0.50
4	Peat	Slightly clayey	-3.30	-3.65	0.35
5	Peat	very clayey	-3.65	-4.45	0.80
6	Clay		-4.45	-5.75	1.30
7	Clay	very peaty	-5.75	-7.80	2.05
8	Clay		-7.80	-8.06	0.26
9	Clay		-8.06	-8.40	0.34
10	Peat	organic material, low mineral content	-8.40	-8.80	0.40
11	Peat	Slightly clayey	-8.80	-9.05	0.25
12	Clay		-9.05	-9.45	0.40
13	Peat	Slightly clayey	-9.45	-9.78	0.33
14	Sand	Moderately silty	-9.78	-11.20	1.42
15	Loam		-11.20	-11.60	0.40
16	Sand	Moderately silty	-11.60	-14.00	2.40
17	Sand	Slightly silty	-14.00	-16.00	2.00

5.1.1.1. Discussion of correlation between CPT and boreholes

Interpretation of both CPT and borehole methods does not fully correlate with each other. There are similarities and differences found from the correlation between two methods. The results that can be observed are related to identification of lithological units and the depths of the upper and lower boundary of lithological units. Several units can be clearly identified while other units may need careful interpretation. Lithological units based on borehole description that are relatively difficult to be distinguished in the CPT interpretation are peat and clay layers. Peat and clay layers can be found at shallow depths as lithology composing the body and foot part of the dike. Both of these soil types have CPT values that sometimes overlap one another. These overlapping values can be caused by the content of each composition of peat and clay layers. Those layers have a different mix composition of peat, clay, and silt. Certain composition of a layer can determine the variation ranges of values interpreted in CPT. Peat with a little composition of clay will have different CPT graphic from peat having more clay in its composition. Similar situation occurs in the clay layer composing of peat materials. This mix composition of lithological units can be related to depositional environments of the study area which will be described later in this study.

Description of lithology from the borehole is not fully similar as the classification of CPT in Robertson diagram. The difference is found especially for peat layers. This condition can be explained by variation of mix composition described earlier. In addition to the composition, another reason is that the classification of Robertson was made based on the results of the interpretation of varieties of soil samples having certain ranges of cone resistance and friction ratio values. The samples were obtained in different locations. The samples were plotted and boundaries between each layer can be illustrated in the diagram. The results of the lithological samples will differ depending on the characteristics of the particular area where the lithology is sampled. The diagram of Robertson analyzed samples located in Vancouver, Canada (Robertson et al., 1986). Furthermore, the types of peat may also determine characteristics of the units in CPT diagram. Peat has different types having different composition in each location. For example, it can be composed by wood or sedge, etc. It can also be deposited in different depositional environments. However, the interpretation of clay and sand layers is different from peat layers. Clay layers and several units of sand layers correlate to CPT diagram. The condition explains that sand may be relatively easy to be defined from peat or clay layers from CPT values. The larger area of clay units in the classification of CPT diagram can also be as explanation of the results of correlation. The situation defines the significance of validation using borehole data. It is also one of the reasons for identifying lithological name based on the interpretation of the boreholes.

Correlation of lithological interpretation obtained from both methods determines depths of the upper and lower boundary of the lithological units. Some lithological units show similarities but other interpretations indicate differences in defining the depths of the lithological units. Remarks that can explain this condition is associated with differences in the composition of lithology. The content of the lithological composition which is nearly similar may cause difficult interpretation. This situation particularly takes place between peat and clay units. Also, boundary of layers can display transition of lithology from one to another unit. The situation can be found in transition of peat to sand layer. The transition between lithological layers can be interpreted in boreholes. Those situations will lead to difficulty in determining the boundaries of the lithology.

In addition to composition of lithological units, the process of investigation methods and characteristics of lithology can influence the depth of measurements in both methods. Peat may subside due to heavy equipment on the surface of CPT. Another reason of different depths can be explained by the difference in the depth and thickness of the soil coring samples resulted by Delft continuous soil sampler. The characteristics of high compressibility of peat cause the materials to be compressed as the result of the drilling process. This situation can be seen in the thickness of coring samples having small difference, for example, the thickness of the first layer of peat in BH01 with a difference of 10 cm from description of depth (Appendix 3).

5.1.2. Structures and characteristics of the study area based on CPTs

CPTs can use values of cone resistance, friction ratio, friction sleeve, and pore water pressure to classify the lithological units of Tempeldijk South. These values can be applied to distinguish clearly between the lithological formation between peat/clay and sand formations. Cone resistance values in the study area have range values of 2-20 (MPa). Cone resistance values of sand are much higher than peat or clay. On the other hand, in the study area, the friction ratio values of sand is extremely low which are less than 1 % compared to clay and peat formation. For this research, the combination of cone resistance, friction ratio, and friction sleeve values will be used to determine the boundary layer of sands. Other values of pore water pressure can also be used although the graphics of these values are less significant. Contact between peat and sand layers in the study area are found at depths of about 10.5 meters below m.s.l. It is interpreted beforehand that the boundary of peat and sand layers is determined by combination of several values. In another interpretation, the classification between sand layers is based on cone resistance values. The first sand layer having finer grain size is described from boreholes overlying the second layers with coarser grain size. From the cone resistance values, we can clearly define the second layer with higher cone resistance values.

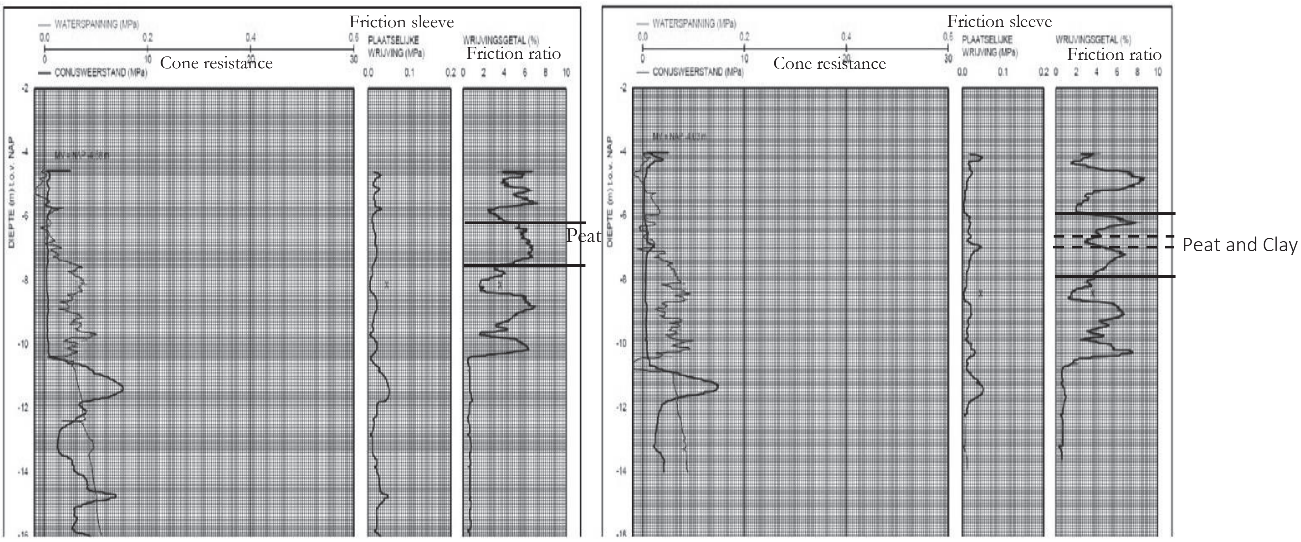
Previously, it is explained that several lithological units can be clearly distinguished from the values of CPT. For example, the difference of values between a sand layer and peat. On the contrary, interpretation of peat and clay will be difficult to do. Occasionally, the values of these peat and clay layers are displayed in similar values. This is shown in the classification of S04 (Fig. 21) where a peat layer at about 8 meters deep shows same friction ratio as the value of clay layer located at about 9.8 meters depth. Interpretation to differentiate the boundary between peat and clay layers is based on the friction ratio values. Lithological layers have the values that are much higher compared to values of sand layers. However, in the study area, peat has friction ratio which is only slightly higher than clay so that the values between peat and clay need to be carefully defined. In the study area, there are some overlapping values interpreted between these units. Peat formations have friction ratio values in approximate ranges from 1.5 % to 9 % while clay formations have friction values in ranges from 0.5 % to 4.5 %.

On the other hand, pore water pressure in the study area has a range of values from negative values to about 0.2 (MPa). Generally, the deeper depths will show the higher pore water pressure. In addition to depth influence, the values can explain some of the characteristics of lithological units although it is not clear to define characteristics of every layer. The pore water pressure is difficult to be distinguished between peat layers and between peat and clay layers. In several locations, relatively similar values are interpreted between the depth having positive values to the depth of approximately 7 meters. Then, there is relatively sudden increase of pore water pressure at depths about 7 meter below m.s.l. at most of CPT data. There is no clear boundary of lithological units of peat and clay that can be determined based on the variation of these values. However, pore water pressure can be used to find changes between peat and sand layers. This condition is indicated by the significant changes of pressure in most of the border of these layers. In another unit, pore pressure is also used to distinguish the loam layer located at about 11 meters below m.s.l. The Loam layer indicates a sudden increase of water pressure compared to sand layer on top and bottom of the unit.

It is interpreted that negative values of pore water pressure can be interpreted in shallow depth of CPT locations. These values are likely located above the water table of the dike showing capillarity of water condition in the soils. Usually, changes from negative to become positive values may indicate depth of water table in the study area (Schmertmann, 1977). It depends on the elevation at each boreholes and CPT. The depth of water table is located approximately at 0.8 - 1 meter below the CPT elevation although deeper depths of water table can be found in several locations.

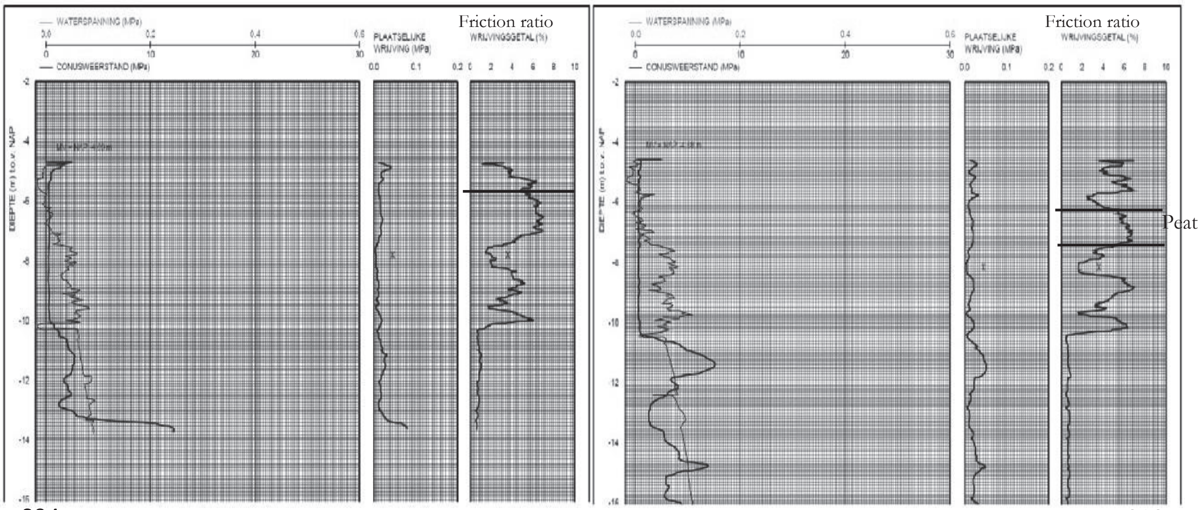
The depths of lithological units are different in each location of CPTs. Layers can be found deeper or shallower in one location compared to other locations. However, several lithological units in the layer below the dike are relatively horizontal while other layers show an undulating and slightly inclined structure. In the study area, it is also interpreted that the existence of the lithological layer changes from one location to another location. These changes can be in different thicknesses and different structure of lithological layers. The layers can have a form of splitting structure and pinched out of layers. Splitting is a structure of a layer that changes into minimum two or more layers in certain locations. This structure is shown by CPT interpretation of S-04 and S-07 of a peat layer (fig. 23). In addition to splitting structure, the unit layers in one location can pinch out or disappear in other locations. The pinched out layers of a peat structure is shown in (fig. 24). Also, changes of lithological thicknesses are able to be determined after interpretation of different CPT data. Changes of thicknesses are in forms of thickening and thinning of lithological layers.

Friction sleeve is one of values obtained in the CPT investigation in Tempeldijk South. In the study area, friction sleeve is used to differentiate between peat and sand layers combined with interpretation using other values. The values are also applicable to determine boundary between sand layers. Tempeldijk South has ranges of friction sleeve from 0 to about 0.135 (MPa). From the comparison of three lithological units, lowest ranges of friction sleeve values indicate clay layers while sand layers show highest values. Peat has slightly higher friction sleeve than clay.

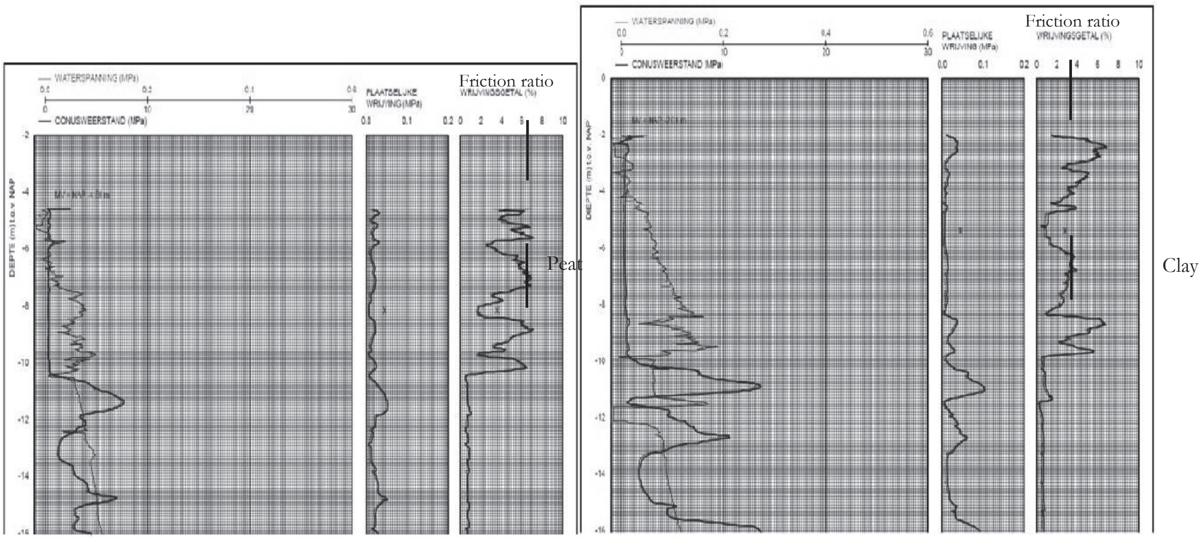


S04 Figure 23 CPT interpretations of S04 and S07 showing splitting structure of a peat layer S07

Another variation of the lithological layers of the dike is changes of composition that can be found at approximately the same depth below the surface (fig. 25). The change of lithological units also happens as variations in the subsurface. The composition of a peat layer in S-04 has changed into a clay layer in the location of S-17. These changes can be discovered by differences in friction ratio values. Borehole description also determines the changes in location having distance about 45 meters from BH01 to BH02. Boundary of these units may be found in location between BH01 and BH02. The border does not divide the two units as an abrupt change of the compositions. From CPT data, the composition changes gradually from S-04 to S-17 locations. The variation of lithology at lateral direction can be related to structures in the boundary, such as splitting and interfingering structures. However, the situation may be clearer to be read by correlation between CPT data. The interfingering structures may be found in correlation of these lithological units in CPT data.



S04 Figure 24 CPT interpretations of S04 and S13 showing pinched out structure of a peat layer S13



S04 Figure 25 CPT interpretations of S04 and S17 showing lithological change S17

5.1.2.1. Discussion of characteristics and structures of the study area based on CPTs

It is interpreted in CPT that sand can be divided into two types. CPT values interpreted in these sand layers display differences. In the study area, lithological units that are located in deeper depths generally show higher cone resistance values. There are several explanations regarding to this situation. The first explanation relates to overburden pressure that influences the condition of sand layer. Thicker lithology overlying sand layers causes increasing pressure in the layers. The stress makes sand to become more dense and compacted resulting in higher resistance values. A second explanation can be related to the mean grain size of sands. The coarser grain size will lead to higher cone resistance values (Robertson, Campanella, & Wightman, 1983). The average grain size of the second sand layer is larger than average grain size of the first sand layer located on top. Another explanation is related to composition of sand layers. The first sand has higher content of silt material than the second sand layer. Also, the presence of loam layer in the first sand contributes to lower cone resistance values. Compared to other units, sands has cone resistance which is much higher than resistance of the peat or clay. It is related to the strength of materials. Bearing capacity and strength of sand are higher than peat or clay. Sand also has higher density than other types of lithology.

CPT values in clay and peat layers show low cone resistance values. These values define lower bearing capacity of materials. In the study, the resistance values between these two layers cannot be clearly differentiated. The identification is done from friction ratio and friction sleeve. Higher friction sleeve is interpreted on peat layers than that of clay. Clay formations have relatively lower values because it contains cohessive materials. Soft and fine materials with very small grain size contributes to these low values. For peat layers, higher friction sleeve interpreted in the data may be caused by the presence of organic materials. On the other hand, peat also has more friction ratio values than clay. Friction ratio is the ratio between the sleeve friction and cone resistance. Peat has cone resistance value that is relatively similar as that of clay but peat has sleeve friction values that are relatively larger. This condition causes friction ratio values of peat to be higher. In addition to that, the value is also related to the compressibility of the materials. Peat has high compressibility and high void ratio that can be related to soft materials and high water content as the characteristics of peat.

Pore water pressure measurement shows geotechnical characteristics that can be related to the permeability of materials. In Tempeldijk south, the values cannot be used accurately to define characteristics of each material. It is not only explaining the water pressure of each lithological unit of but also water condition related to factors in the environment. For example factors of water table and depths. The negative values can be found at or near surface of the CPT location. This situation is related to location of the data that is still located above groundwater table. The changes of the values from negative to positive may be as an indication of water table in the dike. In another situation, the presence of the first clay layers which has relatively lower permeability than formation above results in higher increase of pore water pressure at the depths about 7 meters. Related to depth of locations, pore pressure increases and relatively is higher at deeper depths than water pressure at or near surface. These depth factor can be seen in every data of CPT. Also, the use of pore water pressure for identification of layer can be applied in a loam layer. Characteristics of lower permeability of loam than permeability of sand layers cause changes of water pressure significantly (fig. 28). The change of pore water pressure caused by difference in permeability of the materials is also interpreted in boundary of peat and sand layers. The change in pore water pressure can be seen in CPT data in appendices.

5.1.3. Correlation between CPT data to interpret stratigraphy of the Tempeldijk South

CPT can be applied to describe soil profile below the surface of the dike. The soil profile of each CPT can be correlated to have stratigraphy or relation between layers in the study area. Interpretation of lithological layers in stratigraphy is useful to comprehend subsurface geology of the Tempeldijk South. Stratigraphy defines strata of lithological layers and relation of each layer in vertical and lateral direction. Variations in the stratigraphic layers are determined and identified in each profile of CPT. Identification of lithological units is based on characteristics of the layers and depths of upper and lower boundaries of each unit. Identification with stratigraphic numbers is given to differentiate characteristics of lithological units in the area. Several layers indicate slightly different compositions in one another that need to be explained by giving numbers. In addition to that, the differences of depth of lithological units found at different locations may also complicate the interpretation without identification using numbers. These numbers are different from the numbers in borehole and CPT interpretation explained beforehand.

The identification of lithology by stratigraphic numbers is also done to ease the interpretation. Lithological layer number 1 defines that this layer is the youngest layer of all layers interpreted from CPT data in the Tempeldijk South. The layer can be found overlying layer 2. Depth of the layer 1 can be discovered in shallower depth than depth of the layer 2 at the same location. Also, lithological units can have different variations of layers interpreted in stratigraphy. For example, if it is interpreted that a peat layer 8 is on top of a clay layer 9 in one location, stratigraphy between peat 8 and clay 9 layers can also be interpreted in the same condition in another location of the data. However, in the study area, it is found that the layers can have changes in the lateral and vertical direction. The changes of lithological order are because either some of layers appear or the layers may disappear in other locations. The changes may be easier to be identified from CPTs which are located next to each other. Changes may be associated with different thickness, structure, etc. Layers may disappear or new layers may be found in another location. Furthermore, thickening and thinning of the lithological layers commonly occur in the subsurface.

The purpose of stratigraphy is that we can determine layers and relation between layers from different locations. For instance, if we need to concern only with a peat layer that was found in one location at certain depth, we may expect that the layer can also be found in other locations at approximate depth and with estimated thickness. Another example is related to predicted contact of layers between sand and peat layers. Different layers may show variation of pore water pressure in the subsurface of the dike. The approximate depth of contact layers can be interpreted from stratigraphy before installing instrument (piezometer) to check pore water pressure condition in the subsurface. Additionally, stability of the dike can also be determined from stratigraphy because stability uses thickness of layers in its calculation. Correlation between CPT data defines variations of stratigraphy in 2 dimensional subsurface. The interpretations of lithological units from CPTs and boreholes are displayed in appendices 26. Variation of stratigraphy will be further analyzed in 3D subsurface modeling.

To identify lithology as well as stratigraphy of lithological layers, correlation of lithological layers in CPT needs to be carefully interpreted. The classification of each lithological unit is based on ranges of values of CPT. The ranges of values can be identified by changes interpreted in the graphs. Different unit will show different ranges of values that can be displayed by variations in graphs of CPT. For this research, the interpolation of CPT data will use data of friction ratio values. These values can be used to differentiate most of lithological layers.

On the other hand, the sand identification will use added information of cone resistance and friction sleeve while a loam layer is interpreted from information based on pore water pressure. In the stratigraphy of the study area, the identification of layer's name starts from layer number 1 to layer number 16 located in sequence from top to bottom of stratigraphy. Not all numbers of lithological units can be interpreted in one location of the data. The addition and reduction of number of layers can be found in other locations. All members of stratigraphy can be made after the entire interpretation and interpolation of existing data of CPT are conducted.

Based on CPT interpretation, stratigraphy of the study area has 16 layers of lithology. Layers located near the surface consist of peat layers interpreted from the first to the fifth layers. Peat and clay layers are found in deeper depth identified as six to eight layers of the stratigraphy. These layers experience lithological change from one to another location. Three peat layers can be interpreted in borehole BH01 but the layers entirely change into clay layers interpreted in BH02. Further, the next lithological layers located below the 8 layer are interbedded of clay and peat layers given as layer number eight to the layer number thirteen. Finally, the layers at the bottom of surveyed study area consist of sands. Lithological layers are interpreted from available data. Stratigraphy listing order of lithological layers can be seen in table 8.

S04 CPT which has the same characteristics as BH01 comprises of lithological units of a peat as layer 1 of stratigraphy found at the surface of the dike. Four peat layers identified respectively as layer 5, 6, 7, and 8 of stratigraphy can be interpreted below the first layer. Further, lithological units of Interbedded layers consisting of clay, peat, peat, clay, and peat that are described as layer 9, 10, 11, 12, and 13 can be found as lithological units in deeper depths. Two sand layers are interpreted as 14 and 16 layers of stratigraphy. The maximum depth of CPT survey at this location is about 19 meter below m.s.l. We can read characteristics of those layers in table 7 of CPT interpretation. The stratigraphy is illustrated in (fig. 26).

The labelling of numbers in stratigraphy is also conducted in S17 or BH02. The location represents lithological units in different location of the dike. The first five layers are peat layers which are identified as layer from 1 to layer 5 of stratigraphy. The next four layers located below these peat layers are identified as clay layers having stratigraphic order of layers 6b, 7b, 8b, and 9 respectively. Below these clay layers, two peat layers, clay and peat layers are found overlying sand layers of 14 and 16 of stratigraphic layers. The first sand layer intercalates with a loam (layer 15). The characteristics of lithological units can be seen in table 8 of CPT interpretation. To comprehend stratigraphy and to relate on to another layer, the two data are correlated displayed in (fig 26).

