Netherlands Enterprise Agency

Geological Desk Study

Hollandse Kust (west) Wind Farm Zone

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Document title: Geological Desk Study
Hollandse Kust (west) Wind Farm Zone

Document subtitle: --

Author (s): Arcadis Germany GmbH & Geo-Engineering.org GmbH
Contract manager RVO.nl: Cynthia Mors
Project ID RVO.nl: WOZ2180087
Number of pages: 55 pages

Version	Approved for public disclosure by contract manager RVO.nl	Approved for public disclosure by project manager offshore wind RVO.nl
Final	**Name** Cynthia Mors **Signature** **Date 2018-06-26**	**Name** Ruud de Bruijne **Signature** **Date 2018-06-26**

HOLLANDSE KUST (WEST) WIND FARM ZONE

Geological Desk study

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04. JUNE 2018

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Title
Geological Desk Study Hollandse Kust (west) Wind Farm Zone

Client	Project	Reference
Rijksdienst voor Ondernemend Nederland (RVO)	Arcadis - Geo-Engineering	180017

Keywords

Hollandse Kust (west), geology, bathymetry, Holocene, Pleistocene, geohazards

References

Request for proposal: 201801067 RfP Geological desk study WOZ2180087_F, dated 12. February 2018

Arcadis' proposal: WOZ2180087_Proposal Geological Desk Study - Arcadis NL, dated 5. March 2018

Project award: Notification award decision WOZ2180087 Geological desk studies, dated 13. March 2018

Rev.	Date	Pages total	Pages Annexes	Authors	Review	Edits
3	28.05.2018	74	26	Dr. Janis Thal Lukasz Socko Johannes Brock Sebastian Feldmann	Dr. Jelmer Cleveringa Diederik van Hogendorp	

Citation

Thal, J., Socko, L., Feldmann, S, Brock, J. P. (2018). Geological Desk Study for the Hollandse Kust (west) Wind Farm Zone. Arcadis Nederland B.V. and Geo-Engineering.org GmbH, 180017. Netherlands Enterprise Agency. (RVO.nl).

State

Final.

CONTENTS

ABBREVIATIONS

BGS	British Geological Survey
CPT	Cone Penetration Test
EPSG	European Petroleum Survey Group Geodesy
ETRS89	European Terrestrial Reference System 1989
Fm	Formation (geological formation)
HKNWFZ	Hollandse Kust (noord) Wind Farm Zone
HKWWFZ	Hollandse Kust (west) Wind Farm Zone
HKZWFZ	Hollandse Kust (zuid) Wind Farm Zone
IRIS	Incorporated Research Institutions for Seismology
KNMI	Koninklijk Nederlands Meteorologisch Instituut
LAT	Lowest Astronomical Tide
Mbsf	Metres below seafloor
Mbsl	Metres below sea level
MW	Megawatt
NLHO	Netherlands Hydrographic Office
NLOG	Nederland Olie en Gas (Database for deep subsurface data)
DINOLoket	Data Informatie Nederlandse Ondergrond (Database for shallow subsurface data)
SID	Survey Identification
SD	Standard Deviation
TNO	Netherlands Organisation for applied scientific research
TPU	Total Propagated Uncertainty
UTM	Universal Transverse Mercator
WGS 84	World Geodetic System 1984

MANAGEMENTSAMENVATTING

De Rijksdienst voor Ondernemend Nederland heeft Arcadis Nederland B.V. samen met Arcadis Duitsland GmbH (hierna: Arcadis) en Geo-Engineering.org GmbH (hierna: Geo-Engineering) opdracht gegeven om een geologisch bureauonderzoek uit te voeren naar de geologische eigenschappen van windgebied “Hollandse Kust (west)”. De analyse is gebaseerd op basis van publiek beschikbare databases van overheden en literatuur over het interessegebied. Deze gegevens bestaan onder andere uit bathymetrische data, beschrijvingen van ondiepe en diepe boringen, seismische data en geologische risico’s. Met de beschikbare regionale data is een stratigrafische kader opgesteld voor het windgebied Hollandse Kust (west). De aanbevelingen die volgen uit het bureauonderzoek voor aanvullend seismisch onderzoek zijn openomen in een separaat memo.

Het windgebied Hollandse Kust (west) heeft een oppervlakte van 349 km2 en ligt ongeveer 50 kilometer offshore van de Hollandse Kust.

Op basis van de verzamelde bathymetrische data is een bathymetrische kaart opgesteld. De meest recente bathymetrische surveys die een groot gedeelte van het interessegebied beslaat zijn uitgevoerd in 2014 en 2015. De waterdiepte varieert van 21 tot 33 m (LAT) en de bodemvormen bestaan voornamelijk uit zandbanken en zandgolven. De kammen van de zandbanken hebben een noord-zuid oriëntatie met een gemiddelde hoogte van 10 m, een lengte van 10-30 km en een breedte van 1-3 km. Gemiddeld liggen deze zandbanken 4-8 km van elkaar af. De zandgolven hebben een gemiddelde hoogte van 5 m, een lengte van enkele honderden meters tot een maximum van ongeveer 3 km en een oriëntatie haaks op de zandbanken. De oriëntatie van deze grote bodemvervormingen is van invloed of de gekozen richting van de surveylijn voor de aankomende geofysische surveys.

Op basis van de data uit boringen uit het DINOloket, NLOG databases, informatie van naastgelegen windparken en geologische kaarten is een geologisch model opgesteld. Het focusgebied in de ondergrond, voor het installeren van windparken, ligt tussen de 0 en de 100 meter onder de zeebodem (mbsf). De bodem bestaat voornamelijk uit fijn tot gemiddeld zand met een korreldiameter tussen de 150 en 350 µm. Deze zandlagen zijn in sommige gedeelte zeer kalkrijk en bevatten schaalfragmenten. Op sommige plekken is het zand ingesloten door zeeklei of leem met een dikte van enkele centimeters tot meters.

De stratigrafische indeling van Rijswijk et al. (2005) wordt voorgesteld met een enkele uitzondering: voor de oudere pleistocene formaties zijn de oudere Yamouth Roads formatie en Winterton Shoal formatie gebruikt.