Table 8 Stratigraphy of the study area

Lithological layers	Order of layers
Peat	1
Peat	2
Peat	3
Peat	4
Peat	5
Peat	6
Clay	6b
Peat	7
Clay	7b
Peat	8
Clay	8b
Clay	9
Peat	10
Peat	11
Clay	12
Peat	13
Sand	14
Loam	15
Sand	16

Stratigraphy of four CPTs describes relatively similar lithological layers in the subsurface of the dike. On the left part of the figure, the profile has lower elevation than right part of the figure. Lithological units in the location formed subsurface lithology in foot part of the dike. In the stratigraphy based on these four data, the unit structure shows relatively horizontal layers (Fig. 27). Peat (layer 6) can be interpreted as a layer on the site of S04. However, this layer disappears at different location of S01, S02, and S03. The structure showing the discontinuous layer is called a pinched out structure. The same structure can be found as pinched out structure in the profile. Loam layer can be interpreted on location at S01 and S02, but this layer does not continuously present in other locations of S03 and S04. The pinched out structure is shown in dashed lines because the exact location where the boundary of the structure occurs only in estimated location.

From CPT data correlation, each layer displays various ranges of CPT friction ratio values. It is also interpreted that each layer has different thicknesses. In addition to pinched out structure described previously, thickening and thinning of the layers commonly occur in the subsurface of the dike. This condition can be indicated by variations in layer thickness resulted in correlation of CPT data. Splitting structure is one of the existing structures formed as a variation of lithological units. Based on the correlation between S05, S06, S07, S08 shown in (fig. 28), lithological layers in the subsurface of the dike display relatively horizontal structures. In the location of S07, it is interpreted that splitting structure takes place in a peat layer (layer 7). Peat layer 7 which previously interpreted in the S05 and S06 has turned into two layers. Clay (7b) layer was found located in between the layers of peat 7. This clay layer shows a form of wedge-shaped. In addition to that, splitting structure also marks a change in lithology in the horizontal direction of the dike. Three layers of clay (6b, 7b, and 8b) have been interpreted as the result of changing composition in lateral direction. These changes occur at relatively the same depth. Interfingering structure can be interpreted in the boundary of those lithological units.

Figure 29 and 30 display interpolation of stratigraphic lines from CPT data. There are two lines of stratigraphic interpolation. The first line represents variation of layers which is located perpendicular to the axes of the dike. The second line provides information of stratigraphy parallel to the dike. Different from the first line having higher elevation in one side than the other side, the second line has relatively same elevation.

5.1.3.1. Discussion of correlation between CPT data to interpret stratigraphy of the Tempeldijk South

As results of correlation between CPT data, stratigraphy of study area can be interpreted. Diverse thicknesses can be found in lithological layers. The different thicknesses can be caused by factors in sedimentary environments of each lithological unit. These factors can occur during the process of sedimentation and also the processes that took place when the lithology was formed. During the deposition process, factors can be related to processes such as changes of groundwater level, changes of river, and changes of sea level by processes of transgression or regression. The different thicknesses are not only resulted by processes in the sedimentary environment at the time of deposition (syn sedimentary), but also in the process takes place after deposition (post sedimentary). The thick peat layer is deposited in sedimentary environments having balance condition between the high groundwater table and organic materials to be accumulated. If there is no balance obtained, the peat layer may be less thick than other peat layer condition (Thomas, 2013). On the other hand, the process of post sedimentary can be caused as a result of erosion, decomposition, consolidation, settlement, and subsidence. Also, Lithological units at shallow depths can also be affected by human activities changing the lithology and structure of the subsurface. Based on Holocene channel belts map (fig. 8), there is paleochannel located in the south side of the study area. The channel can give influence in stratigraphy of the study area.

The change in composition of the lithological units can be found in lateral and vertical directions of lithological layers. The change of velocity of water flow in sedimentary environment forms different lithological units. Sand is deposited in the situation with higher velocity of water flow than velocity forming lithology of loam, silt, and clay. However, lithological units in the study area were formed in different depositional environments. The depositional locations comprise of fluvial, aeolian, peat environment, and marine processes. The change of water level in one area, for example in the events of transgression can form different lithological units. The difference can be in the form of granular size especially for sands or it can be difference of lithological units. The Tempeldijk South is located at the edge of intertidal area. The location was still influenced by marine processes. However, since it is located near the maximum transgression line (fig. 13), the clay marine deposit is formed in the condition of low energy of marine processes.

Lithological changes_and different lithological units can be interpreted from CPT correlation of S04 and S17 (Fig. 26). S17 is located in higher elevation than location of S04. Difference in elevation causes some units on shallow depths in S17 cannot be found in S04. It can be explained that part of lithology near the surface in S04 of peat layer 2, 3, and 4 had been excavated in the past. The process caused by the human activity took place recently in geologic time scale. On the other hand, pinched out structure caused by natural process in depositional time can be interpreted as changes of layers to become other layers. Peat layers are interrupted by clay formations and those units formed at the same geological time. Interruption of clay layers in peat layers can be caused by peat environment located near the environment of active clastic sedimentation. The sedimentary environment of clastic sedimentation can be related to river depositional area or it can be related to marine depositional area. This active clastic sedimentation of clay and silt layers can enter peat formation as the result of flooding in form of crevasse splays. Sometime, it is found that sedimentary environment of peat can have location in inter-channel area. The subsidence of this area results in the interference of clastic sediments in the formation of peat (Thomas, 2013).

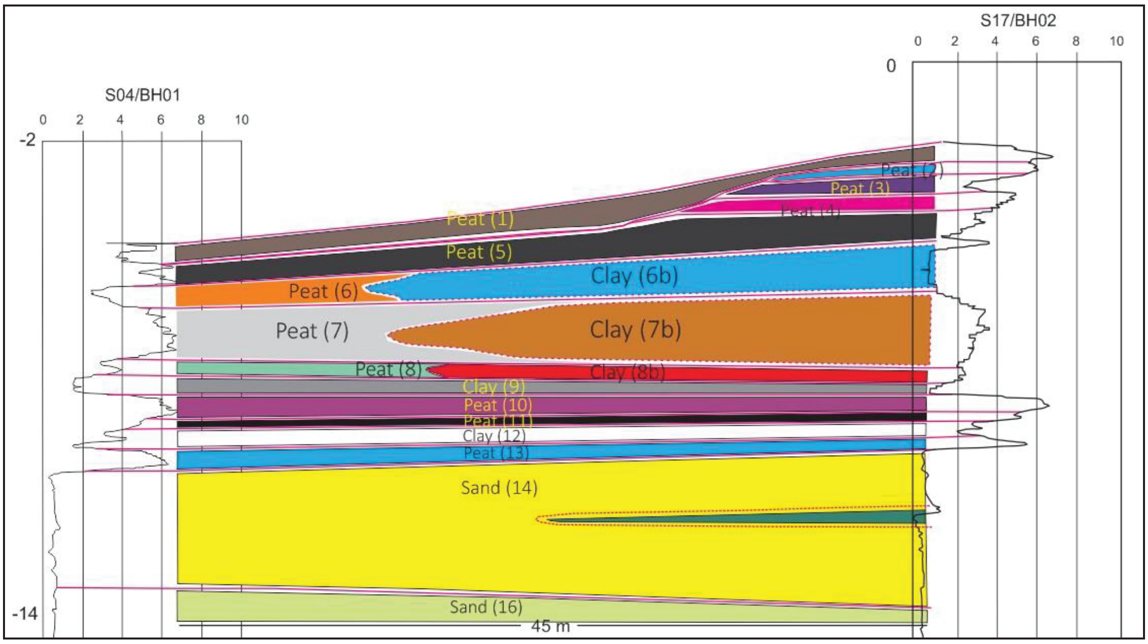


Figure 26 Stratigraphic correlation of two locations of S04/BH01 and S17/BH02

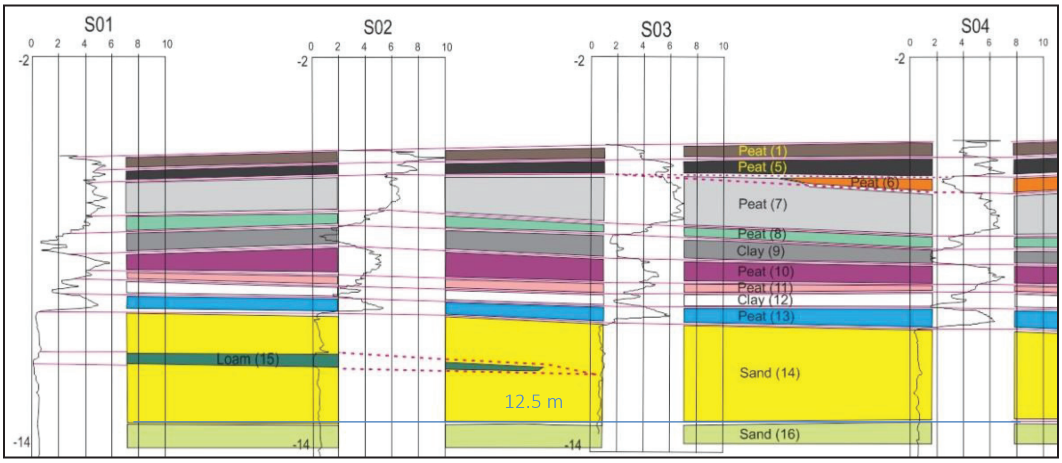


Figure 27 Stratigraphic correlation of S01, S02, S03, and S04 (from left to right of CPTs)

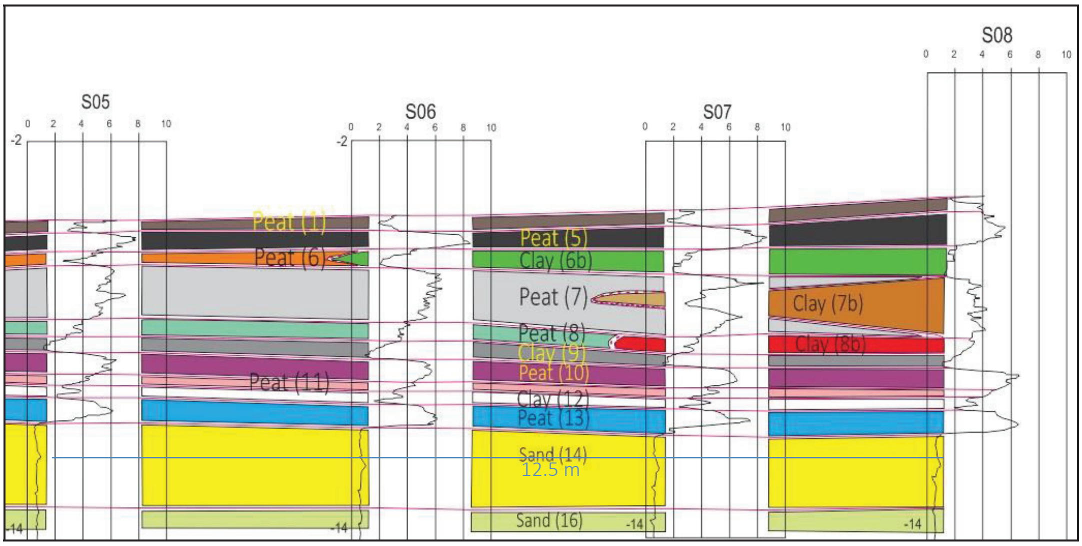


Figure 28 Stratigraphic correlation of S05, S06, S07, and S08 (from left to right of CPTs)

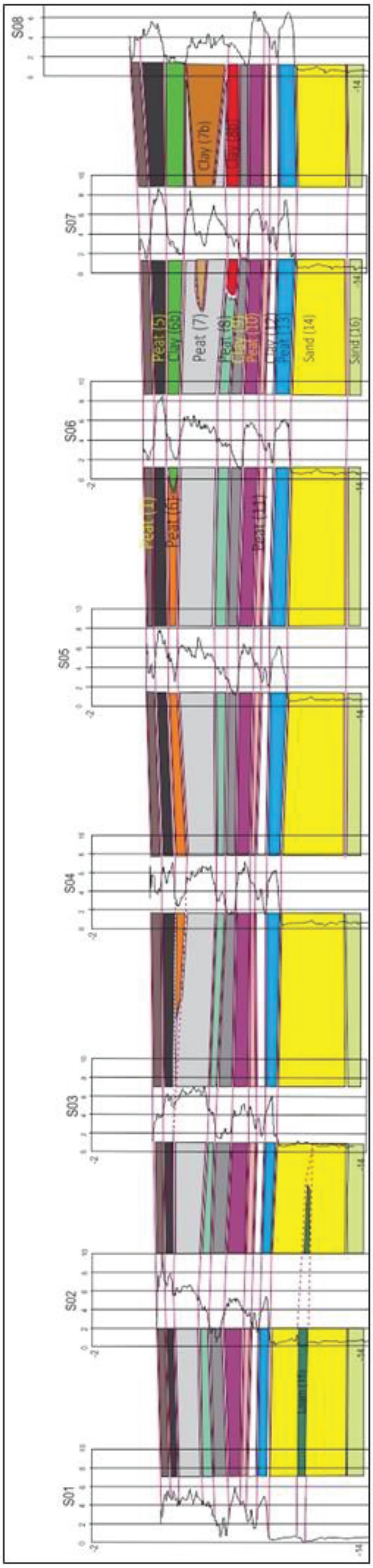


Figure 29 Stratigraphic correlation of the first line perpendicular to the dike

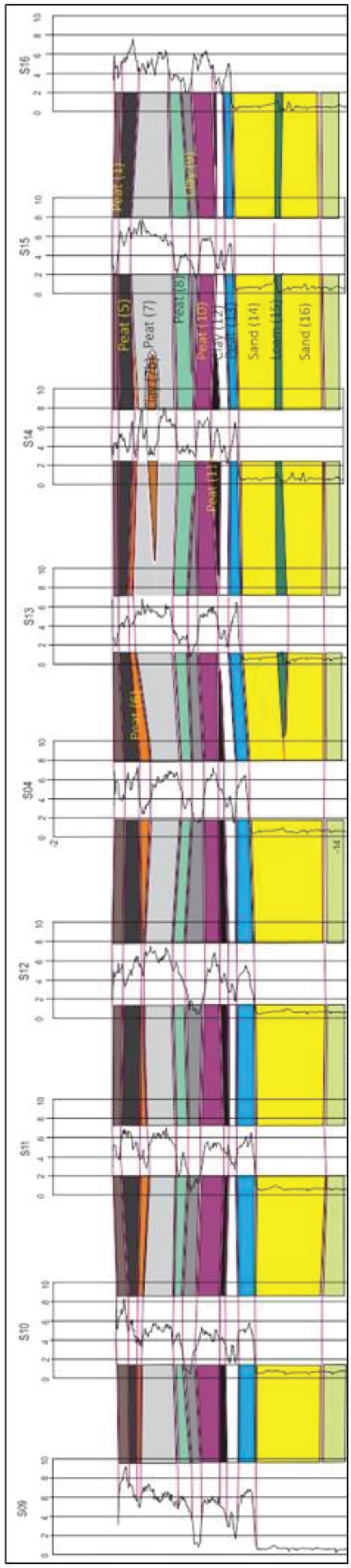


Figure 30 Stratigraphic correlation of the second line parallel to the dike

5.2. 3D Geological Model

Prior to the processing of 3D modeling, it is explained previously that the results of CPT correlation are interpreted into stratigraphy of the study area. The 3D modeling of the dike is an important method to comprehend subsurface geology in the Tempeldijk South. In this study, there are two purposes in applying the modeling of 3D. The first is to interpolate available data of CPT and boreholes three dimensionally. The interpolation of 3D needs to be analyzed whether it results in realistic geological models or it does not show reliable models. The second goal is to display 3D modeling based on geological condition and characteristics that have been interpreted previously from available data. For example, the existence of splitting structure, pinched out, and interfingering structures need to be displayed displaying the stratigraphic relationship is in 3D geological models.

5.2.1. 3D Modelling processes

Based on the interpolation between CPT data, the depths of the upper and lower boundary of the lithological units can be determined. These depths are illustrated in appendices 26. Depths of each boundary of lithological units are entered into the "borehole manager" along with the location coordinates and the elevations of the CPT/boreholes. The data will be plotted in 3D RockWare software based on coordinates. The geology will be modeled in certain locations, so the project dimension in X, Y, and Z has to be made. These project dimensions are related to coordinates and depths of the area that will be modeled. Also, types of stratigraphy should be created comprising total of 19 lithological units that are similar as the interpretation of CPT conducted beforehand.

The processes of 3D geological models depend on several factors, such as factors of total number and separation of available data. The Tempeldijk South has 17 subsurface data located separately in the middle study area. One datum is unevenly located in higher area in one side of dike body. The location has lack of data in the perimeter of the study area (fig. 18). The situation may cause problem in processing the models. For example, if one datum is unevenly located in the top body of the dike, it will be resulted that the area will have the dike body having higher elevation in one location than in another location. This condition can be shown by location of S-17/BH 02 that is unevenly located.

There are several options that determine the result of the models. Process modeling is carried out by the selection of interpolate surfaces consisting of gridding (size) dimensions and gridding algorithm options. The gridding size is very important in displaying stratigraphy of the study area. Bigger size selected in the processing will lead to have coarser resolution of grid of the models. Boundary of stratigraphic layers may result in unreliable border because the data is generalized. The modeling of the study applies small grid size of 0.3 x 0.3 x 0.05 m^3. On the other hand, there are many options available of algorithm methods. The options comprise of kriging, inverse distance, closest point, etc. Those options can be selected during processing of 3D models. However, because of relatively small number of data, the difference of the results of these options cannot be clearly distinguished. Kriging method is used in application. Complete selection of the modeling option can be seen in table 9.

Other selection in the processing of 3D models is diagram option. The item determines a way to display the models including legend, reference cage, explode (boundary between layer), and hide thin zones. One of the options that were significant is "hide thin zones" option. Layers do not continuously present in every location. Sometimes, it disappears in another location because of the variation in stratigraphy of the study area. To display this occurrence, the hide thin zone was applied. Pinched out structure can be shown by selecting "hide thin zone" in the process of interpolation. Minimum thickness of the layers that can be presented in the model is 0.025 meters. The layers with a thickness less than 0.025 meters cannot be found at the model.

Table 9 Gridding option in 3D geological modeling

Interpolation method	Kriging
Grid size	0.3 x 0.3 x 0.05 m^3
Settings	automatic
Logarithmic	The method improves interpolation of anomalous data. The implementation reduces influence of anomaly (outlier data).
High fidelity	The method processes high control points to be slightly higher.
Polynomial Enhancement	The method is used to process data that have regional trend (set to automatic order).
Smooth grid	The method is processed to have smooth grid and reduce "noise" within grid model, and to bring regional trend. (settings: filter size = 2 (i.e. average depth is based on 24 surrounding nodes), iterations = 1 (i.e. the model is one time calculated))
Densified	The method produces additional points automatically using Delaunay triangulation midpoints to the source xyz grid.

5.2.2. Geology of Tempeldijk South in 3D geological models

From 19 available data of the subsurface comprising of CPT and boreholes, we have seen correlation of the data into stratigraphic profiles in perpendicular and parallel lines of Tempeldijk South. At this stage, I am trying to comprehend geological condition in the subsurface of the dike based on 3D subsurface models using available data. The processes will be based on the previous results of interpretation conducted in each location and interpolation between each datum of CPT and boreholes.

Based on 3D Geological Model, Tempeldijk South has 19 lithological layers shown in (fig. 31). The characteristics of geological layers vary in the subsurface of the dike. At the top of stratigraphy, a peat layer (Peat 1) with 50 cm thick can be interpreted. This material is an artificial material made from a mixture between peat and clay materials. The material is used to strengthen the strength and bearing capacity on the surface of the dike. This is necessary because agricultural and cattle activities usually take place on the surface (Rupke, 2008) recited in (Hack et al., 2012). However, in the 3D modeling, the artificial material is removed to obtain a better interpretation on the natural subsurface lithology as well as part of the excavated surface of the dike.

Peat layers (Peat 1, Peat 2, Peat 3, and Peat 4) on shallow depths are present between the man-made top layer and a depth of about – 4 m. These layers show excavated part on the surface. Interfingering structure compose variation of lithological layers in the study area. The structure is present from at depth about -4 to -7.5 m at the boundaries between peat and clay layers having lithological change in horizontal direction (Peat 6 – Clay 6b, Peat 7 – Clay 7b, and Peat 8 – Peat 8b). It is interpreted between about -7.5 and -9.5 that a sequence of peat and clay layers is interpreted (Clay 9, Peat 10, Peat 11, Clay 12, Peat 13). At about -9.5 to -10.5 m a boundary marks the start of a sandy sequence. A sand layer (Sand 14) intercalates with a loam layer (Loam 15) overlying a layer (Sand 16) at the bottom of the stratigraphy.

Stratigraphy in the study area shows relatively horizontal structure of lithological layers with varying thicknesses. In certain locations, multiple layers display undulating structure and some others have slightly inclined structure. There is another variation of layers found in the interpretation. The variation can be characterized by lithological changes. The changes are not only interpreted vertically but also it can be found horizontally in several units of lithology.

The horizontal change takes place on the surface and at certain depths in the subsurface. On the surface, the change is characterized by pinched out structure of peat 2, 3, and 4 layers located at higher elevations in the body of the dike. Peat layers cannot be found in locations situated at lower elevations (foot part of the dike). At a certain depth below the surface, pinched out structures are also found. These structures indicate a change in lateral direction from peat layers into clay. This change does not just happen only in one layer of peat, but it also occurs in three layers of peat to form interfingering structure. Interfingering structure can be shown in the 3D geological model in the south side of the model at depth about 5 meters below the surface. Peat 6, 7, and 8 are changed into clay 6b, 7b, and 8b. The cross section of the study is illustrated in (fig. 33).

There are multiple possibilities to display characteristics of subsurface geology in 3D modeling. One of the options is to display in solid 3D models. Another way is to display in the Fence diagram. Fence diagram is a method used to describe the condition of the stratigraphy in the 2 dimensional slices along multiple different panels. Slices can be selected in every direction of the model (fig. 32). In this diagram, stratigraphy can be shown in both horizontally and vertically. Relationships of stratigraphy having relatively horizontal and undulating structures are also interpreted in the diagram. Fence diagram displays in different slices the situation of interfingering and splitting structures. Slice in the middle shows a more detailed form of the layers. The center area is located closer to the location of the borehole and CPT data than location in the perimeter.

The method of RockWare software can also display spread of each layer of stratigraphy. In figure 34c, stratigraphic relationship between peat 7, peat 6 and clay 6b layers is shown in the 3D geological models based on the available data in Tempeldijk South. Both lithological units have a parallel relationship deposited in relatively similar time. Unlike other peat layers, peat 6 has a narrow spread of stratigraphic layer. This layer is interpreted in the middle while 6b clay formation is found in the west part of the study area. 3D models also show the condition of sand layers at the bottom part of the stratigraphy (fig. 34d). The first sand layer can be shown intercalates with a loam layer in the 3D model. This layer is located at about 10 meters depth overlying sand units interpreted below it. On the other hand, stratigraphic thickness (isopach) maps are processed to determine the thicknesses of peat layers. The thicknesses vary in each layer of peat unit. It is shown in fig 35a and 35b that thickness maps of peat 10 combined with 11 and peat 13.

5.2.3. Discussion of 3D geological modeling

Several layers in certain location displayed in stratigraphic models show horizontal structures while other layers have slightly inclined and undulating structures. The variations of bedding of the layers can be related to processes occurred at the time of deposition (syn-depositional) or also the process after (post-depositional). Moreover, the situation can be linked also to characteristics of peat compositions.

The syn-depositional process influences the structure of layers to be inclined. These older formations formed underneath are sand layers consisting of aeolian sand and fluvial sand. Both processes can result in inclined layers. The aeolian sandstone of Boxtel formation as sand cover was formed by wind sedimentation process. Furthermore, lithological formation interpreted below the aeolian sand formation is interpreted as a unit of Kreftenheye formations formed as channel infill deposits (Hijma et al., 2009). Aeolian sand which was formed as dunes can have different sides with different angles resulting in inclined areas. The inclined surface at the base will make lithology deposited above it to have inclined layers. Also, the fluvial processes of rivers may form stratigraphy to be inclined. The direction of bedding may indicate paleocurrent in the depositional time.

Another explanation related to the sedimentary environments in the study area is the composition of peat materials. There are different types of Peat, and each peat contains different compositions. The composition of the peat comprises mostly of water and organic materials. There are factors that may cause changes in the composition of the peat. One of factors can be related to the process of lowering of water table. The lowering of water table is conducted in order to reclaim low areas to be used as polders. The situation makes the peat to sustain compaction, consolidation, and further subsidence. Lower water levels cause peat to interact directly with air so that the peat becomes oxidized. The oxidation process also occurs through the underground water that carries oxygen content in it. The volume of peat decreases if it dries out.