De toplaag van holocene sediment is ongeveer 2-10 meter dik. De meest belangrijke pleistocene formaties zijn: Eem Formation, Egmond Ground Formation and Yarmouth Roads Formation.

De beschikbare seismische data is onderzocht en beoordeeld. Alleen voor het noordelijke gedeelte van het windgebied is voldoende omvangrijk seismische data beschikbaar op basis van digitale multi-channel surveys. Deze dataset die is ingewonnen voor de olie- en gaswinning heeft een diepte penetratie >1000 m. De verticale resolutie van deze sesimische gegevens is te klein om te gebruiken voor de analyse van de eerste 100 m van de ondergrond.

Op basis van het geologische bureauonderzoek zijn er geen zwaarwegende beperkingen gevonden voor de ontwikkeling van windgebied Hollandse Kust (west). Mogelijke beperkingen die nader verkend kunnen worden voor de voorgenomen geofysische en geologische survey zijn:

Door het hele interessegebied van Hollandse Kust (west) kan veen voorkomen. Dit kan een risico zijn voor de basis van de werkplatforms, de installatie en het leggen van de kabels.

Er moet rekening gehouden worden met een zeer bewegelijke zeebodem in relatie tot de diepte waarop de kabels worden ingegraven om te voorkomen dat deze vrij komen te liggen. Tevens moet er rekening gehouden worden met de diepte tot aan de harde ondergrond waarop de funderingspalen worden aangebracht voor de bodembescherming.

Stenen en lagen stijve klei- en leemlagen kunnen mogelijk voorkomen als gevolg van ijsbedekking tijdens de ijstijden over het windgebied. Dit kan gevolgen hebben voor de uitvoerbaarheid van de benodigde fundering en voor de funderingsdiepte.

Aan de oostelijke rand van het windgebied loopt een grote vallei van glaciale oorsprong. De mogelijkheid bestaat dat er meer van deze ondiepe holocene valleien zijn, die een mogelijk negatief effect hebben op het horizontale en verticale draagvermogen van de ondergrond als gevolg van afwijkende sedimentatie van klei en veen. Echter, veel van deze valleien in het gebied zijn gevuld met zand en vormen daarom geen risico. Aanbevolen wordt om dit mee te nemen in de geotechnische survey.

De onttrekking van gas en olie uit gas- en olievelden in en nabij het windgebied kan resulteren in verhoogde seismische activiteit in de vorm van lokale aardbevingen.

Ondiepe gaslagen kunnen effect hebben op de geotechnische parameters en kunnen een risico vormen voor offshore werk en installaties. Op basis van de beperkte hoeveelheid beschikbare data voor dit bureauonderzoek is er geen gas gevonden in de ondiepe lagen.

Samenvattend wordt geconcludeerd dat er geen zwaarwegende beperkingen zijn voor de ontwikkeling van windgebied Hollandse Kust (west). Aanbevolen wordt om een gedetailleerde geofysische en geotechnische survey uit te voeren voorafgaand aan de verdere ontwikkeling van dit windgebied.

EXECUTIVE SUMMARY

The Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland) requested Arcadis Nederland B.V. together with Arcadis Germany GmbH (hereinafter called Arcadis) and Geo-Engineering.org GmbH (hereinafter called Geo-Engineering) to undertake a geological desk study to provide an overview of the geology of the Hollandse Kust (west) Wind Farm Zone. The analyses are based on publicly available data from governmental online data bases and published literature covering the area of interest. These publicly available data sets include bathymetric data, logs from shallow and deep boreholes, seismic data and sources of geohazards. This provides sufficient information together with published regional geological studies to build a local stratigraphic framework for the Hollandse Kust (west) Wind Farm Zone. In addition to this study a memo with recommendations for a following geophysical site survey is developed and attached in a separate memo.

The area of Hollandse Kust (west) covers an area of 349 km² and is located about 50 km west offshore of the central Westcoast of the Netherlands.

A compilation of bathymetric data sets was performed to construct a bathymetric map. The most recent bathymetric surveys covering most of the area are from 2014 and 2015. A brief morphological analysis revealed a water depth between 21 and 33 m (LAT) and a morphology dominated by sand banks and sand waves. These banks strike N-S and are approximately 10 m high, 10-30 km long, 1-3 km wide and around 4-8 km apart from each other. The sand waves are smaller with a height of roughly 5 m, a length of several hundreds of metres to ~3 km and an orientation perpendicular to the sand banks. The orientation of these large bedforms influence the survey line orientation for the upcoming geophysical surveys.

A geological model was constructed based on borehole data extracted from the DINOloket and NLOG databases together with information from neighbouring wind farms and geological maps. The subsurface section of interest concerning the installation of a wind farm is considered to be 0 – 100 metres below seafloor (mbsf). The subsurface consists mainly of fine to medium sand with a grain size median between 150 and 350 µm. These sandy deposits are in parts highly calcareous and include shell fragments. Occasionally the sand is inter-bedded by marine clay or loam with a thickness of several centimetres to metres.

The stratigraphic framework of Rijswijk et al. (2005) was applied with only a few exceptions: For the older Pleistocene formations the older names Yarmouth Roads Formation and Winterton Shoal Formation are used. The Holocene is roughly between 2-10 m thick. The most important Pleistocene formations are: Eem Formation, Egmond Ground Formation and Yarmouth Roads Formation.

Available seismic data was researched and assessed. Only the northern part of the wind farm zone has a decent coverage of digital multi-channel seismic data. This data set has a deep penetration of >1000 m and the vertical resolution is too low to be used for analyses of the first 100 m.

No major constraint for the development of Hollandse Kust (west) Wind Farm Zone could be identified during the course of this study. Minor constraint that should be addressed in the upcoming geophysical and geotechnical surveys are the following:

Peat can be encountered throughout the investigation area in several geological formations which can cause spudcan failure and obstruct the cable laying procedure.

A high mobility seabed needs to be considered for the depth of burial of cables to avoid free span sections and for the pile fixation levels with regard to scour.

Boulders and consolidated layers are possible to encounter due to the history of glacial cover in the area. This could affect the drivability of pile foundations.