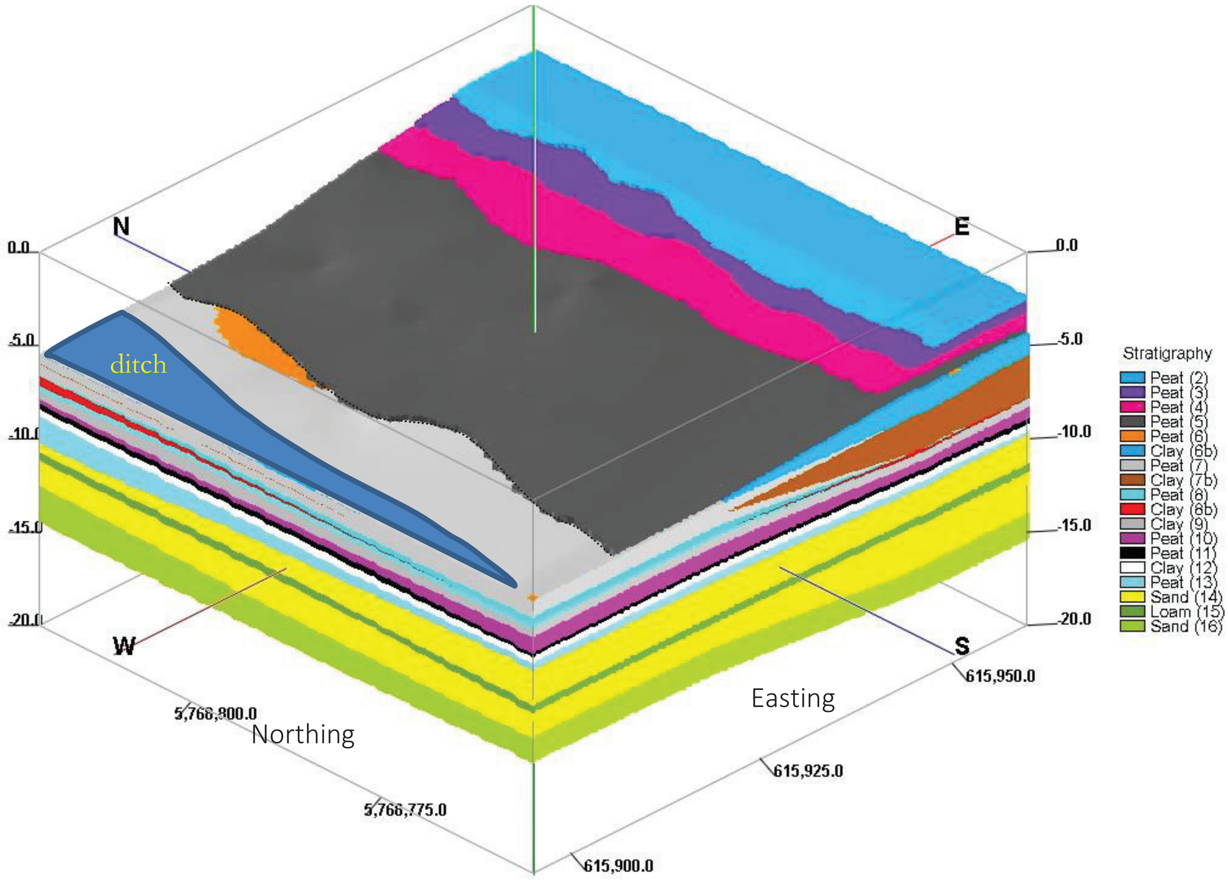


Figure 31 3D geological model of Tempeldijk South

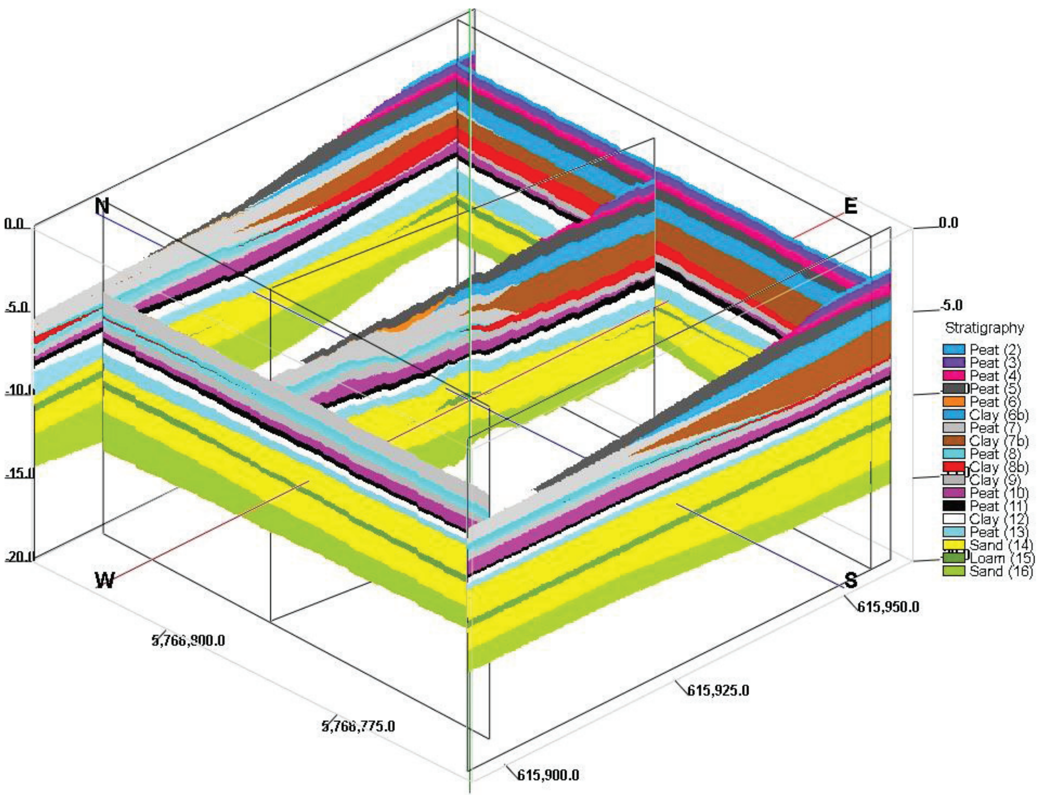


Figure 32 3D diagram fence of Tempeldijk South

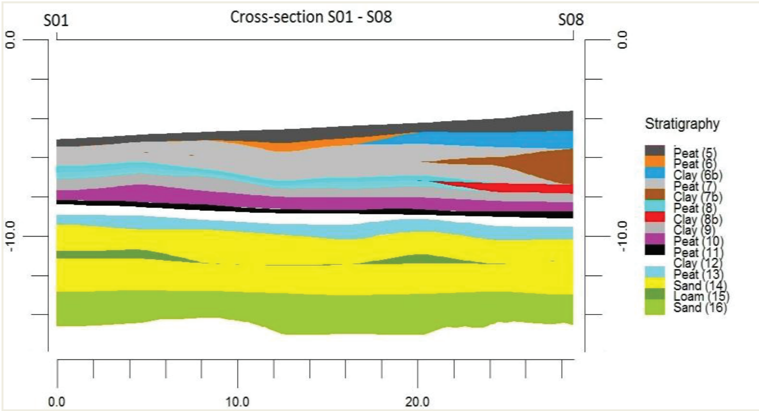
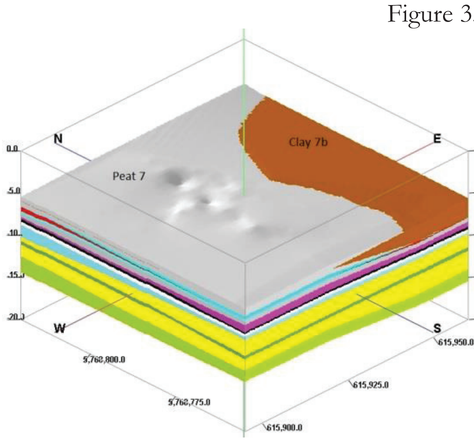
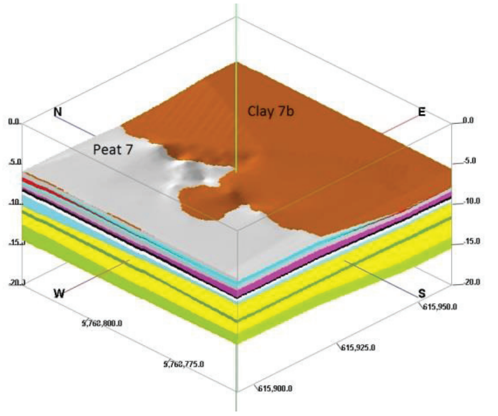


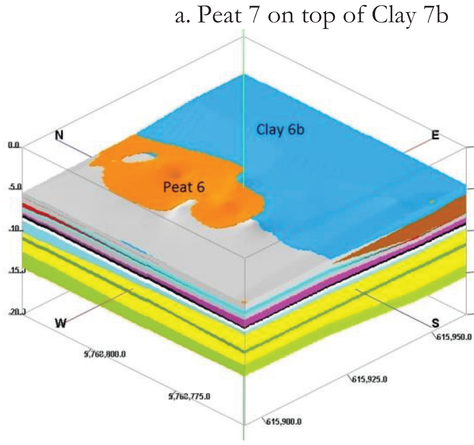
Figure 33 Stratigraphic profile of CPT S-01 to S-08



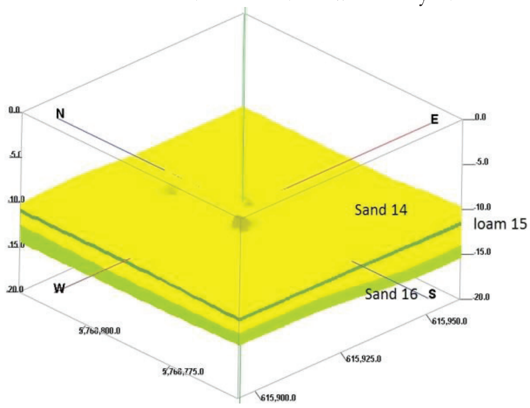
a. Peat 7 on top of Clay 7b



b. Peat 7 below of Clay 7b

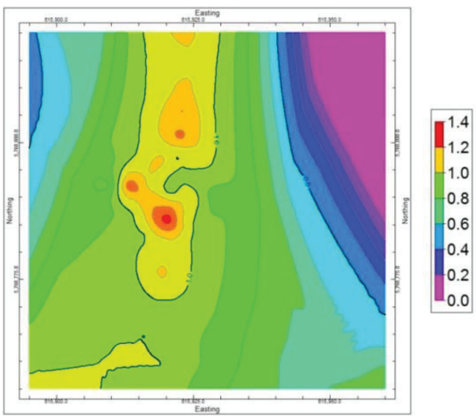


c. Peat 6 and Clay 6b

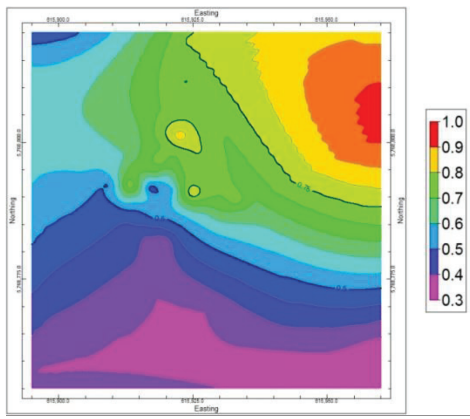


d. Sand and Loam

Figure 34 3D of lithological layers of Tempeldijk South



a. Peat 10 and Peat 11 isopach maps



b. Peat 13 isopach map

Figure 35 Isopach maps of Layers in Tempeldijk South

Thickness differences of each lithology can also be displayed by 3D geological models. The difference can be formed naturally during the depositional process or formed after deposition. In the depositional process of peat environment, peat formation was formed in certain conditions. The first is the situation where high groundwater alters dry area to become peat environment. The second condition is the filling of water area such as pond, lake, lagoon, and bay with organic materials in peat environment (Thomas, 2013). Different groundwater and source of organic materials in depositional environment can cause peat formations to be different in thicknesses. The types of peat define certain composition and processes. There are many different types of peat. In Nieuwkoop formation, peat is classified into four different types comprising of Oligotrophic, Fen wood, Fen, and Lacustrine deposits (Hijma et al., 2009). Each type of peat may give different characteristics. For example oligotrophic peat is formed in the area of poor nutrition environment or poorly fed while fen peat as type of rheotrophic was fed by water flow during depositional time (Thomas, 2013).

Also, characteristics of relatively high compressibility of peat play roles in different thicknesses of layers. It is related to the weight of the loading or overburden (especially if peat is located in deeper depth) and the groundwater level below surface. The decrease in ground water level made for use as a polder can accelerate consolidation and subsidence of peat layers. Furthermore, the difference thickness and inclined structures can be further explained by thickness (isopach) map of the study area. The variation of thicknesses in the study area can be shown in 3D models and isopach maps. The variation may indicate different rate of consolidation and subsidence took place in the study area. This explains the high compressibility of peat.

On the surface, as shown in the stratigraphic interpolation of CPT data, the 3D geological models show several layers in higher areas that cannot be found at a lower level. This is caused by the excavation of peat by men occurred in the past for fuel purposes. The layers show pinched out structures. Because it was caused by human activities, we can see in the figure that the boundary of layers having pinched out structures has slightly abrupt changes. If the pinched out structure was caused by natural environment, the boundary of peat formation show relatively smooth border depending on its depositional environments.

At certain depths, interfingering, splitting, and pinched out can be interpreted and displayed in 3D geological models. Interfingering and splitting structures can be caused by the interruption of peat sedimentary environment by clastic depositional environments. The occurrence of splitting structure displayed by small dimension of clastic sedimentary layers indicates that the interference of clastic deposition was only in a short period of time. However, in the study area, the splitting structures completely changes lithological unit to become clay layers. The clay layer also shows the continuous structure which is laterally developed. It can be interpreted that the interference of clastic depositional area was in long period of time. Clastic sediments may originate in the form of flood by river as crevasse splay or overbank deposits. It can also be derived from the flooding or transgression of the marine process. The process of clastic interference is illustrated by fig. 36. The figure explains that depositional environments of peat may experience interruptions both from rivers and the sea.

Related to sedimentary environments described previously, part of the study area is a location that is affected by the development and evolution of Rheine River Meuse. Crevasse splay of these rivers influences the deposition of clay into peat environment. On the other hand, Holocene transgression affects peat formation forming marine clay or silt layers. Holocene transgression can occur through the river. Paleochannel during Holocene can be found near the study area. It is located in the southern part of Tempeldijk South (fig. 8). It is interpreted also that the geological map indicates that the study area was surrounded by fluvial deposits called Gorkum deposits (fig. 11). The geological model is used to display stratigraphic relationships three dimensionally. This is processed to determine the spread of stratigraphic units and to know processes related to depositional of study area.

Formerly, it is defined that the 3D modeling will be used to interpolate stratigraphy of available data. The result of the models should be checked whether it forms reliable geological model or not. The reliability of the model can be determined based on geological interpretation of the study area that has been interpreted. It contains information related to stratigraphy and characteristics of lithology.

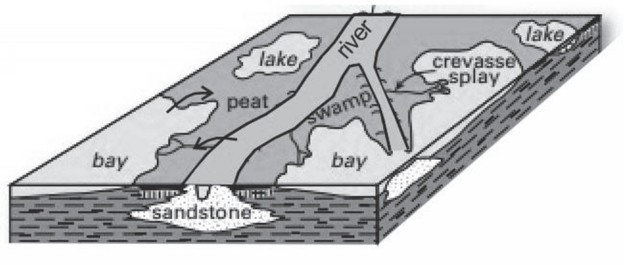


Figure 36 Sedimentary environment of peat formations (after(Crowell, 2008))

From results of modeling, it is interpreted that reliability of the model defining characteristics of lithology in locations that are closer to the borehole/CPT is better than the locations in farther away. These unreliable results are normally found on the perimeters of the study area. To overcome this problem, artificial boreholes are needed to obtain better results of the model showing geology in the subsurface. Relationship of stratigraphy obtained from boreholes and CPT can be used as a standard in analyzing situations on the model. Additional points are added in perimeter of Tempeldijk South. The main aim of these artificial boreholes is to control elevation on the surface of the dike and to adjust boundaries of layers related to excavated parts of lithology. The stratigraphy in the perimeter area becomes very unreliable because the data are limited and are not evenly distributed. The data of artificial borehole is in appendix 27.

5.3. Resistivity Investigation in study area

The measurements of resistivity have been conducted in the study area. The measurement is examined to comprehend subsurface condition of the dike that can be related to lithological variations and presence of water. The results of resistivity measurements will be correlated to geology based on geological profile of 3D models to add the information in the subsurface of the dike. Based on previous study from (Cundill et al., 2013c) the general resistivity values in Tempeldijk South are relatively low since the study area is located in the deltaic area having influence of sea water. The process of Holocene transgression influences low values of resistivity in the study area. The location of study area and situation of transgression during Holocene can be seen in (fig. 13).

The resistivity values of Tempeldijk South vary in lateral and vertical directions. The Tempeldijk South has ranges of inverted resistivity values from minimum 9 to maximum 40 Ohm-meter. Most parts of area of the Tempeldijk South have relatively medium values having about 18-25 Ohm-meter. However, in several parts of the area, we can interpret anomalies having slightly different resistivity. One part has slightly lower values while another area shows higher values. Figure 38 shows values of resistivity in Tempeldijk South displaying lithological characteristics and variation of water content in the study area. The possible upwelling water in Tempeldijk South can be interpreted in foot part of the dike by relatively higher resistivity values than values in other locations. It has plume structure and interpretation of the upwelling structure is from fresh ground water originated from deeper layers (Cundill et al., 2013c)

After description of resistivity, resistivity profile is correlated to the stratigraphy of Tempeldijk South. This is done to determine the characteristics of lithology from resistivity values as well as to interpret variations of resistivity values. The resistivity of each lithology is different. Structure of subsurface condition resistivity values shows relatively non horizontal structures. From figure 37b, it is displayed that relatively higher resistivity values can be interpreted in foot part of the dike. The body of the dike, which is located in slightly higher elevation, has relatively lower resistivity values.

The stratigraphic profile based on 3D geological model can partly be interpreted in resistivity measurements. Started from the interpretation near surfaces, the lithological layers have slightly inclined structures with higher elevation located in the east (right) part of the cross section having dip of layer to the west. Also, the correlation of layers can be relatively interpreted in sand layers at depths about 10 m below m.s.l. However, the inclined layer has dipping from left to the right part of stratigraphic profiles. Resistivity values can show characteristics of subsurface geology in the Tempeldijk South. It can be interpreted that resistivity values in the right part of the section may show layers of lithology. However, the layer of resistivity values do not show exactly the same layers as interpreted in the stratigraphic profile.
Another interpretation that can be resulted is transition of the lithological layers in the subsurface. The change can also be interpreted from CPT. The resistivity values in right part of section may also represent the condition. For example, at depth about 5 m below m.s.l. there are changes of lithological composition and lithological units from the west (left) part of the dike to the east (right) part of the dike. It is changes from Peat 7 to Peat 6 and to Clay 6b relatively at the same depths. It is interpreted in CPT that peat 6 is transition of peat and clay having higher amount of clay composition than clay in Peat 7. It also has less composition than Clay 6b. The changes also can be seen in the lower depths than previous layer showing Peat 7 and Peat 8 that have changed to be Clay 7b and Clay 8b. These changes have transition of composition in between.

5.3.1. Discussion of resistivity investigation in the study area

Generally, geology in the Tempeldijk South has characteristics of low resistivity. The Tempeldijk South has variations of lithology comprising of sand, peat, and clay layers. Peat and clay are soft materials composing the dike at surface or relatively near the surface. Both lithological units have characteristics of low resistivity. For the interpretation of clay in the study area, this lithology shows relatively lower resistivity values compared to other lithological units. Clay has many active ions that can be released and it is conductive materials. Also, clay in the study area is interpreted to be identified as marine clay deposited in intertidal area (Hijma et al., 2009). This deposit was formed during the process of Holocene transgression. This lower resistivity of lithological units is caused by the influence of sea water. Sea water has very low resistivity about 0.3 ohm-meters (fig. 20). Transgression process during Holocene invaded the study area. The situation of transgression line and marine deposits can be seen in figure 8 and 17 respectively. The transgression of water can make the lithology to contain salt water in the pores. Sea water is very conductive materials because it contains dissolved salt which is mainly sodium chloride (Milsom, 2003).
Peat layers can be interpreted having low resistivity values. This lithology may also be influenced by transgression marine processes having low resistivity values. However, peat has high water content and the lithology is also influenced by the change of water table or water condition surrounding the study area. The condition makes the peat material to have slightly higher resistivity values in the right part of the section although boundaries of layers do not show exactly the same between both results.
It is explained previously that lithological change can be interpreted in the Tempeldijk South. The lithological change between clay and peat formations at the same relative depth is not an abrupt change, but in gradual variation of those units. Peat at depth about 6 m below m.s.l. located underneath the foot part of the dike has a certain amount of clay as its composition. The composition of the clay increases towards the dike body or the right part of the figure until it can be classified as clay units. It is also interpreted that in the east or right part of the figure, the influence of clastic deposit is higher. It is likely that the source of these clay deposits were from the east part of the study area. It may be related to the presence of Holocene paleochannel. Peat was formed during regression phase or at condition where sea water level started to decrease (Bijlsma, 1982). However, transgression or sea level rise might be still present. The transgression invaded land through the channel or river during Holocene time.

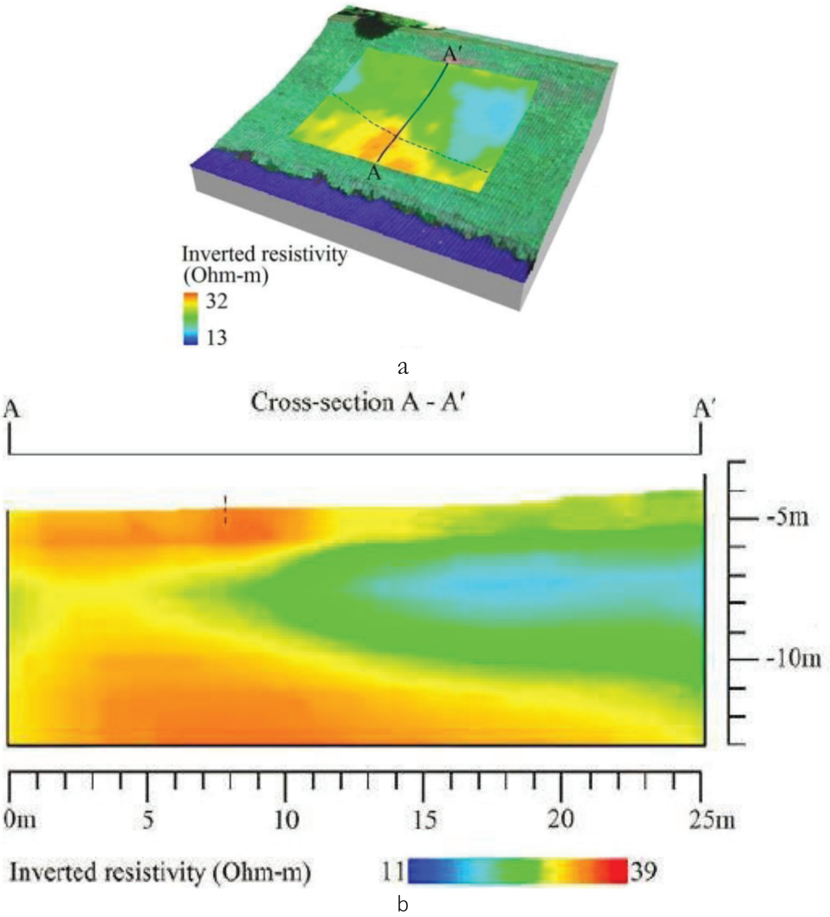


Figure 37 Resistivity values in Tempeldijk (a) location of a resistivity section; (b) profile of the A-A' section (Cundill et al., 2013c)

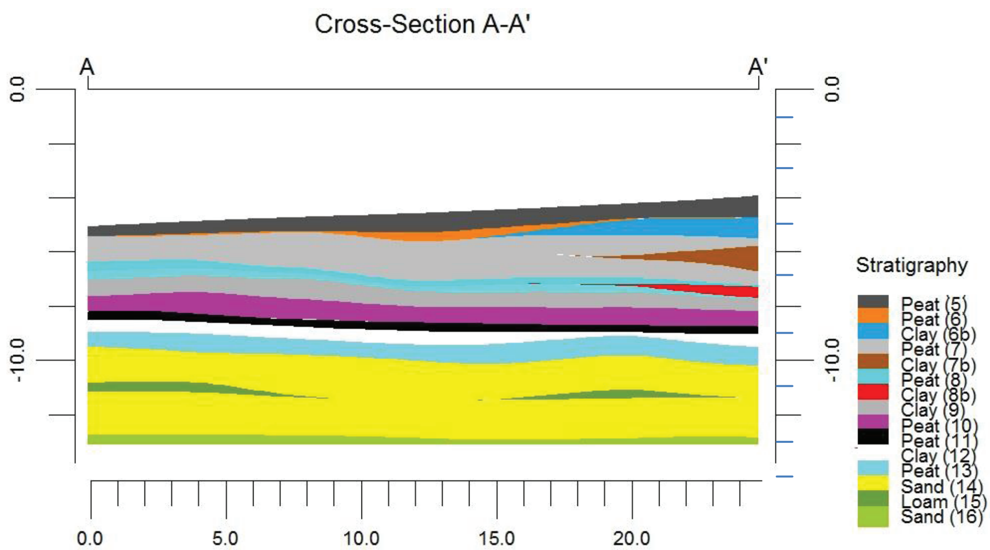


Figure 38 Stratigraphic profile of Tempeldijk South

Difference in variations of lithology can influence condition of Tempeldijk South. It is related to the occurrence of upwelling water and the stability of the dike. Based on the study of (Cundill et al., 2013c). It is interpreted that upwelling water can be interpreted in the lower part of the dike having relatively higher resistivity. From resistivity values in the resistivity profile, the upwelling water has ranges of resistivity values from above 25 to 39 ohm-meter. From the literature, it is defined that fresh groundwater has values between 10 and 100 ohm-meter (fig. 16). It has plume structure with no horizontal layers. Based on literature review, there are four mechanisms of the possible upwelling water in the Tempeldijk South. Another issue related this upwelling water that needs to be considered is as the effect of gas in resistivity results. This condition needs to be further studied in order to know characteristics and reason of the upwelling water.