One large glacial valley runs close to the East of the investigation area. Additional shallow Holocene channels are possible which can have a lower bearing capacity than the surrounding area due to their potential filling with soft sediments. However, many channels in this area are filled with sand and thus cause no risk. This should be addressed in the geotechnical survey.

Induced seismicity sourced from deep subsurface resource extraction like oil and gas are known to cause local earthquakes. Active and inactive gas and oil fields are situated below the investigation area. This implies an active change of conditions in the deeper subsurface.

Shallow gas can affect the geotechnical parameters and cause a threat to offshore work and installations. No signs for gas could be identified in this study because of a lack of data.

Summarizing this study we conclude that no major constraints could be found that would counterargue the development of the Hollandse Kust (west) Wind Farm Zone. A comprehensive geophysical and geotechnical survey is suggested to follow this study prior to further development of the wind farm area.

1 INTRODUCTION

1.1 General information

The Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland) requested Arcadis Nederland B.V. together with Arcadis Germany GmbH (hereinafter called Arcadis) and Geo-Engineering.org GmbH (hereinafter called Geo-Engineering) to undertake a geological desk study for the Hollandse Kust (west) Wind Farm Zone.

1.2 Aim of this study

This study aims to provide an overview of the geology of the Hollandse Kust (west) Wind Farm Zone. The analyses are based on publicly available data from governmental online data bases and published literature covering the area of interest. These publicly available data sets include bathymetric data, CPT data, logs from shallow and deep boreholes, geohazards and seismic data. This provides sufficient information together with published regional geological studies to build a local stratigraphic framework for the Hollandse Kust (west) Wind Farm Zone. In addition to this study a memo with recommendations for a future geophysical site survey is developed.

1.3 Content and structure of this report

This study is organised in 8 chapters. The publicly available data is presented and assessed in chapter 2. The data includes bathymetric, seismic and borehole data within the investigation area and the vicinity. A literature review regarding the geological development of the Dutch North Sea is given in chapter 3. Based on the literature and borehole information a stratigraphic framework is shown in chapter 4. This chapter includes the geological profile and Holocene subcrop map. Possible constraints of the data are elaborated in chapter 5. The report closes with a conclusion in chapter 6 followed by the references used for this study (chapter 7) and additional information in the Appendices (chapter 8).

2 AVAILABLE DATA AND ASSESSMENT

The publicly available data used in this study is assessed within this chapter. The characteristics of each data type is described together with the date and number of measurements.

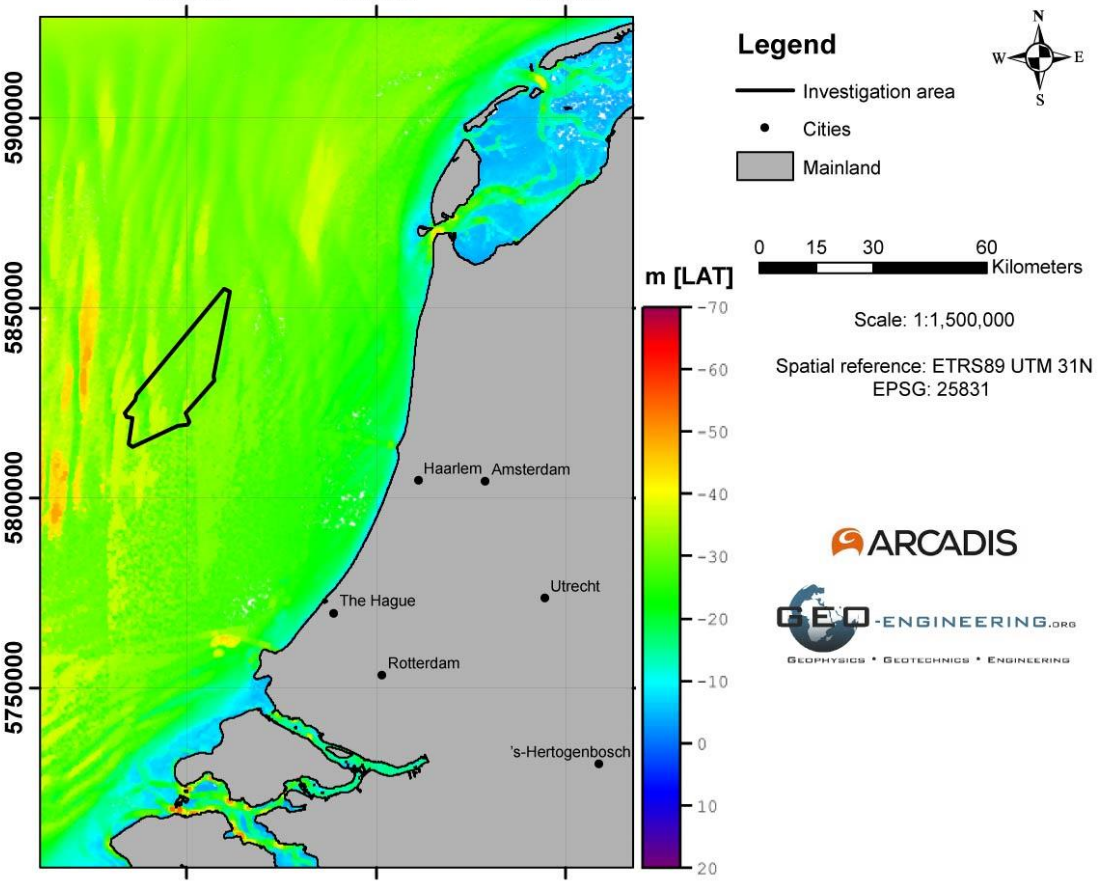

Figure 1. Map of the location of Hollandse Kust (west) Wind Farm Zone. Bathymetry from https://inspire.caris.nl. City location are extracted from World Populated Places data set by ESRI. Due to copyright issues, this data set is excluded from the published GIS.

2.1 Bathymetric data

2.1.1 General information

The Dutch North Sea (Figure 1) is very well mapped by echo sounder surveys over the last three to four decades. Surveys have been undertaken by the Netherlands Hydrographic Office (NLHO) first with single beam echo sounders and later on with multibeam echo sounders. Based on the data sets analysed the change of the survey equipment occurred between 2002 and 2006 since the surveys later than 2006 have been carried out with a multibeam echo sounder system.