The upwelling water originated from deeper layer took place in foot part of the dike only. Clay layers as lithology below body part of the dike have characteristics of lower permeability than peat layers at depth below foot part of the dike. On the other hand, the stability of the dike is very important factor in defining function and condition of the dikes. It depends on characteristics and lithological layers in the subsurface of the dike. Characteristics such as lithological units, thicknesses, and the difference in variations of lithology can result in different behavior and characteristics of the Tempeldijk South, for example, different between peat and clay. Characteristics from both methods may represent difference in water content below the dike caused by the effect of dry or wet seasons. Difference in compaction, consolidation, and subsidence in both lithological units may also be resulted. This interpretation is essential to be considered in monitoring activities of the Tempeldijk South.

The resolution of resistivity measurements is less to define clearly characteristics of lithological variations in the subsurface. It depends on electrodes space during the survey of measurements. The survey in the Tempeldijk South was conducted applying 2 meters distance of electrodes space. The results may be more detail if electrode space has closer distance.

6. CONCLUSION & RECOMMENDATION

6.1. Conclusion

The 3D geology of the Tempeldijk South has been modeled based on available data of boreholes and CPTs. To have interpretation applied in 3D model, the data from boreholes and CPT are correlated previously to comprehend lithological units, characteristics, and to be used as validation of other CPT data with no boreholes. The identification of structures, characteristics is conducted after correlation between both methods. The available CPT data is correlated one to another to have interpretation of stratigraphy of the Tempeldijk South. The interpretation in the subsurface is also based on correlation between stratigraphic profile and resistivity profile.

The answers of the research question are:

1. How does lithology from borehole description correlate to lithology in CPT interpretation?
   As the results of correlation, interpretation between boreholes and Cone Penetration Tests does not show high correlation in describing lithological units in Tempeldijk. For example, there is similarity in identification of clay from borehole description and CPT diagram. The classification of peat shows difference interpreted from both methods. However, the variations and characteristics of lithological units can be identified in both methods.
2. What are geological structures, characteristics, and lithology in the subsurface of the dike interpreted from CPTs, boreholes, and resistivity?
   Lithology of the Tempeldijk South consists of variations of peat, clay, loam, and sand layers. Structures and characteristics of geological subsurface vary in lateral and vertical directions. The structures of lithological layers show relatively horizontal structures although some locations have undulating layers and inclined structures. In CPT, Lithological units of sand layers can be distinguished clearly from peat and clay from cone resistance, sleeve friction, and friction ratio. However, differentiation of peat and clay need careful interpretation.
3. How many lithological units can be interpreted in stratigraphy of the Tempeldijk South?
   By correlation between CPT data into stratigraphy, the classification of total lithological layers can be done in the Tempeldijk South based on available data. The stratigraphy of the Tempeldijk South has 19 lithological units.
4. How is the stratigraphy of Tempeldijk South from correlation of subsurface data?
   The stratigraphy of the area can be interpreted from correlation between CPT data. It is found that the characteristics of structures comprise of interfingering, splitting, pinched out, thickening and thinning of layers. The stratigraphy shows characteristics of the study area having lateral changes of lithology at different depths.
5. How does subsurface geology vary three dimensionally?
   The structures, characteristics, and lithological variations defined in the description from both methods or in correlation of CPT data into stratigraphy can be illustrated in 3D geological models. Geological characteristics and structures in Tempeldijk South vary three dimensionally. There variations of lithology and composition that can be interpreted. The variations of lithology can be determined not only in vertical directions but also in lateral changes. For example, there are changes of lithological units in horizontal directions from peat layers to clay layers at depth about 5 to 8 meters below m.s.l. The changes can be seen in the model.
6. How do stratigraphic layers correlate to resistivity values in the Tempeldijk South?
   The results show that stratigraphic layers can be represented by resistivity values in the right part of the section although the boundaries of layers do not show exactly the same as boundaries of stratigraphic layers. It is interpreted that lower resistivity values represent clay layers. These layers are influenced by sea water during transgression phase in the Holocene. However, another part of

the section does not show stratigraphic layers. The left part showing relatively higher resistivity values is interpreted as the upwelling water having no horizontal layers. Lithological and composition changes can be interpreted by resistivity values in horizontal directions below the dike.

6.2. Recommendations

The recommendations for research as continuation of this study are:

1. Analysis of subsurface geology in surrounding area of the Tempeldijk South. The data can be based on borehole of TNO geological services. The geological model can also be processed using these data to know variations of lithological layers especially in lateral directions.
2. Surface and subsurface investigations in Tempeldijk North (about 1 km distance) have been conducted. It comprises also CPT and resistivity surveys. The comprehension of geological condition of the Tempeldijk can be interpreted in both locations.
3. Research to investigate the exact reason of resistivity results in Tempeldijk South can be conducted although it may need to enlarge the study area of the Tempeldijk.

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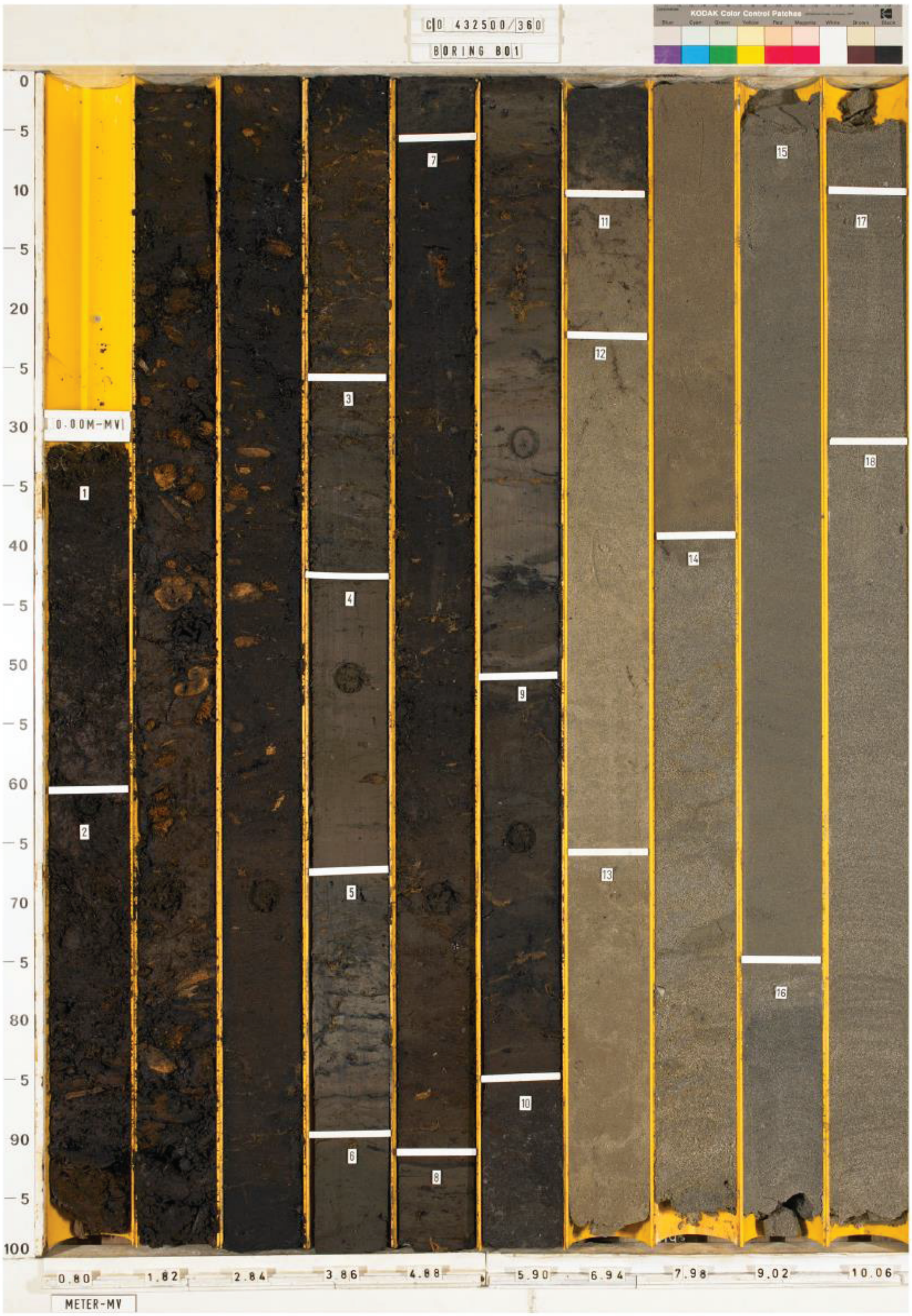
Appendix 1 Borehole photo BH-01

RSDYK2008 - boreholes and Dutch Cone Penetration (CPT) tests



BESCHRIJVING: ZIE GETEKENDE VERSIE VAN BORING	Filenaam: B01bijS04	Gewijzigd: 2008-12-18	Blad 1/2

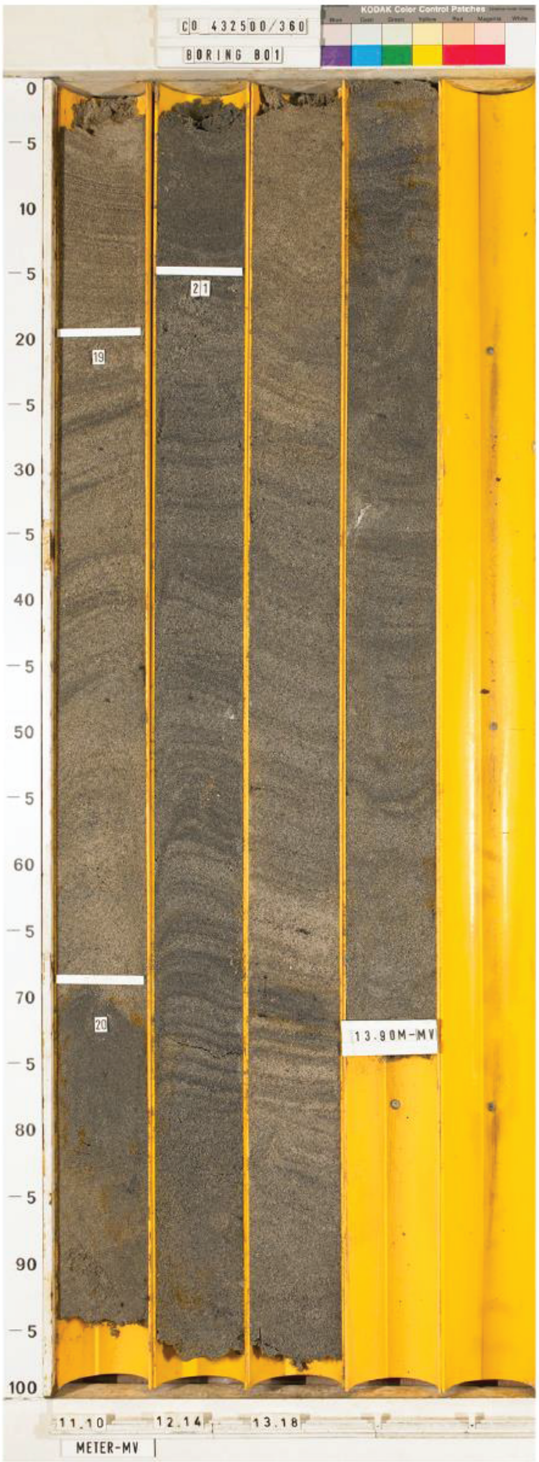
Deltares Postbus 177 2600 MH Delft, Stieltjesweg 2, 2628 CK Delft Telefoon (0)15 269 35 00 Telefax (0)15 261 08 21 www.deltares.nl info@deltares.nl	datum 2008-12-18	get. Mar
Grondonderzoek Reeuwijk FC 2015 Reeuwijk	CO-432500/360	gez.
FOTO BORING B01 bij S04 Type: Begemannboring 66 mm	BIJL. BFB1	form. A4

*) Vrijgegeven door Hsd op 2009-01-05 08:44

(Hack et al., 2008)

Appendix 2 Borehole photo BH-01 continued

RSDYK2008 - boreholes and Dutch Cone Penetration (CPT) tests



BESCHRIJVING: ZIE GETEKENDE VERSIE VAN BORING	Filenaam: B01bijS04A	Gewijzigd: 2008-12-18	Blad 2/2

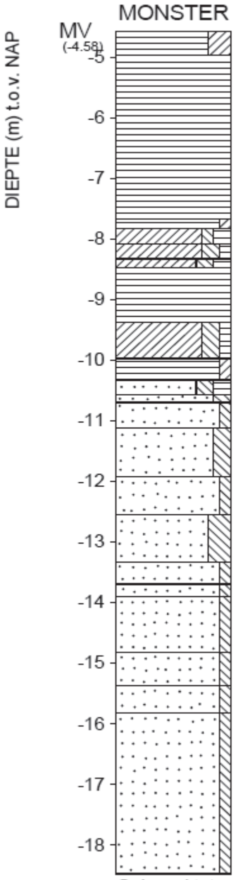
Deltares — Postbus 177 2600 MH Delft, Stieltjesweg 2, 2628 CK Delft — Telefoon (0)15 269 35 00, Telefax (0)15 261 08 21 — www.deltares.nl, info@deltares.nl		datum 2008-12-18	get. Mar
Grondonderzoek Reeuwijk FC 2015 Reeuwijk		CO-432500/360	gez.
FOTO BORING B01 bij S04	Type: Begemannboring 66 mm	BIJL. BFB1	form. A4

*) Vrijgegeven door Hsd op 2009-01-05 08:44

(Hack et al., 2008)

Appendix 3 Borehole description BH-02 by Deltares

RSDYK2008 - boreholes and Dutch Cone Penetration (CPT) tests



Geboord tot NAP -18.48 m

LAAG	DIEPTE NAP [m] VAN	TOT	BESCHRIJVING
1	-4.58	-4.98	VEEN, sterk kleiig
2	-4.98	-7.68	VEEN, mineraalarm
3	-7.68	-7.83	VEEN, zwak kleiig
4	-7.83	-8.08	KLEI, zwak siltig, matig humeus
5	-8.08	-8.33	KLEI, matig siltig, zwak humeus Met plantenresten.
6	-8.33	-8.48	KLEI, matig siltig, matig humeus
7	-8.48	-9.38	VEEN, mineraalarm
8	-9.38	-9.98	KLEI, matig siltig, zwak humeus Met plantenresten en enkele veenlaagjes.
9	-9.98	-10.33	VEEN, zwak kleiig
10	-10.33	-10.58	ZAND, matig siltig, matig humeus ZM=0.150 mm
11	-10.58	-10.70	ZAND, matig siltig Enkele plantenrest. ZM=0.150 mm
12	-10.70	-11.13	ZAND, zwak siltig ZM=0.150 mm
13	-11.13	-11.93	ZAND, matig siltig Met leemstukjes. ZM=0.125 mm
14	-11.93	-12.56	ZAND, zwak siltig Enkele grindstukjes, enkel leemstukje. ZM=0.350 mm
15	-12.56	-13.33	ZAND, sterk siltig ZM=0.125 mm
16	-13.33	-13.70	ZAND, zwak siltig ZM=0.210 mm
17	-13.70	-13.90	ZAND, zwak siltig ZM=0.250 mm
18	-13.90	-14.83	ZAND, zwak siltig ZM=0.300 mm
19	-14.83	-15.38	ZAND, zwak siltig ZM=0.420 mm
20	-15.38	-15.83	ZAND, zwak siltig ZM=0.175 mm
21	-15.83	-18.48	ZAND, zwak siltig ZM=0.350 mm

Einde Boring B01 bij S04 (Labbeschrijving)

X = 107238.38 m Y = 452370.59 m (RD)

Deltares Deltares — Stieltjesweg 2, 2628 CK Delft — Telefoon +31-15-2693500, Telefax +31-15-2610821	datum 2008-08-26	get. Hsd
Grondonderzoek Reeuwijk FC 2015 Reeuwijk	CO-432500/360	gez.
Begemannboring 66 mm B01 bij S04 (Labbeschrijving)	BIJL. BB1	24

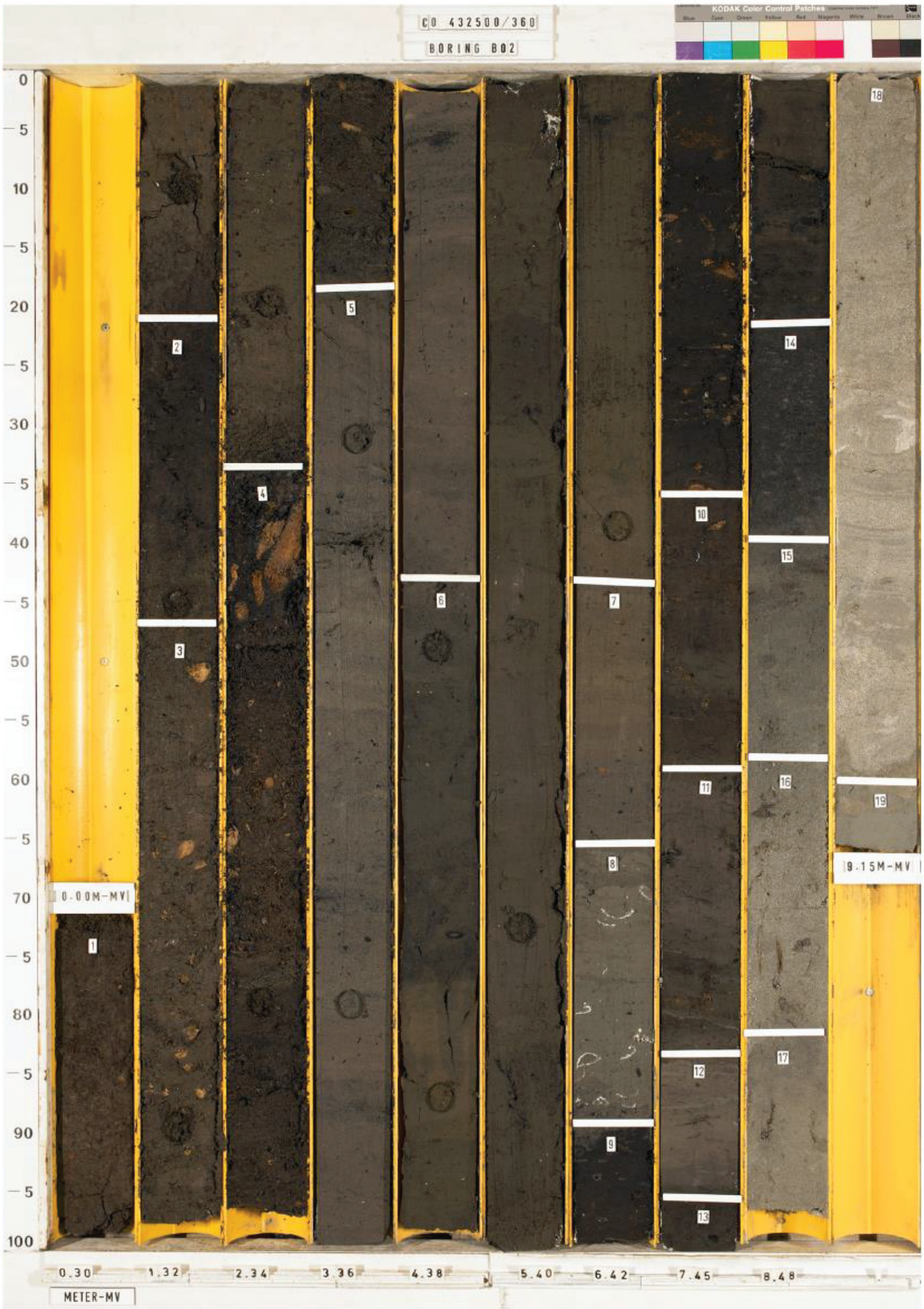
*) Vrijgegeven door Bjl op 2009-01-07 15:35

Flood Control 2015
Delft, The Netherlands
www.floodcontrol2015.com

(Hack et al., 2008)

Appendix 4 Borehole Photo BH02

RSDYK2008 - boreholes and Dutch Cone Penetration (CPT) tests



BESCHRIJVING: ZIE GETEKENDE VERSIE VAN BORING	Filenaam: B02bijS17	Gewijzigd: 2008-12-18	Blad 1/1

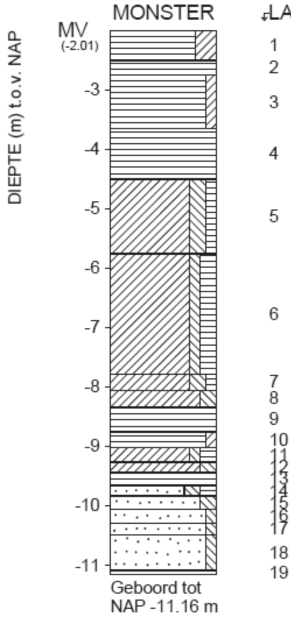
Deltares Postbus 177 2600 MH Delft, Stieltjesweg 2, 2628 CK Delft Telefoon (0)15 269 35 00 Telefax (0)15 261 08 21 www.deltares.nl info@deltares.nl	datum 2008-12-18	get. Mar
Grondonderzoek Reeuwijk FC 2015 Reeuwijk	CO-432500/360	gez.
FOTO BORING B02 bij S17 Type: Begemannboring 66 mm	BIJL. BFB2	form. A4

*) Vrijgegeven door Bjl op 2008-12-24 15:28

(Hack et al., 2008)

Appendix 5 Borehole description BH-02 by Deltares

RSDYK2008 - boreholes and Dutch Cone Penetration (CPT) tests



LAAG	DIEPTE NAP [m] VAN	TOT	BESCHRIJVING
1	-2.01	-2.51	VEEN, sterk kleiig Enkele puinstukjes.
2	-2.51	-2.76	VEEN, mineraalarm
3	-2.76	-3.65	VEEN, zwak kleiig
4	-3.65	-4.51	VEEN, mineraalarm
5	-4.51	-5.76	KLEI, matig siltig, zwak humeus Enkele plantenrest.
6	-5.76	-7.79	KLEI, zwak siltig, matig humeus Enkele plantenrest.
7	-7.79	-8.06	KLEI, matig siltig, zwak humeus Enkele plantenrest.
8	-8.06	-8.33	KLEI, matig siltig Met schelpresten.
9	-8.33	-8.76	VEEN, mineraalarm
10	-8.76	-9.03	VEEN, zwak kleiig
11	-9.03	-9.27	KLEI, zwak siltig, matig humeus Met plantenresten.
12	-9.27	-9.43	KLEI, matig siltig Met plantenresten.
13	-9.43	-9.66	VEEN, mineraalarm
14	-9.66	-9.84	ZAND, matig siltig, matig humeus ZM=0.150 mm
15	-9.84	-10.06	ZAND, matig siltig Enkele plantenrest ZM=0.150 mm
16	-10.06	-10.29	ZAND, zwak siltig Enkele plantenrest. ZM=0.175 mm
17	-10.29	-10.49	ZAND, zwak siltig ZM=0.125 mm
18	-10.49	-11.09	ZAND, zwak siltig Enkele siltlaagjes. ZM=0.150 mm
19	-11.09	-11.16	LEEM, zwak zandig

Einde Boring B02 bij S17 (Labbeschrijving)

X = 107267.02 m Y = 452338.03 m (RD)

Deltares Deltares Stieltjesweg 2 2628 CK Delft Telefoon +31-15-2693500 Telefax +31-15-2610821

datum 2008-08-27 get. Hsd gez.