2.1.2 Available data

A total of 18 surveys have been conducted between 1991 and 2015 that cover at least some parts of the investigation area. Table 1 shows a list of surveys with the month and year of measurement as well as the type of echo sounder system. Every survey gets a unique survey ID number (SID), given by the Netherlands Hydrographic Office, to guarantee the identification of each survey.

Table 1. List of available bathymetric surveys covering parts of the investigation area.

Year of survey	Survey ID	Type of echosounder
1991-12	398	SBES
1996-03	2422	SBES
1996-03	2423	SBES
1996-04	2404	SBES
1997-02	2679	SBES
1997-02	2681	SBES
1997-02	2682	SBES
2002-04	8444	SBES
2006-11	13924	MBES
2006-12	13923	MBES
2008-10	14441	MBES
2009-01	14619	MBES
2009-01	14624	MBES
2009-03	14558	MBES
2012-03	16790	MBES
2012-08	16992	MBES
2014-07	18329	MBES
2015-07	18878	MBES

The NLHO processed the raw data and stored the processed minimum depth to save disc space. The data is binned to cell size of 5x3 m and additional information like Total Propagated Uncertainty (TPU), Standard Deviation (SD) and Hits per Bin are used in the processing work flow but are not available for end users (Righolt et al. 2010). Deltares produced a 25x25 m interpolated data set of bathymetric data covering the entire Dutch part of the North Sea and integrated all available surveys. For this study the most recent release from 2017 is used and the data set is published via the Open Earth platform:

Open Earth: http://www.openearth.nl

Deltares data set: http://opendap.deltares.nl/thredds/catalog/opendap/hydrografie/surveys/catalog.html (data set accessed on 2018-03-21)

Documentation and additional information is available on the Deltares webpage:

https://publicwiki.deltares.nl/display/OET/Dataset+documentation+bathymetry+NLHO

All depths are calculated to Lowest Astronomical Tide (LAT), the lowest tide level which can be predicted to occur under average meteorological conditions and under any combination of astronomical conditions. The spatial reference system of the Deltares data set is WGS84 UTM zone 31N EPSG code 32631. For the use in this study the data has been transformed into ETRS89 UTM zone 31N EPSG code 25831 within the ESRI ArcDesktop software suite using standard transformation tools (no shift is applied). The data set is diverted into multiple tiles that can be downloaded separately. For easier handling a single grid file was produced by merging latest data from multiple tiles.

For overview graphics in this study another data access was used:

https://inspire.caris.nl

This data set has a low resolution and was only used for background bathymetry display of the Dutch shelf.

A bathymetric map (Figure 2) produced from the latest NLHO surveys shows the most recent seafloor morphology in the investigation area and the vicinity.