Grondonderzoek Reeuwijk FC 2015
Reeuwijk

CO-432500/360

Begemannboring 66 mm B02 bij S17 (Labbeschrijving)

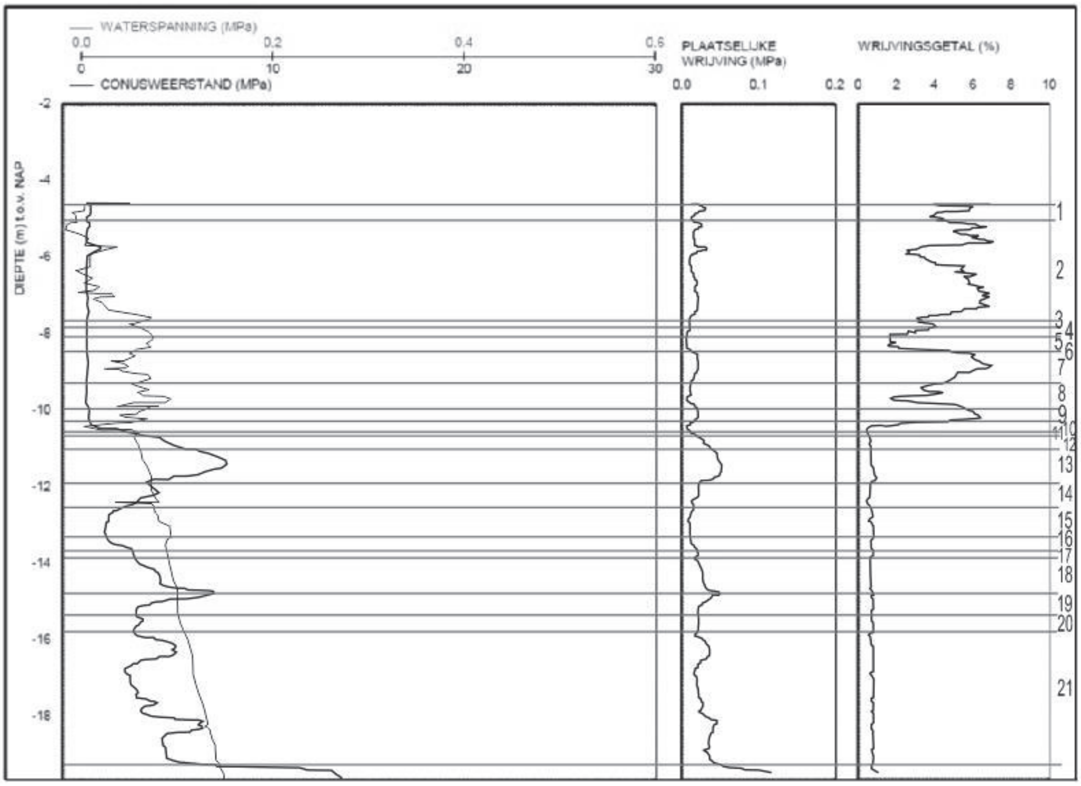
BIJL. BB2

Flood Control 2015
Delft, The Netherlands
www.floodcontrol2015.com

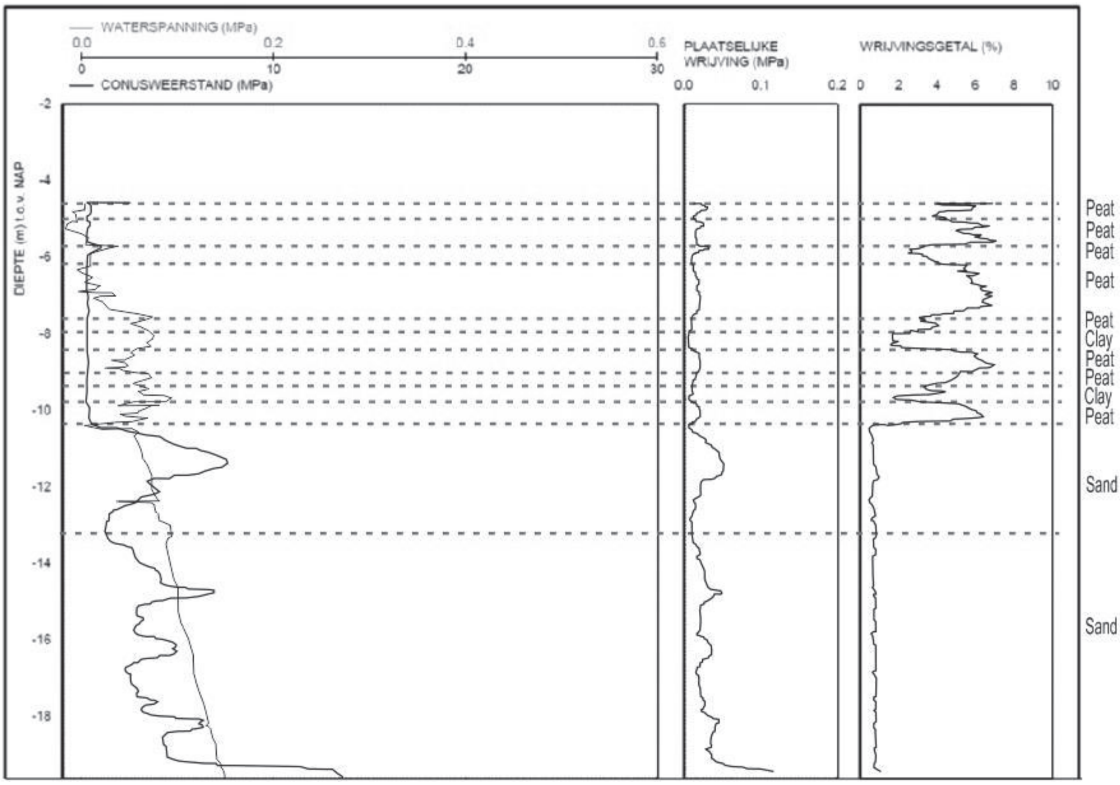
*) Vrijgegeven door Hsd op 2009-01-06 12:34

(Hack et al., 2008)

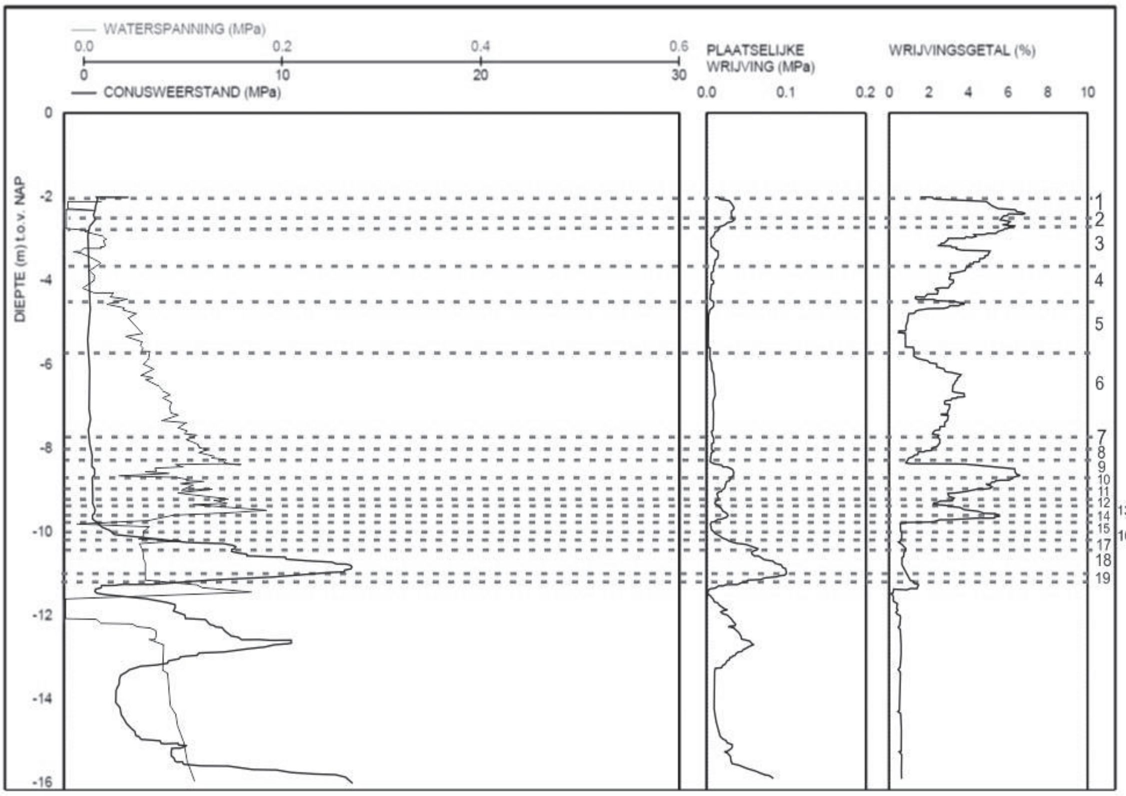
Appendix 6. Data interpretation of CPT-S04 and boreholes-BH01. The numbers on the right side represent order of description in boreholes BH01 (table 4/appendix 3 (in Dutch))



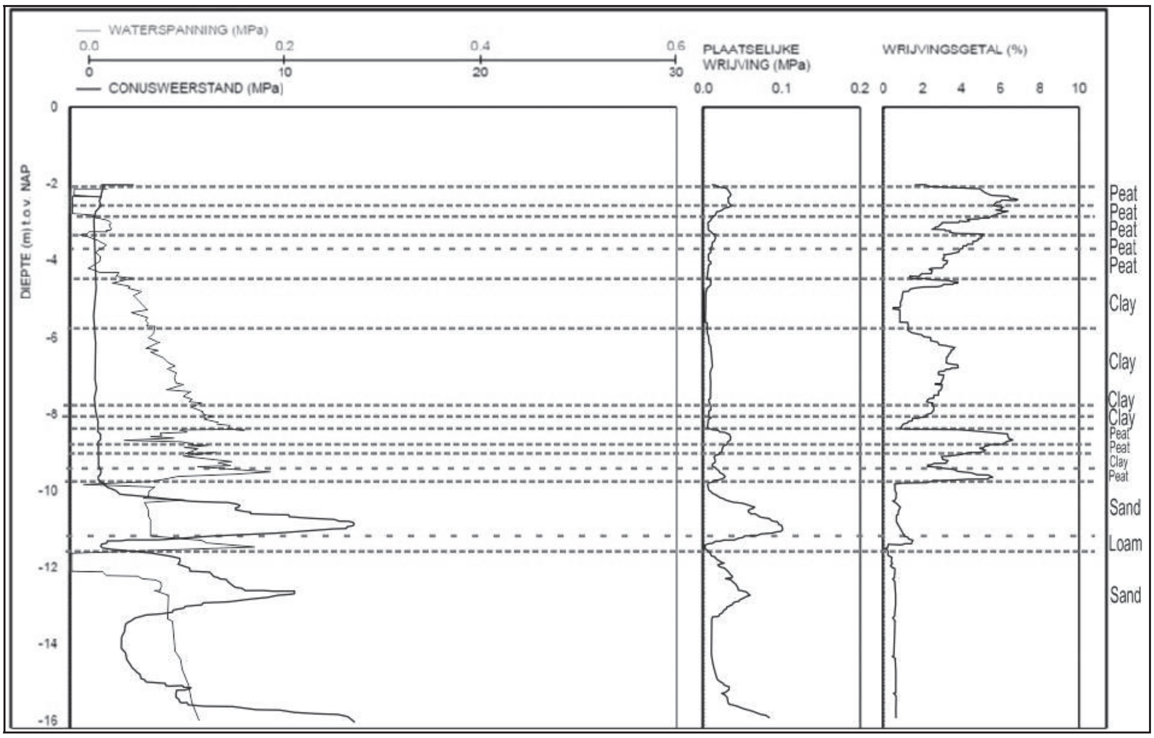
Appendix 7. Data interpretation of CPT-S04.



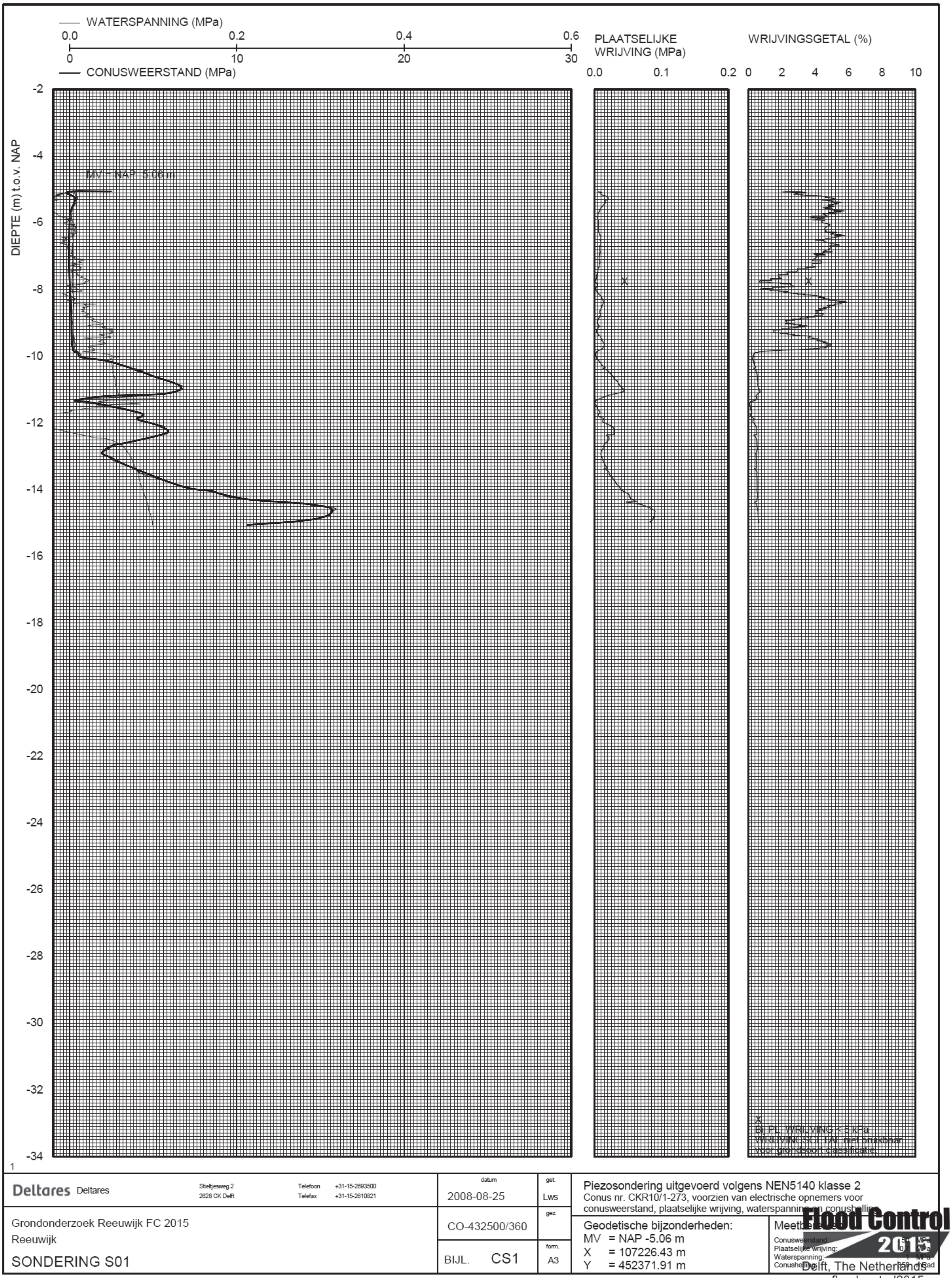
Appendix 8 Interpretation of CPT-S17 and boreholes-BH02. The numbers on the right side represent order of description in boreholes BH01 (table 4/appendix 3 (in Dutch))



Appendix 9 Data interpretation of CPT-S17.



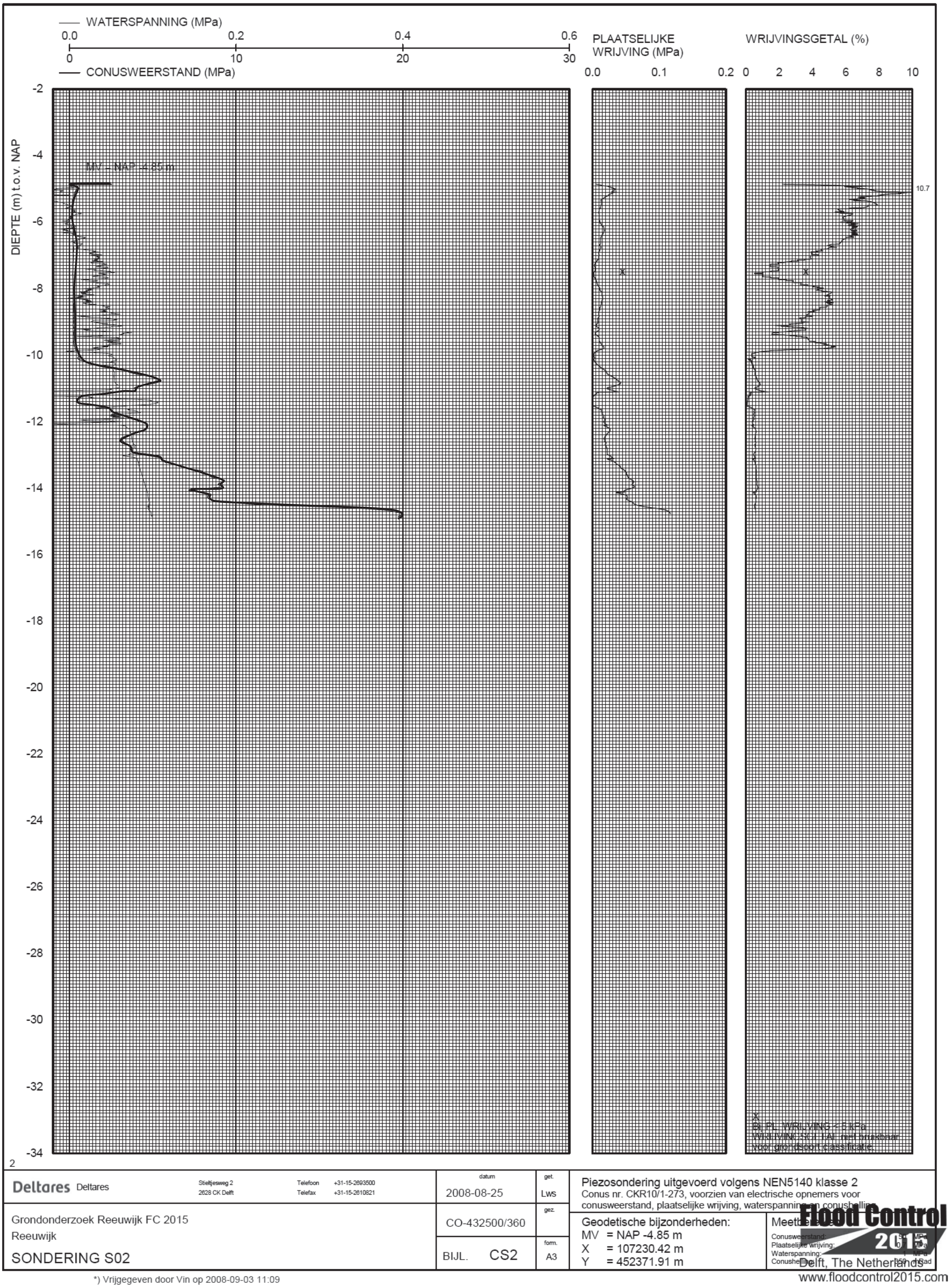
Appendix 10 CPT S-01



*) Vrijgegeven door Vin op 2008-09-03 11:09

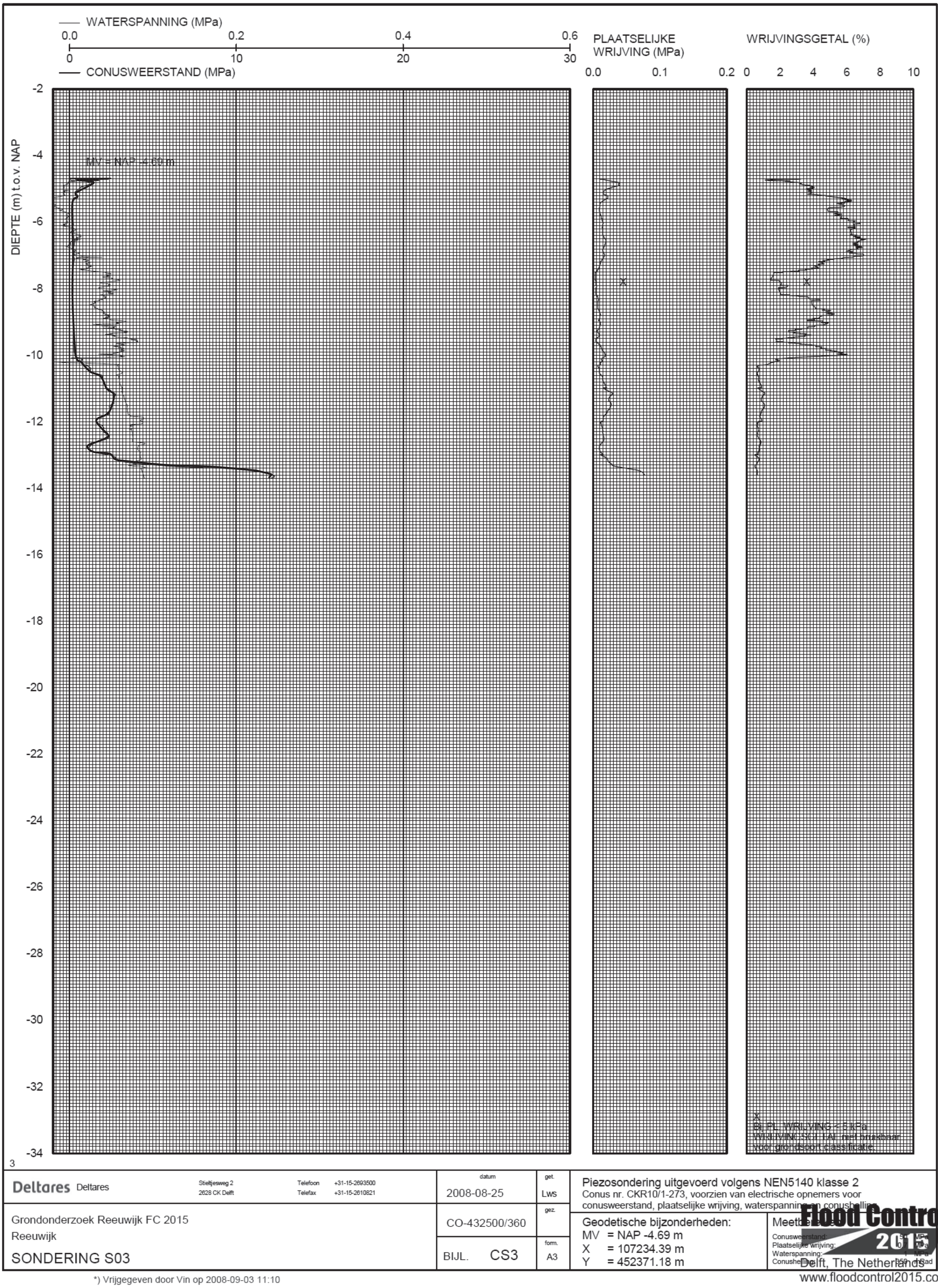
(Hack et al., 2008)

Appendix 11 CPT-S02



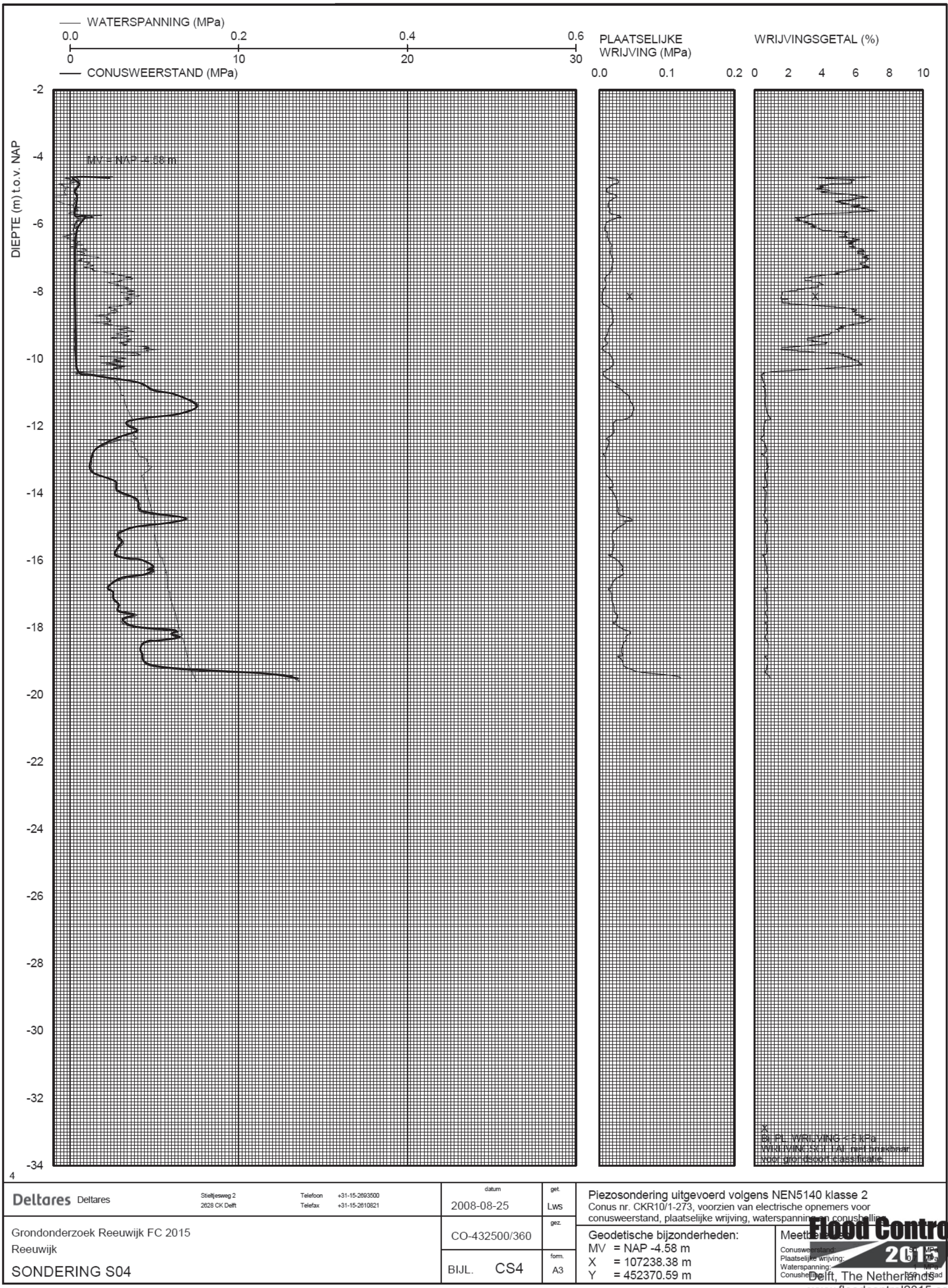
(Hack et al., 2008)

Appendix 12 CPT-S03



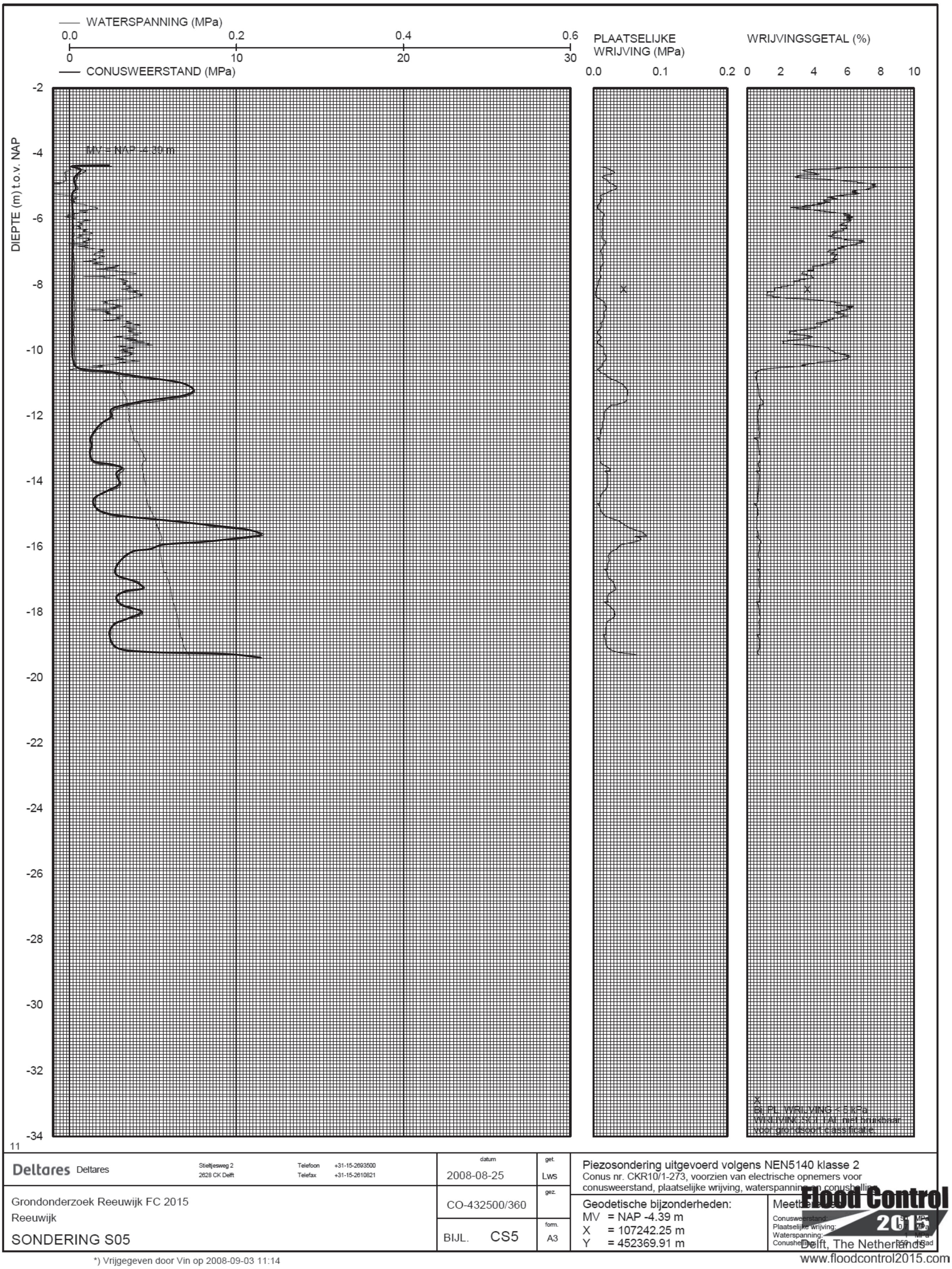
(Hack et al., 2008)

Appendix 13 CPT-S04



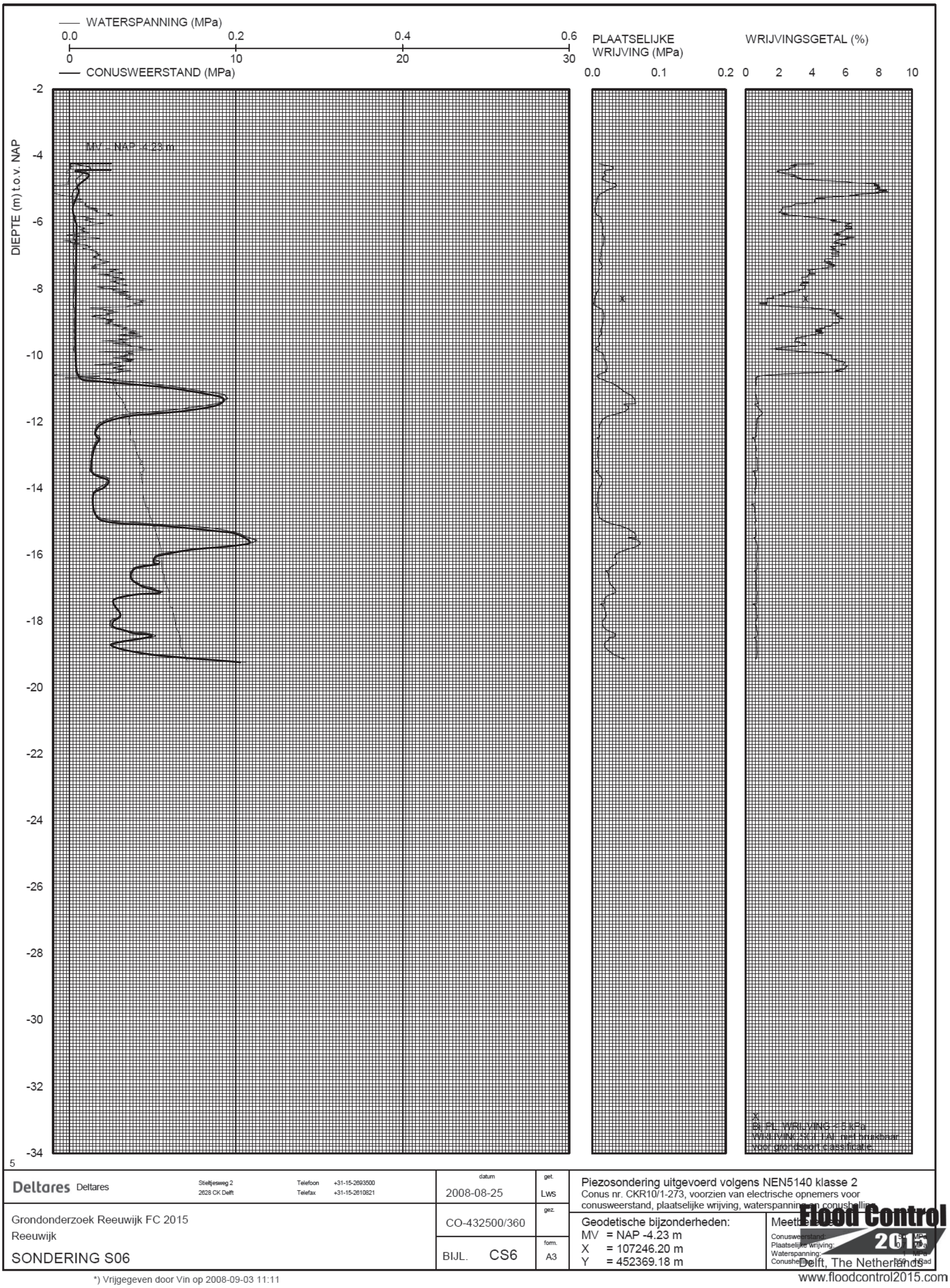
*) Vrijgegeven door Vin op 2008-09-03 11:10

(Hack et al., 2008)



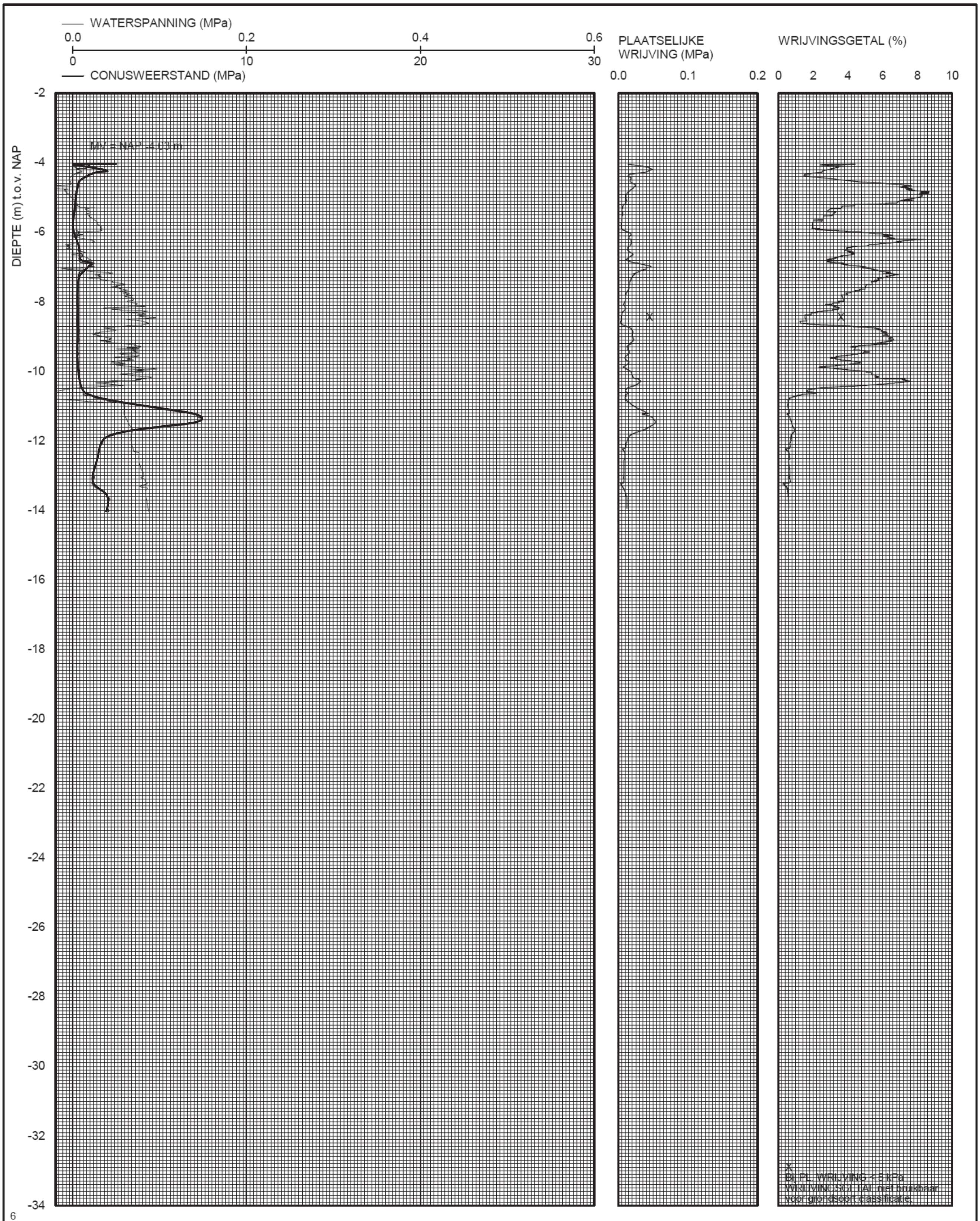
(Hack et al., 2008)

Appendix 15 CPT-S06



(Hack et al., 2008)

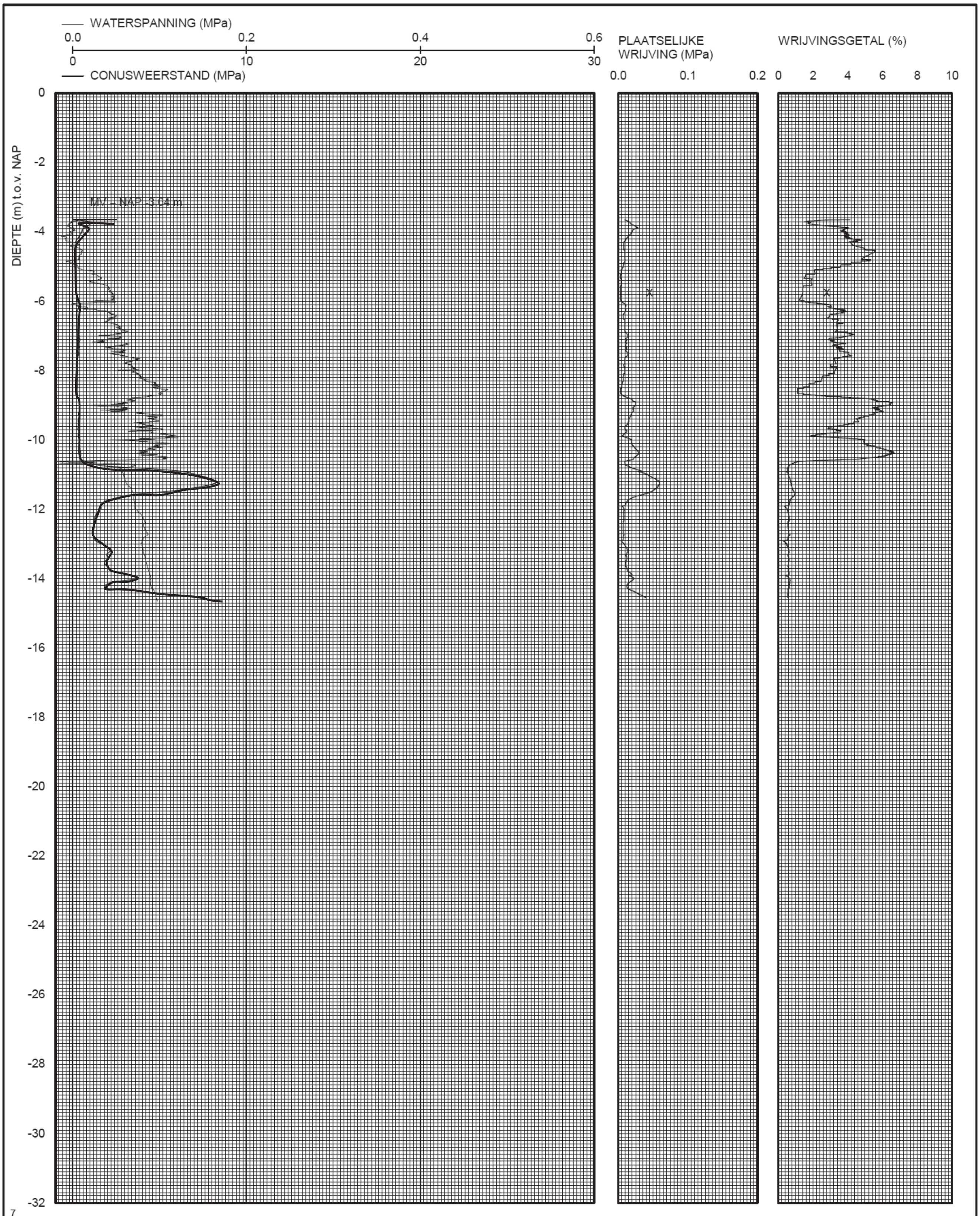
Appendix 16 CPT-S07



Deltares Deltares Stieltjesweg 2, 2628 CK Delft, Telefoon +31-15-2693500, Telefax +31-15-2610821	datum 2008-08-25	get. Lws	Piezosondering uitgevoerd volgens NEN5140 klasse 2 Conus nr. CKR10/1-273, voorzien van electrische opnemers voor conusweerstand, plaatselijke wrijving, waterspanning en conushelling
Grondonderzoek Reeuwijk FC 2015 Reeuwijk SONDERING S07	CO-432500/360 BIJL. CS7	gez. form. A3	Geodetische bijzonderheden: MV = NAP -4.03 m X = 107250.23 m Y = 452368.51 m

*) Vrijgegeven door Vin op 2008-09-03 11:12

Appendix 17 CPT-S08



7

Deltares Deltares	Stieltjesweg 2 2628 CK Delft	Telefoon +31-15-2693500 Telefax +31-15-2610821	datum 2008-08-25	get. Lws
Grondonderzoek Reeuwijk FC 2015 Reeuwijk			CO-432500/360	gez.
SONDERING S08			BIJL. CS8	form. A3

Piezosondering uitgevoerd volgens NEN5140 klasse 2
Conus nr. CKR10/1-273, voorzien van electrische opnemers voor conusweerstand, plaatselijke wrijving, waterspanning en conushelling

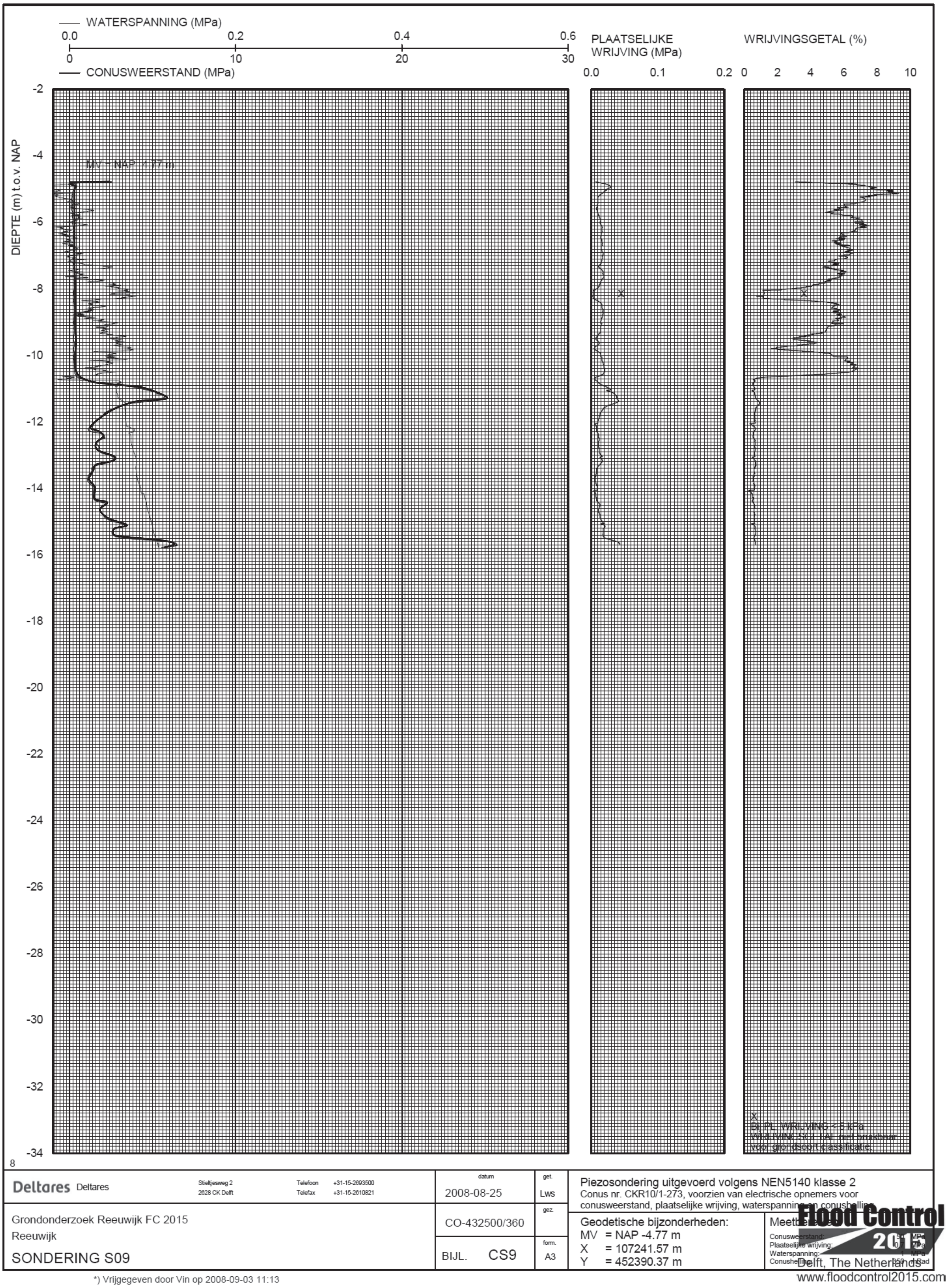
Geodetische bijzonderheden:
MV = NAP -3.64 m
X = 107254.09 m
Y = 452367.90 m

Meetbereik:
Conusweerstand: 50 MPa
Plaatselijke wrijving: 0.7 MPa
Waterspanning: 1 MPa
Conushelling: [illegible]