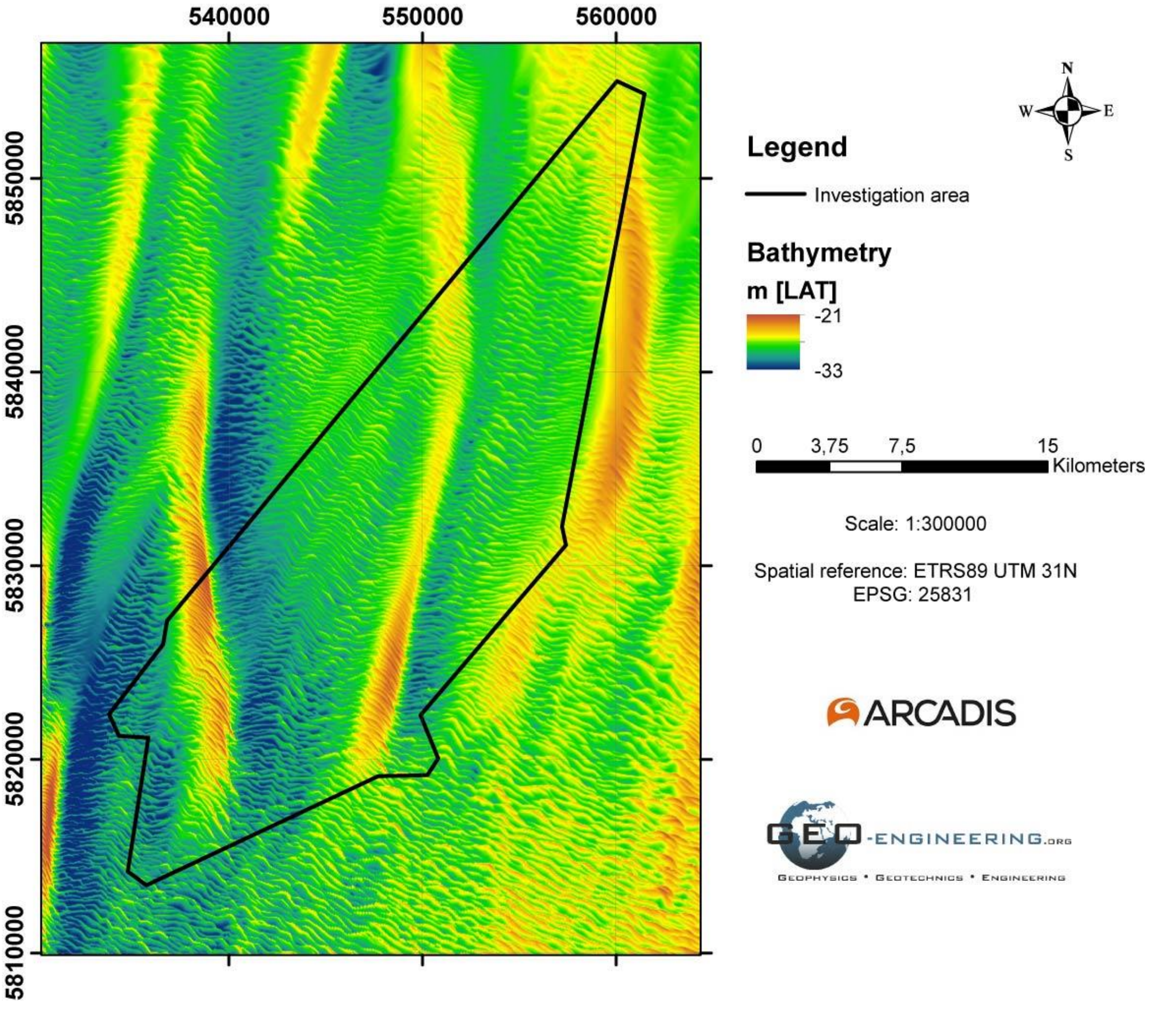

Figure 2. Most recent bathymetry of the investigation area

2.1.3 Assessment of data

The bathymetric data has no data gaps for the entire area of the Hollandse Kust (west) Wind Farm Zone. Most of the latest data within the investigation area was recorded in 2014 and 2015. The bathymetry from today is therefore similar to the morphology in Figure 2.

The water depth varies between 21 and 33 m (LAT). The morphology will be addressed in more detail in a separate study which is why only a brief description is provided in this report. Remarkable are the sand banks striking N-S with an elevation change of up to 10 m from top to bottom. These banks are approximately 10-30 km long, 1-3 km wide and around 4-8 km apart from each other. Further noticeable are the smaller scale sand waves that create a relief with up to 5 m in height difference from crest to surrounding lows. They are between several hundreds to ~3 km long and oriented in a NW-SE direction, more or less perpendicular to the sand banks.

A detailed comparison of all available bathymetric data can be used to analyse sediment movement over time but investigation of time series data is outside the scope of this study.

2.2 CPT Data

No Cone Penetration Test data (CPT) is available for the Hollandse Kust (west) Wind Farm Zone on the web portal of TNO, the Geological Survey of the Netherlands:

https://www.dinoloket.nl/

Proprietary CPT data may exist but investigation of such data is outside the scope of this study.

2.3 Borehole data

2.3.1 General information

Shallow core and borehole data can be accessed through the web portal of TNO, the Geological Survey of the Netherlands:

https://www.dinoloket.nl/

(Data accessed on 2018-03-19)

The database hosts logging information, locations, photos, and chemical as well as sedimentary analyses which can be publicly accessed and downloaded.

Deep borehole information can be accessed via the NLOG data portal:

http://www.nlog.nl/

The database hosts logging information and locations and is free and publicly accessible.

The selected boreholes used in this study are listed in the Appendix 4.

2.3.2 Available data

Shallow cores, grab samples and boreholes

A total of 673 shallow boreholes and cores were extracted from the DINOloket database for analyses. These include 197 within the investigation area and 476 within the vicinity (Figure 3). 36 are surface grab samples with sample depth of 10-15 cm. The metadata to most of these samples, cores and boreholes is missing the water depth at the time of investigation. The core description is mostly very brief or non-existent.

Information on grab samples within DINOloket is limited. The seabed sediment map (Figure 16) by Cameron et al. 1984b is the best source for shallow sediment properties.

Deep boreholes

Within the investigation area 4 deep boreholes give insights into the deep subsurface. For completeness 1 additional borehole has been selected from the vicinity.

Neighbouring wind farm zones

The neighbouring wind farms HKZWFZ and HKNWFZ are about 20 km away from the Hollandse Kust (west) Wind Farm Zone and have been studied already. Some borehole descriptions and stratigraphic information on the shallow subsurface from the other wind farm zones were used to support the interpretation of the core and borehole data for Hollandse Kust (west) Wind Farm Zone.

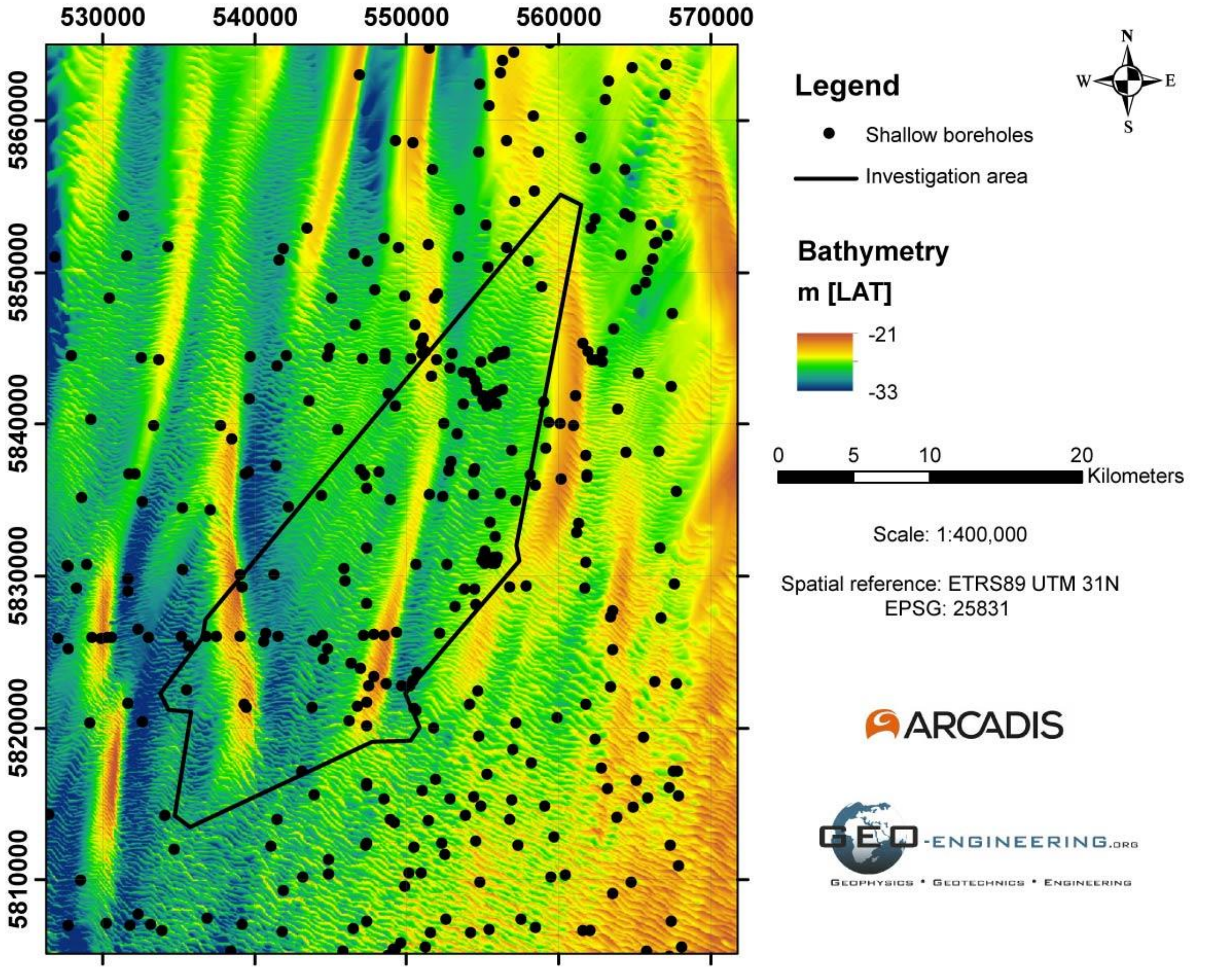

Figure 3. Locations of all available shallow cores and boreholes at DINOloket.

2.3.3 Assessment of data

Shallow cores and boreholes

Most of the shallow cores and boreholes lack necessary information and have only very limited seafloor penetration depth of less than 10 mbsf. The logs of grab samples and shallow cores mostly state very brief information about the sediment, i.e. sand. 63 cores and samples have only been analysed for grain size distribution, which could be useful to calibrate an Acoustic Ground Discrimination System.

For the purpose of this study the first 100 mbsf are of interest. Only 6 cores and boreholes lie within the Hollandse Kust (west) Wind Farm Zone and have a sufficient sample depth and useful metadata. These were selected for further analyses.

Additional 6 shallow cores and boreholes were selected for analyses due to their adequate core description and metadata even though their location lies outside the investigation area (see Figure 4).

The seafloor penetration depth varies between 10 – 100.3 mbsf and the majority of the cores consist of fine to medium sand with a grain size median between 150 and 350 µm. These sandy deposits are in parts highly calcareous and include shell fragments. Occasionally the sand is interbedded by marine clay or loam with a thickness of several centimetres to metres.

Some restrictions apply for the use of such data as the metadata of the shallow cores do not include information about the water depth at the time of measurement. Because of the high mobility of the seabed the water depth most likely differs from the present-day bathymetry. Thus, connecting lithologies between cores bears additional uncertainties.

Another source of errors are the core descriptions by different geologists with variant terminology and interpretations regarding the identification of lithologies and stratigraphy. As stratigraphic information is rare in most core descriptions a deeper borehole (125 m, B19C0033) at the coast with complete stratigraphy is used for connecting and identifying stratigraphic units in other cores.

The resolution of the data description also varies between centimetre- to metre-scale, depending on the purpose of sampling, and further enhances the difficulty to compare samples.

Deep boreholes

4 deep boreholes have been selected for analyses of which 3 lie within the investigation area and 1 in the vicinity. The total penetration depth of these deep drill sites reaches down to 4200 mbsf. An advantage to the DINOloket data is that the seafloor depth at the time of drilling is stored in the metadata which makes the use of the data easier for embedding information into a geological cross section. The disadvantage is a lower resolution of lithological descriptions and no stratigraphy is available.

The cores mainly consist of fine to coarse sand interbedded with clay and calcareous layers including shell fragments. Peat and fibrous layers are also located in the first 100 m of the boreholes. The quality of the cores differs, depending on the drilling and sampling methods used and the numbers of samples taken in the shallow section (up to 100 mbsf). Some of the lithologies are only inferred from offset wells and gamma ray measurements.

Regarding the reliability of logging information it is necessary to point out that the borehole data needs to be handled with caution.

Seafloor depth of boreholes is provided in NAP and was transformed to LAT. The differences between NAP an LAT was calculated with the software PC Trans (Version 5). This Software is provided by the Dutch Ministry of Defences and is free available on www.defensie.nl.