*) Vrijgegeven door Vin op 2008-09-03 11:13

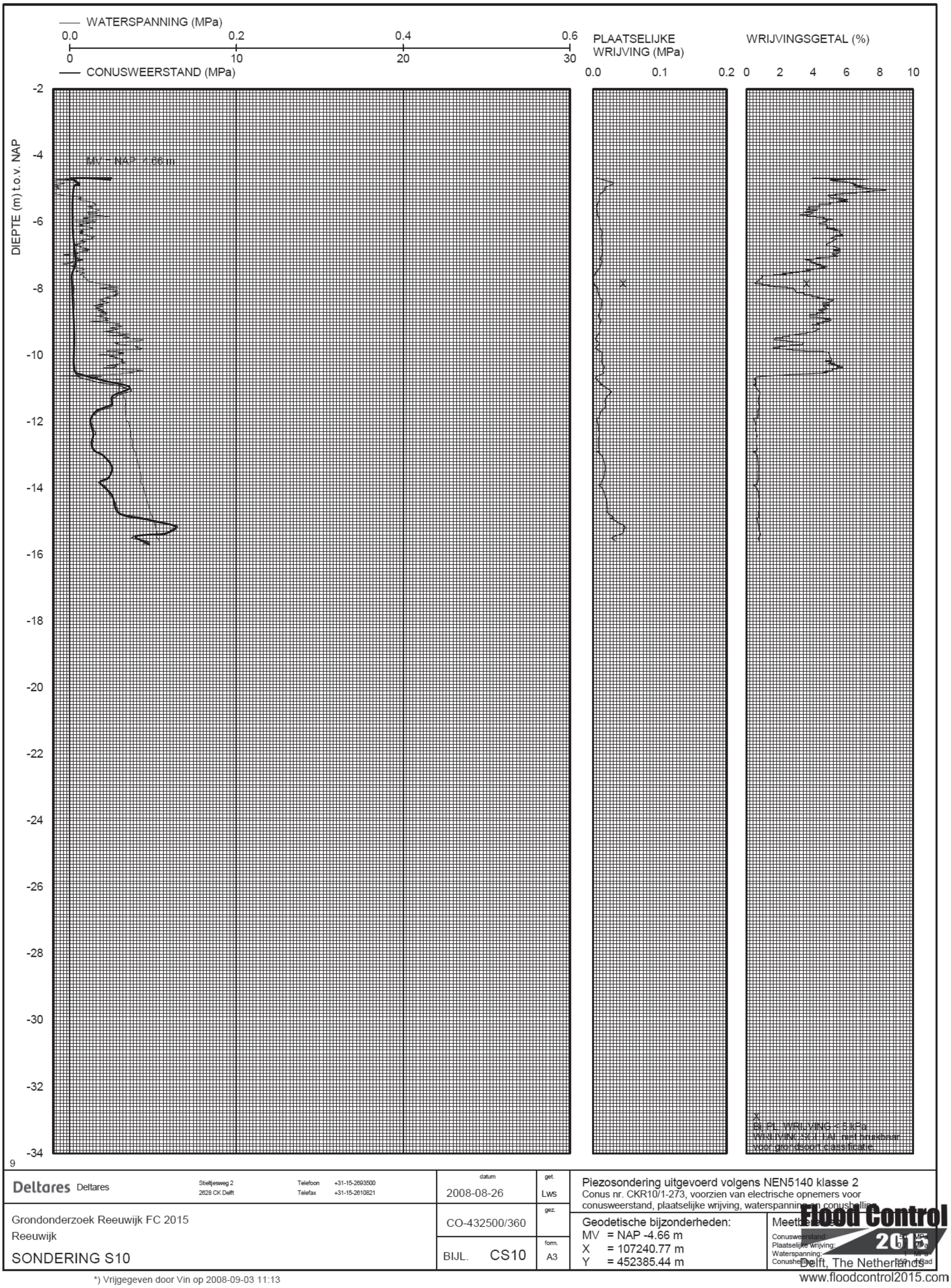
(Hack et al., 2008)

Appendix 18 CPT-S09



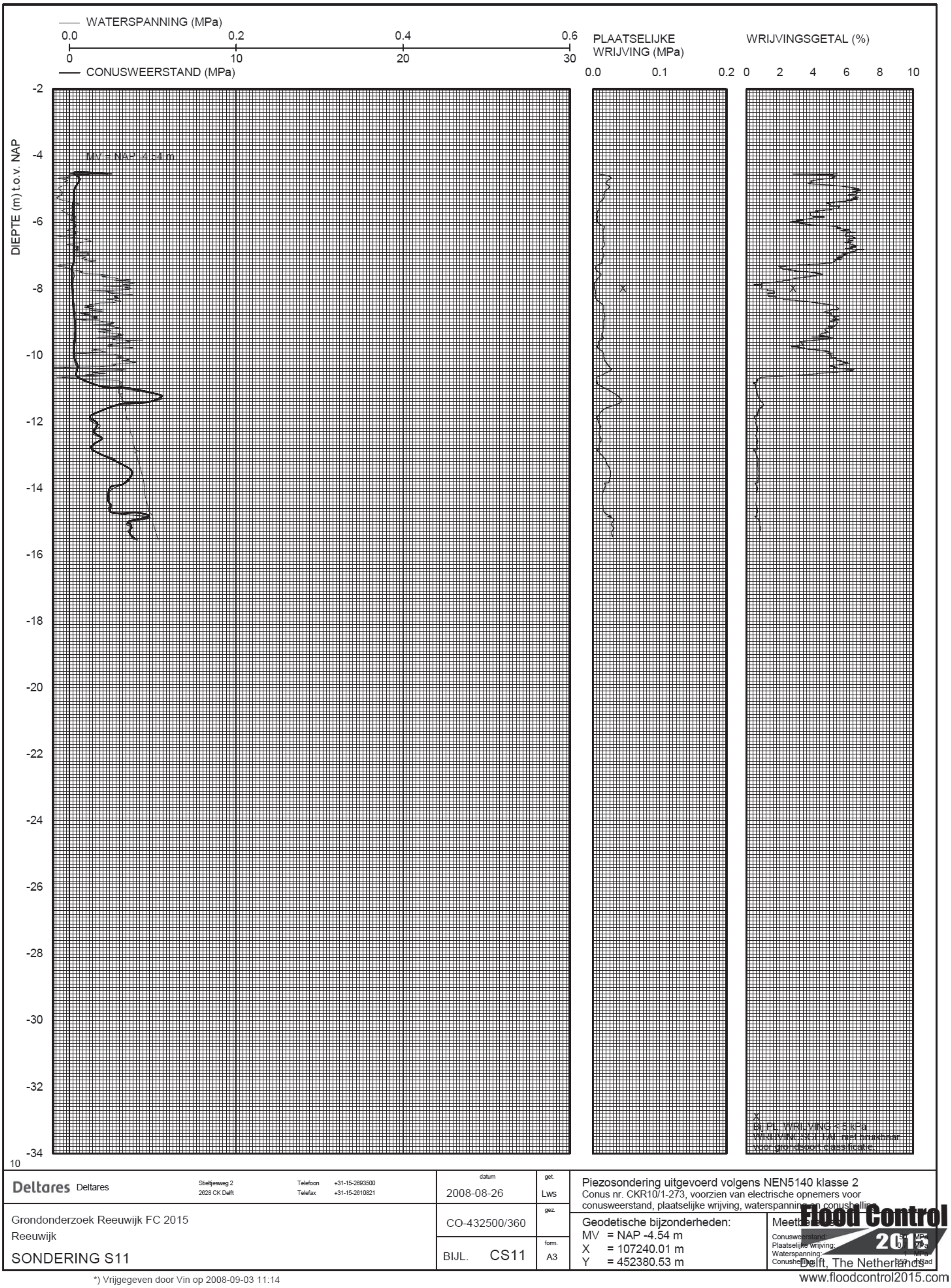
(Hack et al., 2008)

Appendix 19 CPT-S10



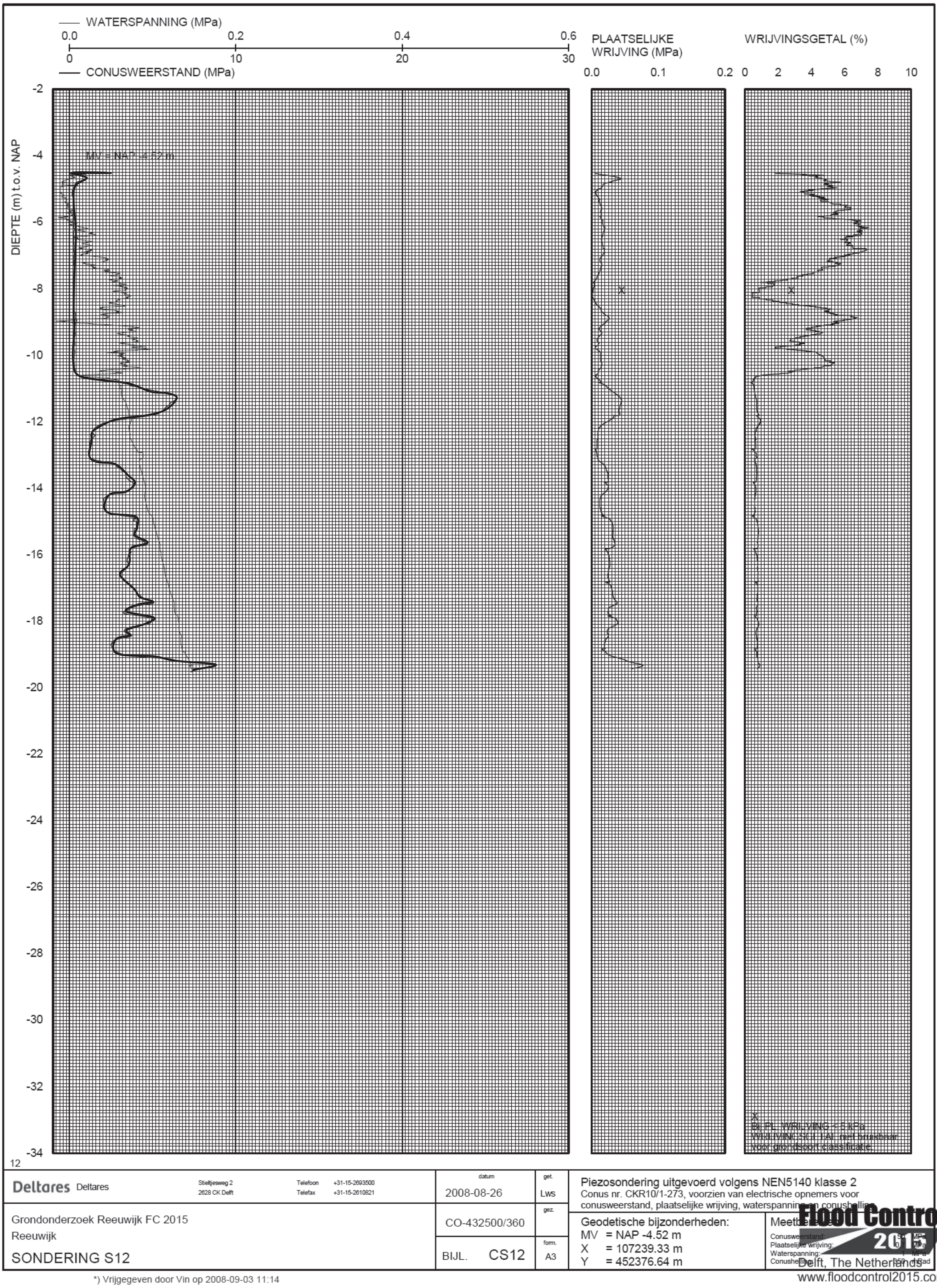
(Hack et al., 2008)

Appendix 20 CPT-S11



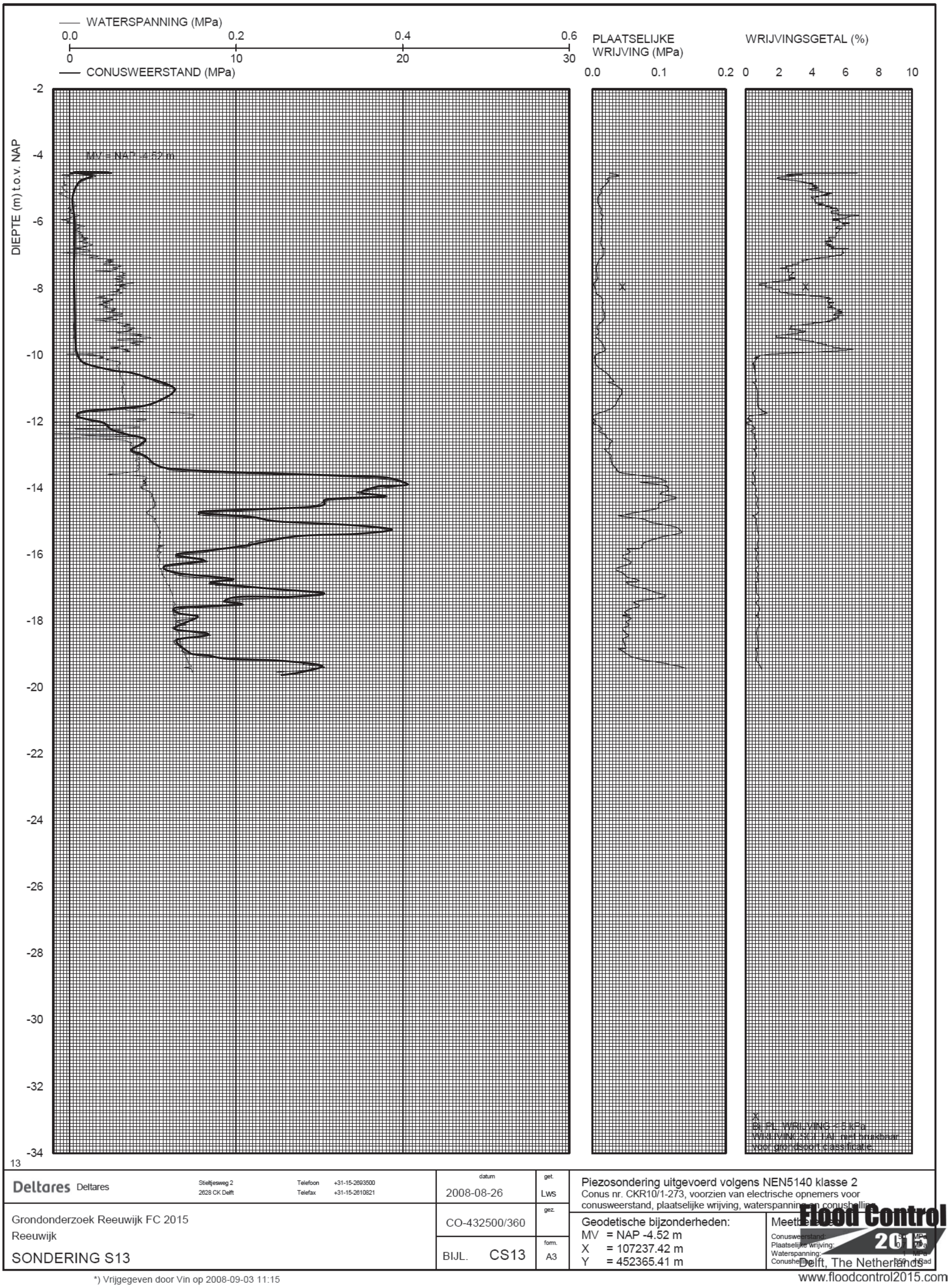
(Hack et al., 2008)

Appendix 21 CPT-S12



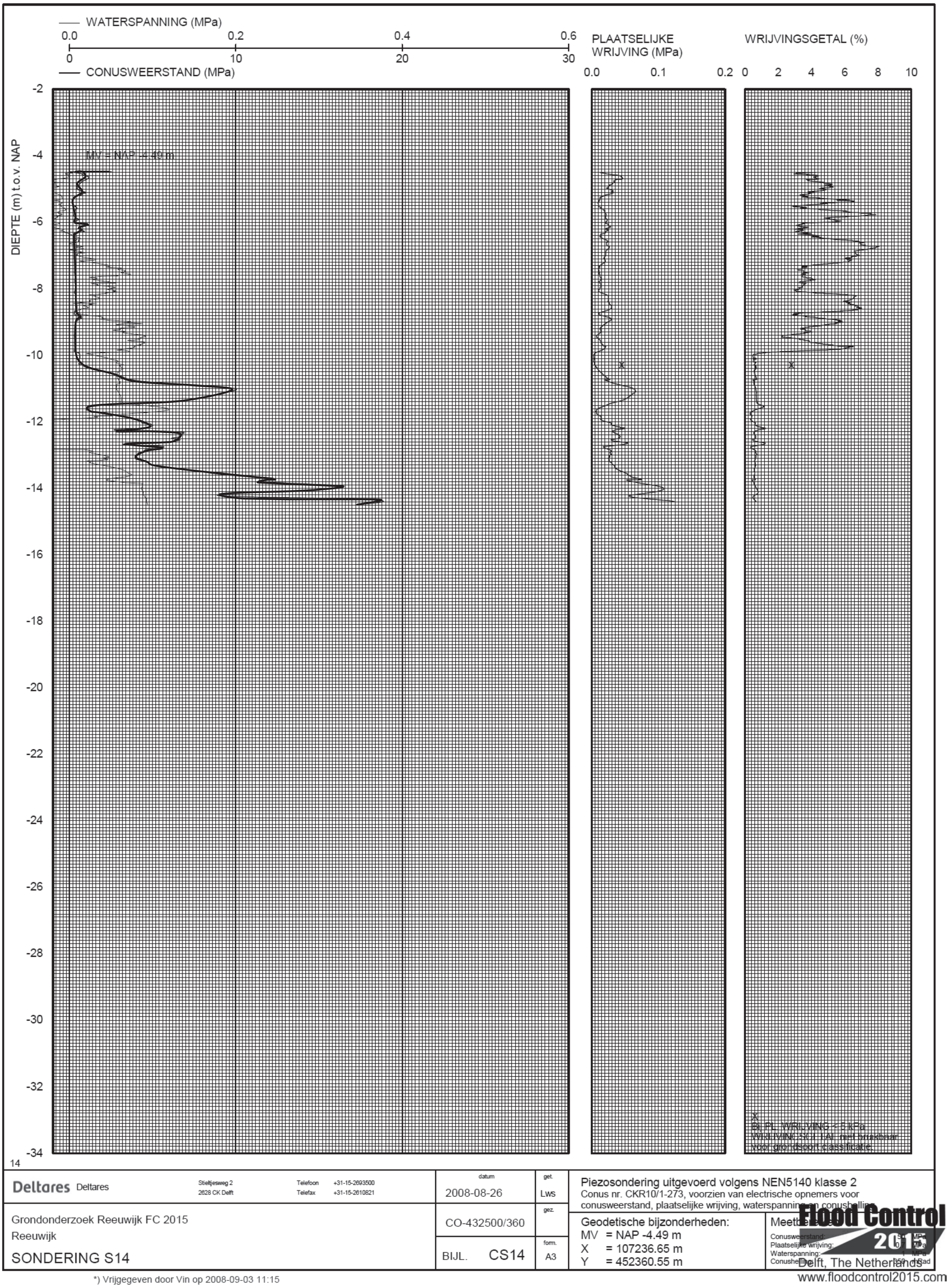
(Hack et al., 2008)

Appendix 22 CPT-S13



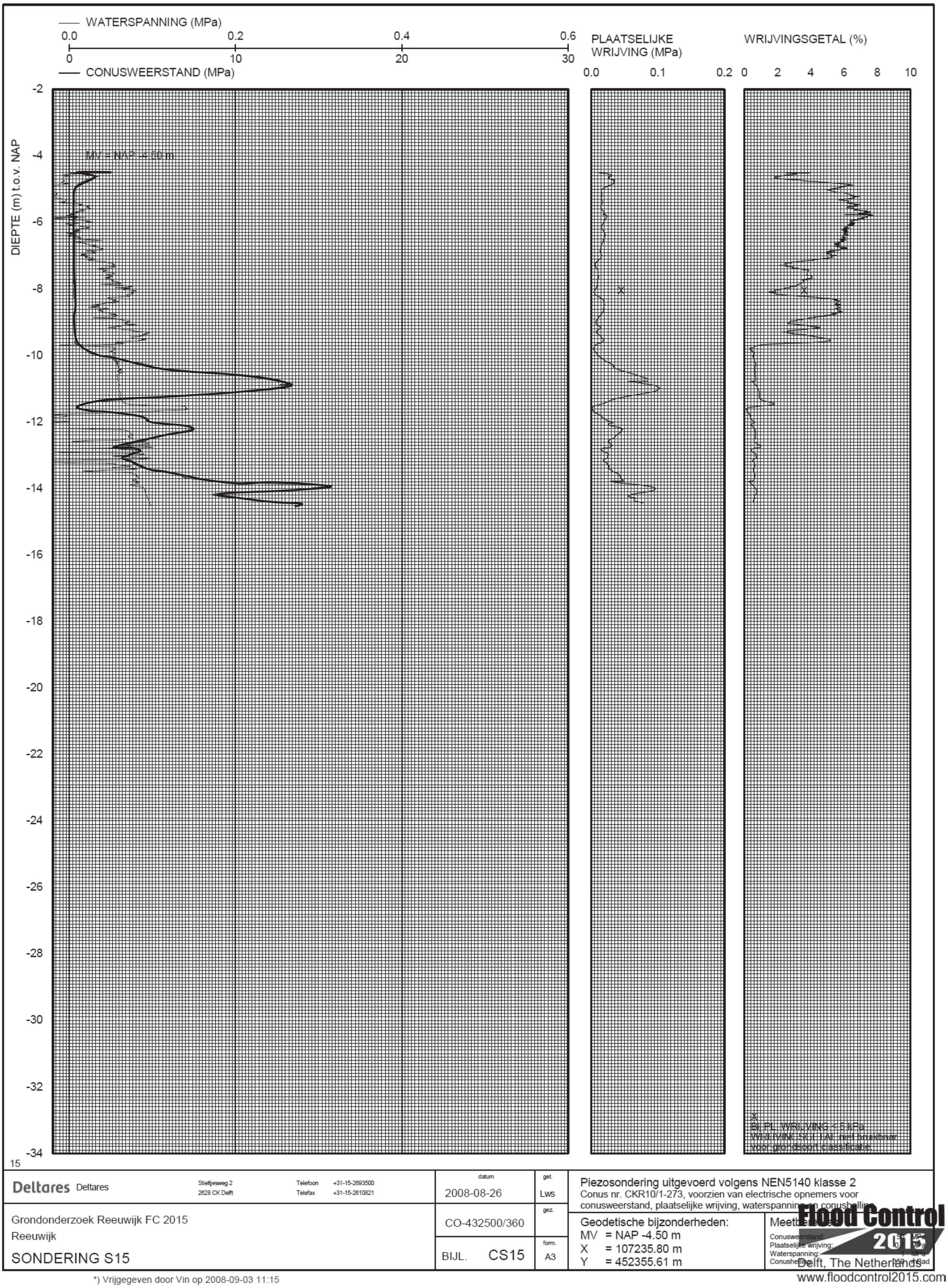
(Hack et al., 2008)