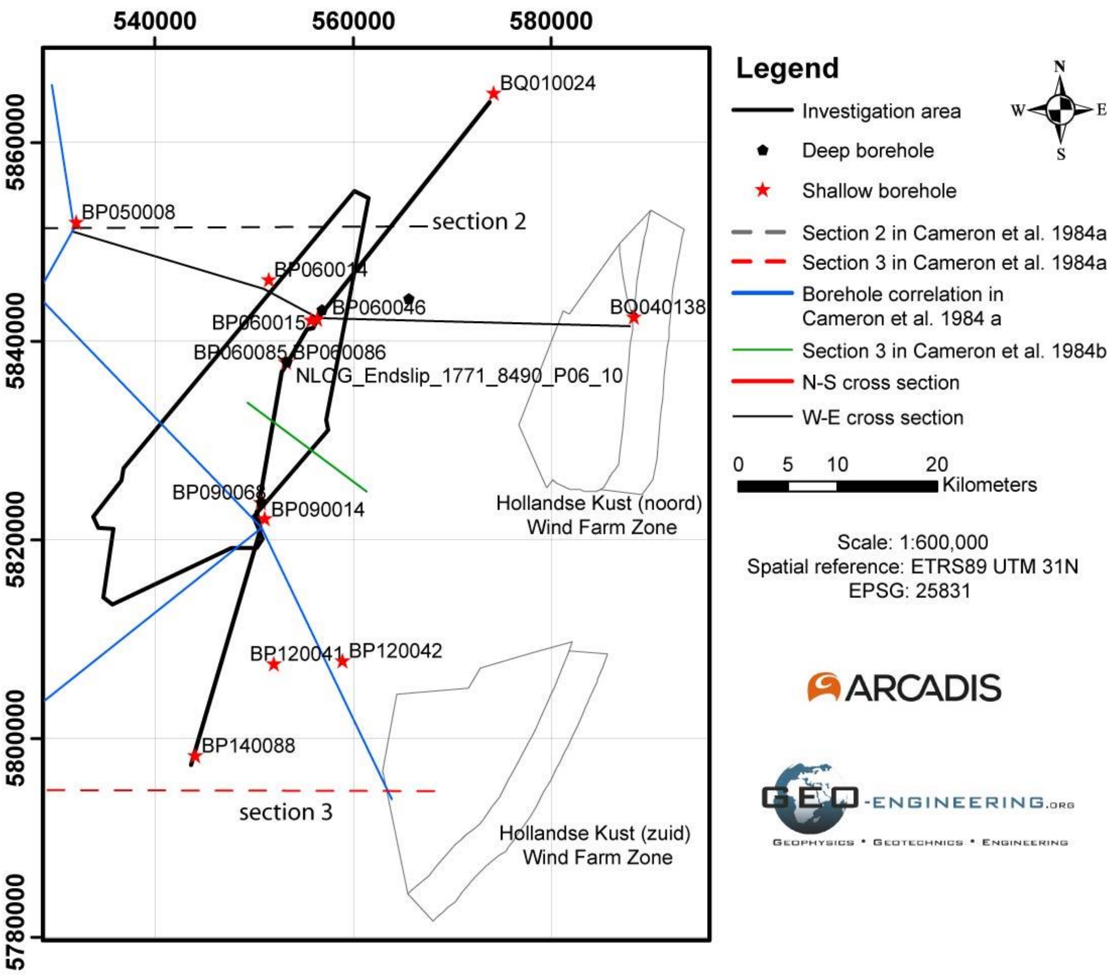

Figure 4. All locations of borehole data used for analyses in this study with the position of cross sections used to develop the geological model.

2.4 Seismic data

2.4.1 General information

Digital and analogue seismic data are publicly available on the NLOG web portal:

http://www.nlog.nl/ (accessed on 2018-03-26)

This portal contains a large amount of information about several seismic surveys from the last decades. The data sets include analogue and digital 2D seismic profiles and 3D seismic data. However, only a limited amount of data is publicly available without extra charge.

2.4.2 Available data

For this study, only publicly available and online accessible data was analysed. In the area of the Hollandse Kust (west) Wind Farm Zone three different types of seismic data exist. 3D seismic data can be purchased at NLOG data portal for a certain fee. 2D seismic data is available as analogue and digital data sets. For this report, the difference between analogue and digital seismic data is defined by the availability at the NLOG database. Analogue data is not stored as digital data sets in the online data base whereas digital seismic data is stored in the NLOG data base as digital data sets (SEG-Y).

The analogue seismic data has the best coverage for the area of investigation which is shown in Figure 5. In total 40 analogue seismic surveys cover the area of interest. However, for 29 surveys only the navigational data are available online. For the remaining 11 surveys signal documents (e.g. tiff-files) from selected survey lines are available. 15 analogue seismic surveys are specified as multi-channel seismic data. For 25 surveys, no information are available whether it is multi-channel or single-channel seismic. The seismic data can be purchased at NLOG data portal for a certain fee.

Five digital seismic surveys are covering the area of HKWWFZ (Figure 6). However, only three of them are available free of charge as can be seen in Table 2.

For this study only digital 2D seismic data from three multi-channel seismic surveys are analysed. Velocity data are not available for any of these surveys. Further details to the seismic survey lines are given in Table 2 and the coverage is shown in Figure 7.

Additional data from reconnaissance surveys used to develop geological maps of the Dutch continental shelf (Cameron et al. 1984a, b) do exist but are not available yet. The coverage of this data set is shown in Cameron et al. 1984a, b.

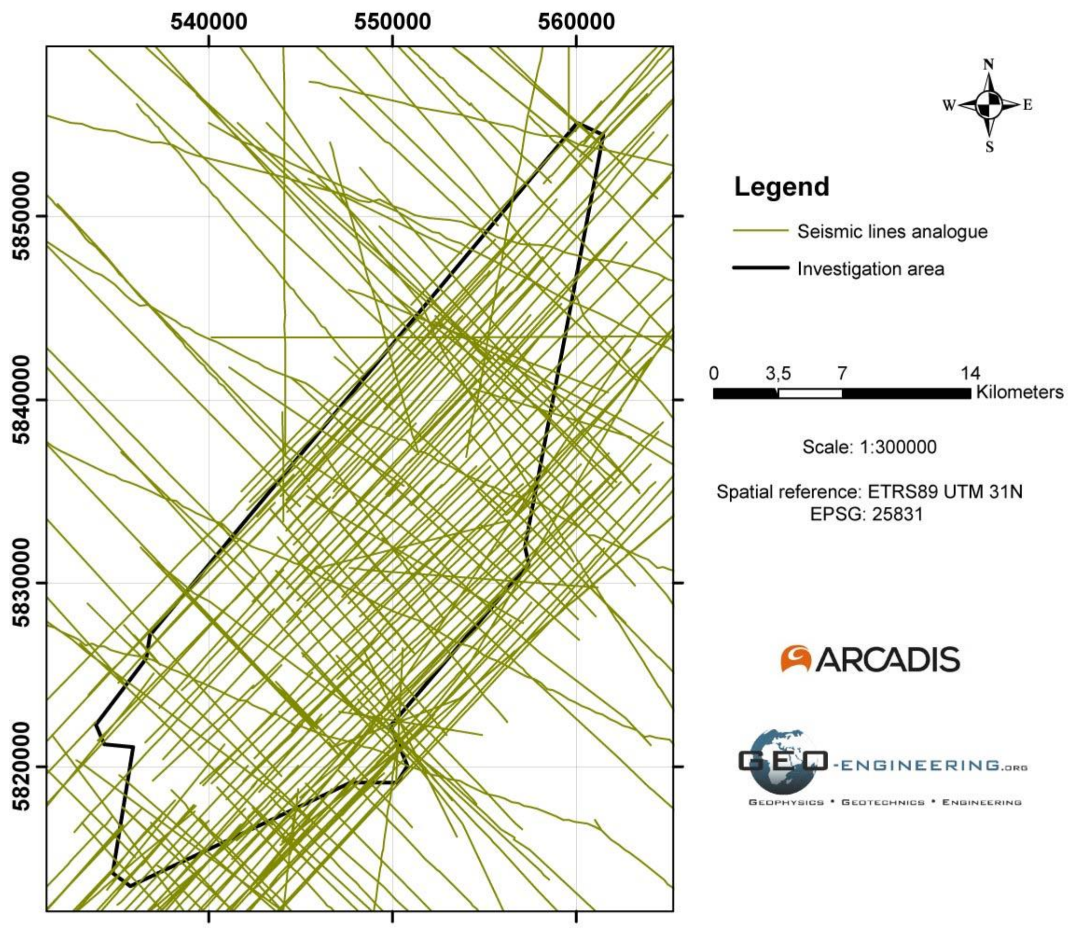

Figure 5. Lines of analogue 2D seismic surveys across the investigation area.