Appendix 23 CPT-S14



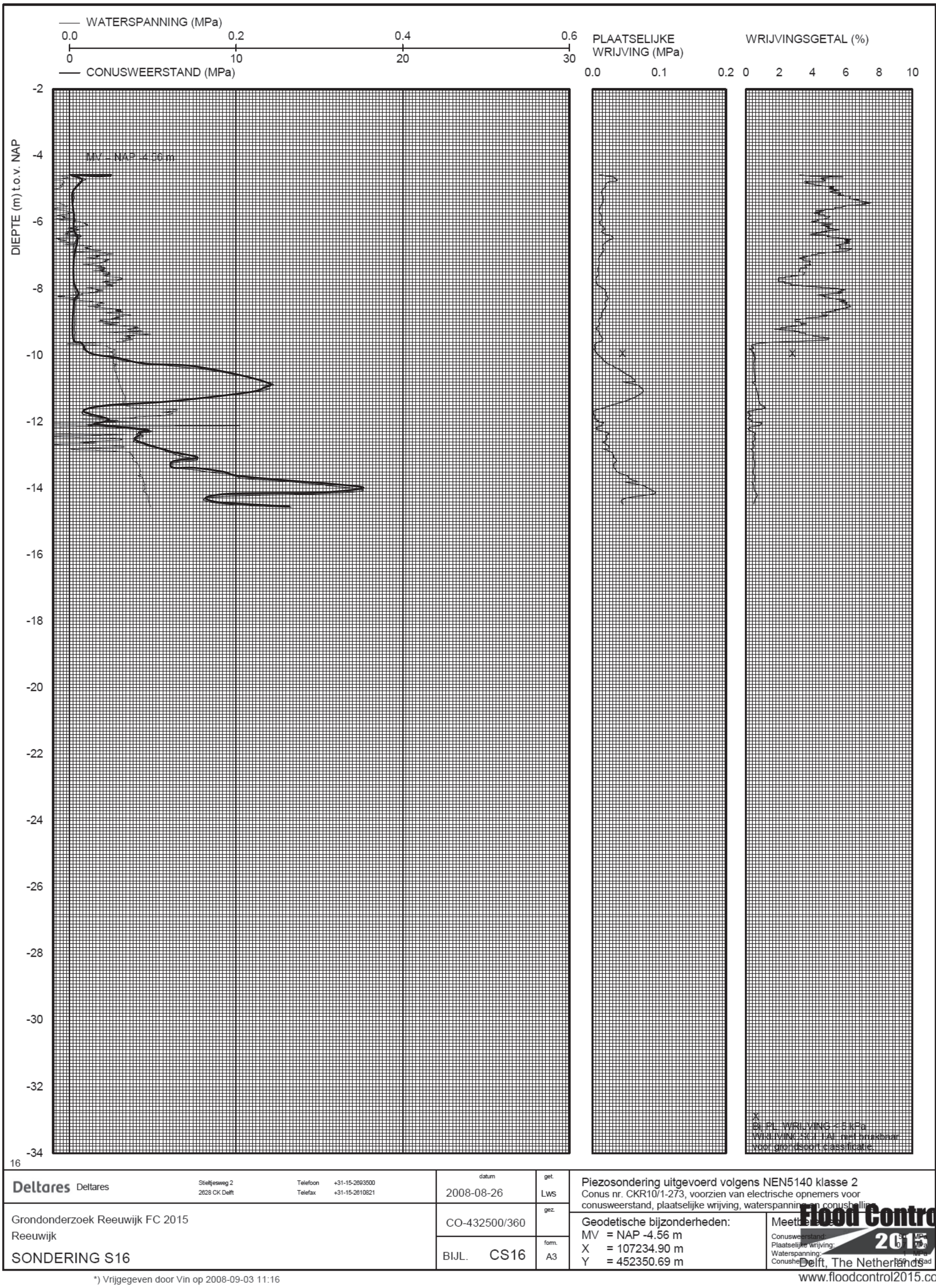
(Hack et al., 2008)

Appendix 24 CPT-S15



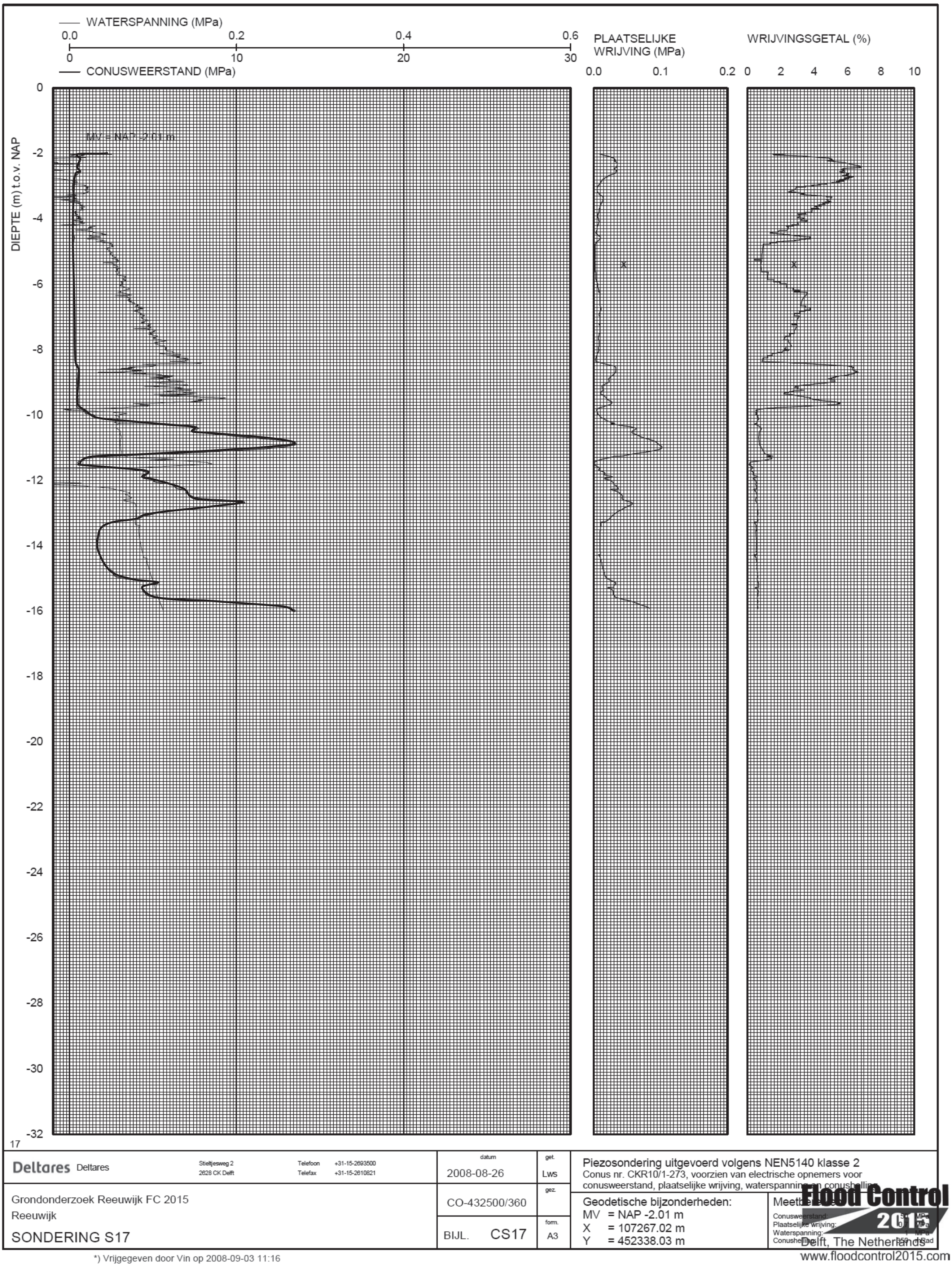
(Hack et al., 2008)

Appendix 25 CPT-S16



(Hack et al., 2008)

Appendix 26 CPT-S17



(Hack et al., 2008)

Appendices 26. Data correlation of CPTs and boreholes (the data applied in 3D geological modeling are without the first peat (Layer1)).

BH01/CPT-S04

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 1)	-4.58	-4.98	0.40
Peat (Layer 5)	-4.98	-5.70	0.72
Peat (Layer 6)	-5.70	-6.15	0.45
Peat (Layer 7)	-6.15	-7.65	1.50
Peat (Layer 8)	-7.65	-7.95	0.30
Clay (Layer 9)	-7.95	-8.42	0.47
Peat (Layer 10)	-8.42	-9.02	0.60
Peat (Layer 11)	-9.02	-9.38	0.36
Clay (Layer 12)	-9.38	-9.81	0.43
Peat (Layer 13)	-9.81	-10.40	0.59
Sand (Layer 14)	-10.40	-13.30	2.90
Sand (Layer 16)	-13.30	-19.30	6.00

BH02/CPT-S17

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 1)	-2.01	-2.51	0.50
Peat (Layer 2)	-2.51	-2.80	0.29
Peat (Layer 3)	-2.80	-3.30	0.50
Peat (Layer 4)	-3.30	-3.65	0.35
Peat (Layer 5)	-3.65	-4.45	0.80
Clay (Layer 6b)	-4.45	-5.75	1.30
Clay (Layer 7b)	-5.75	-7.80	2.05
Clay (Layer 8)	-7.80	-8.06	0.26
Clay (Layer 9)	-8.06	-8.40	0.34
Peat (Layer 10)	-8.40	-8.80	0.40
Peat (Layer 11)	-8.80	-9.05	0.25
Clay (Layer 12)	-9.05	-9.45	0.40
Peat (Layer 13)	-9.45	-9.78	0.33
Sand (Layer 14)	-9.78	-11.20	1.42
Loam (Layer 15)	-11.20	-11.60	0.40
Sand (Layer 14)	-11.60	-14.00	2.40
Sand (Layer 16)	-14.00	-16.00	2.00

CPT-S01

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 1)	-5.06	-5.50	0.44
Peat (Layer 5)	-5.50	-5.90	0.40
Peat Layer 7)	-5.90	-6.92	1.02
Peat (Layer 8)	-6.92	-7.50	0.58
Clay (Layer 9)	-7.50	-8.12	0.62
Peat (Layer 10)	-8.12	-8.60	0.48
Peat (Layer 11)	-8.60	-8.89	0.29
Clay (Layer 12)	-8.89	-9.35	0.46
Peat (Layer 13)	-9.35	-9.90	0.50
Sand (Layer 14)	-9.90	-11.18	1.33
Loam (Layer 15)	-11.18	-11.60	0.42
Sand (Layer 14)	-11.60	-13.30	1.70
Sand (Layer 16)	-13.30	-15.05	1.75

CPT-S02

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 1)	-4.85	-5.28	0.43
Peat (Layer 5)	-5.28	-5.65	0.37
Peat Layer 7)	-5.65	-6.68	1.03
Peat (Layer 8)	-6.68	-7.20	0.52
Clay (Layer 9)	-7.20	-7.80	0.60
Peat (Layer 10)	-7.80	-8.70	0.90
Peat (Layer 11)	-8.70	-9.05	0.35
Clay (Layer 12)	-9.05	-9.40	0.35
Peat (Layer 13)	-9.40	-10.00	0.60
Sand (Layer 14)	-10.00	-11.12	1.12

Loam (Layer 15)	-11.12	-11.58	0.46
Sand (Layer 14)	-11.58	-13.25	1.67
Sand (Layer 16)	-13.25	-14.85	1.60

CPT-S03

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 1)	-4.69	-5.15	0.46
Peat (Layer 5)	-5.12	-5.60	0.48
Peat Layer 7)	-5.60	-7.10	1.50
Peat (Layer 8)	-7.10	-7.40	0.30
Clay (Layer 9)	-7.40	-8.18	0.78
Peat (Layer 10)	-8.18	-8.92	0.74
Peat (Layer 11)	-8.92	-9.28	0.36
Clay (Layer 12)	-9.28	-9.65	0.37
Peat (Layer 13)	-9.65	-10.20	0.55
Sand (Layer 14)	-10.20	-13.25	3.10
Sand (Layer 16)	-13.25	-13.70	0.45

CPT-S05

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 1)	-4.39	-4.78	0.39
Peat (Layer 5)	-4.78	-5.40	0.62
Peat (Layer 6)	-5.40	-5.75	0.35
Peat (Layer 7)	-5.75	-7.45	1.70
Peat (Layer 8)	-7.45	-7.95	0.50
Clay (Layer 9)	-7.95	-8.42	0.47
Peat (Layer 10)	-8.42	-9.08	0.66
Peat (Layer 11)	-9.08	-9.45	0.37
Clay (Layer 12)	-9.45	-9.82	0.37
Peat (Layer 13)	-9.82	-10.60	0.78
Sand (Layer 14)	-10.60	-13.40	2.80
Sand (Layer 16)	-13.40	-19.10	5.70

CPT-S06

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 1)	-4.23	-4.71	0.50
Peat (Layer 5)	-4.71	-5.20	0.49
Clay (Layer 6b)	-5.20	-5.82	0.62
Peat (Layer 7)	-5.82	-7.45	2.25
Peat (Layer 8)	-7.45	-7.95	0.50
Clay (Layer 9)	-7.95	-8.55	0.60
Peat (Layer 10)	-8.55	-9.20	0.65
Peat (Layer 11)	-9.20	-9.40	0.20
Clay (Layer 12)	-9.40	-9.90	0.50
Peat (Layer 13)	-9.90	-10.60	0.75
Sand (Layer 14)	-10.60	-13.45	2.80
Sand (Layer 16)	-13.45	-19.10	5.65

CPT-S07

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 1)	-4.03	-4.50	0.47
Peat (Layer 5)	-4.50	-5.20	0.70
Clay (Layer 6b)	-5.20	-5.95	0.75
Peat (Layer 7)	-5.95	-6.45	0.50
Clay (Layer 7b)	-6.45	-6.90	0.45
Peat (Layer 7)	-6.90	-7.80	0.90
Clay (Layer 8b)	-7.80	-8.25	0.45
Clay (Layer 9)	-8.25	-8.70	0.45
Peat (Layer 10)	-8.70	-9.25	0.55
Peat (Layer 11)	-9.25	-9.55	0.30
Clay (Layer 12)	-9.55	-9.98	0.43
Peat (Layer 13)	-9.98	-10.70	0.72
Sand (Layer 14)	-10.70	-13.30	2.60
Sand (Layer 16)	-13.30	-14.03	0.73

CPT-S08

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 1)	-3.64	-4.10	0.46
Peat (Layer 5)	-4.10	-5.11	1.01
Clay (Layer 6b)	-5.11	-6.03	0.92
Clay (Layer 7b)	-6.03	-7.85	2.07
Clay (Layer 8b)	-7.85	-8.10	0.25
Clay (Layer 9)	-8.10	-8.75	0.65
Peat (Layer 10)	-8.75	-9.25	0.50
Peat (Layer 11)	-9.25	-9.55	0.30
Clay (Layer 12)	-9.55	-10.00	0.45
Peat (Layer 13)	-10.00	-10.65	0.65
Sand (Layer 14)	-10.65	-13.00	2.35
Sand (Layer 16)	-13.00	-14.65	1.65

CPT-S09

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 1)	-4.77	-5.25	0.48
Peat (Layer 5)	-5.25	-5.60	0.35
Peat (Layer 6)	-5.60	-5.70	0.10
Peat (Layer 7)	-5.70	-7.35	1.65
Peat (Layer 8)	-7.35	-7.95	0.60
Clay (Layer 9)	-7.95	-8.31	0.36
Peat (Layer 10)	-8.31	-9.10	0.79
Peat (Layer 11)	-9.10	-9.42	0.32
Clay (Layer 12)	-9.42	-9.90	0.48
Peat (Layer 13)	-9.90	-10.70	0.80
Sand (Layer 14)	-10.70	-12.90	2.20
Sand (Layer 16)	-12.90	-15.80	2.90

CPT-S10

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 1)	-4.66	-5.20	0.54
Peat (Layer 5)	-5.20	-5.60	0.40
Peat (Layer 6)	-5.60	-5.75	0.15
Peat (Layer 7)	-5.75	-7.11	1.36
Peat (Layer 8)	-7.11	-7.50	0.39
Clay (Layer 9)	-7.50	-8.10	0.60
Peat (Layer 10)	-8.10	-9.15	1.05
Peat (Layer 11)	-9.15	-9.30	0.15
Clay (Layer 12)	-9.30	-9.87	0.57
Peat (Layer 13)	-9.87	-10.65	0.78
Sand (Layer 14)	-10.65	-12.90	2.25
Sand (Layer 16)	-12.90	-15.70	2.80

CPT-S11

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 1)	-4.54	-4.80	0.26
Peat (Layer 5)	-4.80	-5.70	0.90
Peat (Layer 6)	-5.70	-6.10	0.40
Peat (Layer 7)	-6.10	-7.25	1.15
Peat (Layer 8)	-7.25	-7.78	0.53
Clay (Layer 9)	-7.78	-8.30	0.52
Peat (Layer 10)	-8.30	-9.35	1.05
Peat (Layer 11)	-9.35	-9.52	0.17
Clay (Layer 12)	-9.52	-9.88	0.36
Peat (Layer 13)	-9.88	-10.75	0.87
Sand (Layer 14)	-10.75	-13.00	2.25
Sand (Layer 16)	-13.00	-15.55	2.55

CPT-S12

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 1)	-4.52	-5.00	0.48
Peat (Layer 5)	-5.00	-5.80	0.80
Peat (Layer 6)	-5.80	-5.90	0.10
Peat (Layer 7)	-5.90	-7.12	1.22
Peat (Layer 8)	-7.12	-7.50	0.53
Clay (Layer 9)	-7.65	-8.50	0.85

Peat (Layer 10)	-8.50	-9.12	0.62
Peat (Layer 11)	-9.12	-9.50	0.38
Clay (Layer 12)	-9.50	-9.90	0.40
Peat (Layer 13)	-9.90	-10.65	0.75
Sand (Layer 14)	-10.65	-13.20	2.55
Sand (Layer 16)	-13.20	-19.50	6.30

CPT-S13

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 1)	-4.52	-4.82	0.30
Peat (Layer 5)	-4.82	-5.20	0.38
Peat (Layer 6)	-5.20	-5.50	0.30
Peat (Layer 7)	-5.50	-7.15	1.65
Peat (Layer 8)	-7.15	-7.75	0.60
Clay (Layer 9)	-7.75	-8.20	0.45
Peat (Layer 10)	-8.20	-9.05	0.85
Clay (Layer 12)	-9.05	-9.55	0.50
Peat (Layer 13)	-9.55	-10.10	0.55
Sand (Layer 14)	-10.10	-11.58	1.48
Loam (Layer 15)	-11.58	-12.12	0.54
Sand (Layer 14)	-12.12	-13.50	1.38
Sand (Layer 16)	-13.50	-19.50	6.00

CPT-S14

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 1)	-4.49	-4.79	0.30
Peat (Layer 5)	-4.79	-5.50	0.71
Peat (Layer 6)	-5.50	-5.60	0.10
Peat (Layer 7)	-5.60	-6.00	0.40
Clay (Layer 7b)	-6.00	-6.48	0.48
Clay (Layer 7)	-6.48	-7.27	0.79
Peat (Layer 8)	-7.27	-8.10	0.83
Peat (Layer 10)	-8.10	-8.75	0.65
Peat (Layer 11)	-8.75	-9.15	0.40
Clay (Layer 12)	-9.15	-9.55	0.40
Peat (Layer 13)	-9.55	-9.95	0.40
Sand (Layer 14)	-9.95	-11.30	1.35
Loam (Layer 15)	-11.30	-11.90	0.60
Sand (Layer 14)	-11.90	-13.30	1.40
Sand (Layer 16)	-13.30	-14.50	1.20

CPT-S15

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 1)	-4.50	-4.80	0.30
Peat (Layer 5)	-4.80	-5.30	0.50
Peat (Layer 7)	-5.30	-7.10	1.80
Peat (Layer 8)	-7.10	-7.85	0.75
Clay (Layer 9)	-7.85	-8.23	0.38
Peat (Layer 10)	-8.23	-8.97	0.74
Clay (Layer 12)	-8.97	-9.33	0.36
Peat (Layer 13)	-9.33	-9.70	0.37
Sand (Layer 14)	-9.70	-11.38	1.68
Loam (Layer 15)	-11.38	-11.75	0.37
Sand (Layer 14)	-11.75	-13.40	1.65
Sand (Layer 16)	-13.40	-14.55	1.15

CPT-S16

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 1)	-4.56	-4.90	0.34
Peat (Layer 5)	-4.90	-5.60	0.70
Peat (Layer 6)	-5.60	-6.40	0.80
Peat (Layer 7)	-6.40	-6.90	0.50
Peat (Layer 8)	-6.90	-7.45	0.55
Clay (Layer 9)	-7.45	-7.90	0.45
Peat (Layer 10)	-7.90	-8.90	1.00
Clay (Layer 12)	-8.90	-9.25	0.35
Peat (Layer 13)	-9.25	-9.65	0.40
Sand (Layer 14)	-9.65	-11.45	1.80

Loam (Layer 15)	-11.45	-11.90	0.45
Sand (Layer 14)	-11.90	-13.30	1.40
Sand (Layer 16)	-13.30	-14.58	1.28

Appendices 27 Data artificial boreholes applied in 3D geological modeling.

AP-01

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 2)	-2.51	-2.8	0.29
Peat (Layer 3)	-2.8	-3.3	0.5
Peat (Layer 4)	-3.3	-3.65	0.35
Peat (Layer 5)	-3.65	-4.45	0.8

AP-02

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 7)	-5.35	-6.35	1

AP-03

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 7)	-5.41	-6.4	1
Peat (Layer 8)	-6.4	-6.95	1.35
Clay (Layer 9)	-6.95	-7.4	0.45
Peat (Layer 10)	-7.4	-8.2	0.8
Peat (Layer 11)	-8.2	-8.4	0.2
Clay (Layer 12)	-8.4	-8.75	0.35
Peat (Layer 13)	-8.75	-9.1	0.35
Sand (Layer 14)	-9.1	-10.95	1.85
Loam (Layer 15)	-10.95	-11.4	0.45
Sand (Layer 14)	-11.4	-12.8	1.4
Sand (Layer 16)	-12.8	-14.08	2

AP-04

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 4)	-3.29	-3.59	0.30
Peat (Layer 5)	-3.59	-4.44	0.85

AP-05

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 2)	-2.49	-2.785	0.295
Peat (Layer 3)	-2.785	-3.268	0.483
Peat (Layer 4)	-3.268	-3.644	0.376
Peat (Layer 5)	-3.644	-4.46	0.816

AP-06

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 3)	-2.9	-3.35	0.45
Peat (Layer 4)	-3.35	-3.655	0.305
Peat (Layer 5)	-3.655	-4.345	0.69

AP-07

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 4)	-3.3	-3.65	0.35
Peat (Layer 5)	-3.65	-4.45	0.8
Clay (Layer 6b)	-4.45	-5.75	1.3
Clay (Layer 7b)	-5.75	-7.8	2.05
Clay (Layer 8b)	-7.8	-8.06	0.26
Clay (Layer 9)	-8.06	-8.4	0.34

Peat (Layer 10)	-8.4	-8.8	0.4
Peat (Layer 11)	-8.8	-9.05	0.25
Clay (Layer 12)	-9.05	-9.45	0.4
Peat (Layer 13)	-9.45	-9.78	0.33
Sand (Layer 14)	-9.78	-11.2	1.42

AP-08

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 3)	-2.887	-3.334	0.447
Peat (Layer 4)	-3.334	-3.639	0.305
Peat (Layer 5)	-3.639	-4.331	0.692

AP-09

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 3)	-3.3	-3.6	0.30
Peat (Layer 4)	-3.6	-4.4	0.80

AP-10

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 3)	-2.87	-3.37	0.5
Peat (Layer 4)	-3.37	-3.72	0.35
Peat (Layer 5)	-3.72	-4.52	0.8
Clay (Layer 6b)	-4.52	-5.82	1.3
Clay (Layer 7b)	-5.82	-7.87	2.05
Clay (Layer 8b)	-7.87	-8.13	0.26
Clay (Layer 9)	-8.13	-8.47	0.34
Peat (Layer 10)	-8.47	-8.87	0.4
Peat (Layer 11)	-8.87	-9.12	0.25
Clay (Layer 12)	-9.12	-9.52	0.4
Peat (Layer 13)	-9.52	-9.85	0.33
Sand (Layer 14)	-9.85	-11.27	1.42
Loam (Layer 15)	-11.27	-11.67	0.4
Sand (Layer 14)	-11.67	-13.97	2.3
Sand (Layer 16)	-13.97	-15	1.03

AP-11

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 5)	-4.53	-5.24	0.71
Peat (Layer 7)	-5.24	-6.53	1.29
Peat (Layer 8)	-6.53	-7.08	0.55
Clay (Layer 9)	-7.08	-7.53	0.45
Peat (Layer 10)	-7.53	-8.33	0.8
Peat (Layer 11)	-8.33	-8.53	0.2
Clay (Layer 12)	-8.53	-8.89	0.36
Peat (Layer 13)	-8.89	-9.23	0.34
Sand (Layer 14)	-9.23	-11.08	1.85
Loam (Layer 15)	-11.08	-11.53	0.45
Sand (Layer 14)	-11.53	-12.91	1.38
Sand (Layer 16)	-12.91	-14.21	1.3

AP-12

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 5)	-3.66	-4.66	1

AP-13

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 7)	-5.37	-6.38	1.01
Peat (Layer 8)	-6.38	-7.04	0.66
Clay (Layer 9)	-7.04	-7.702	0.662
Peat (Layer 10)	-7.702	-8.09	0.388
Peat (Layer 11)	-8.09	-8.5	0.41
Clay (Layer 12)	-8.5	-8.93	0.43
Peat (Layer 13)	-8.93	-9.47	0.54
Sand (Layer 14)	-9.47	-10.81	1.34
Loam (Layer 15)	-10.81	-11.14	0.33
Sand (Layer 14)	-11.14	-12.77	1.63
Sand (Layer 16)	-12.77	-14.47	1.7

AP-14

Lithology	Depth (m)		Thicknesses (m)
	from	to	
Peat (Layer 7)	-5.355	-6.475	1.12