Table 2. Available digital 2D seismic survey data in the investigation area.

Survey	No. of lines within investigation area	Year of survey	Source	Number of channels	Suitable for depth 0-100 m?	Availability
Z2NOP1987A	1	1987	Airgun	n/a	No	Fee applies
Z2PEN1983A	1	1983	Watergun array	132	No	Free of charge
Z2MOB1979B	3	1979	Airgun array	96	No	Free of charge
Z2MOB1980A	3	1980	Airgun array	96	No	Free of charge
Z2UNI1980D	34	1980	Airgun	96	No	Fee applies

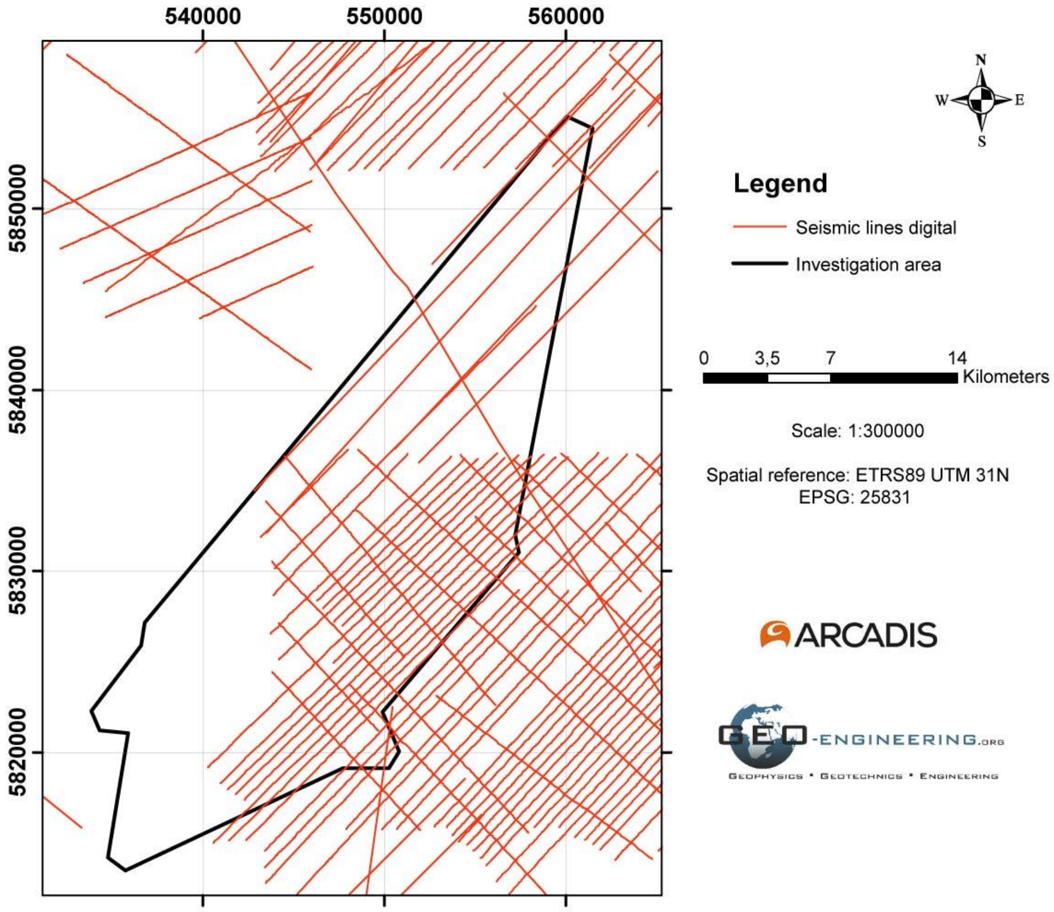

Figure 6. Lines of digital 2D seismic surveys across the investigation area and in the vicinity. See Table 2 for information to the individual seismic survey.

2.4.3 Assessment of data

The 2D seismic data in this area was acquired for the oil and gas industry. It is assumed that the focus for such survey lies on the deep subsurface to find reservoir features which is why this data is not applicable to analyse the shallow subsurface for an offshore wind farm.

For this study only digital seismic data from three multi-channel seismic surveys are analysed. The line spacing of the digital surveys varies between approx. 0.5 km and 2.5 km. The survey lines are mainly NE-SW or NW-SE oriented and are available as migrated data.

All available digital seismic data were performed for deep exploration with high penetration depth (hundreds of metres to kilometres) but with a low vertical resolution. Therefore, the data are suitable to analyse large geological units but lack the small structures and heterogeneities which are not visible in the data. Due to the low resolution, these surveys are not useful for most interpretations of the first 100 m of subsoil which is the vertical section of interest regarding the planning of offshore wind farms. Possible use for these surveys are an initial mapping of gross features (e.g. glacial valleys) within the top 100 mbsf and the identification of potential gas seeps, the latter was not the case in the analysed profiles.

A re-processing of the data could be done to improve the imaging of certain geological layers. However, the surveys were designed for identification of large-scale geological features and not for site surveys for offshore wind farms which is why a re-processing is not recommended.

The analogue data cannot be assessed within the scope of this study but the purpose of these surveys was not connected to wind farm installations. Therefore, a costly purchase and time-consuming assessment of the analogue data is not recommended.

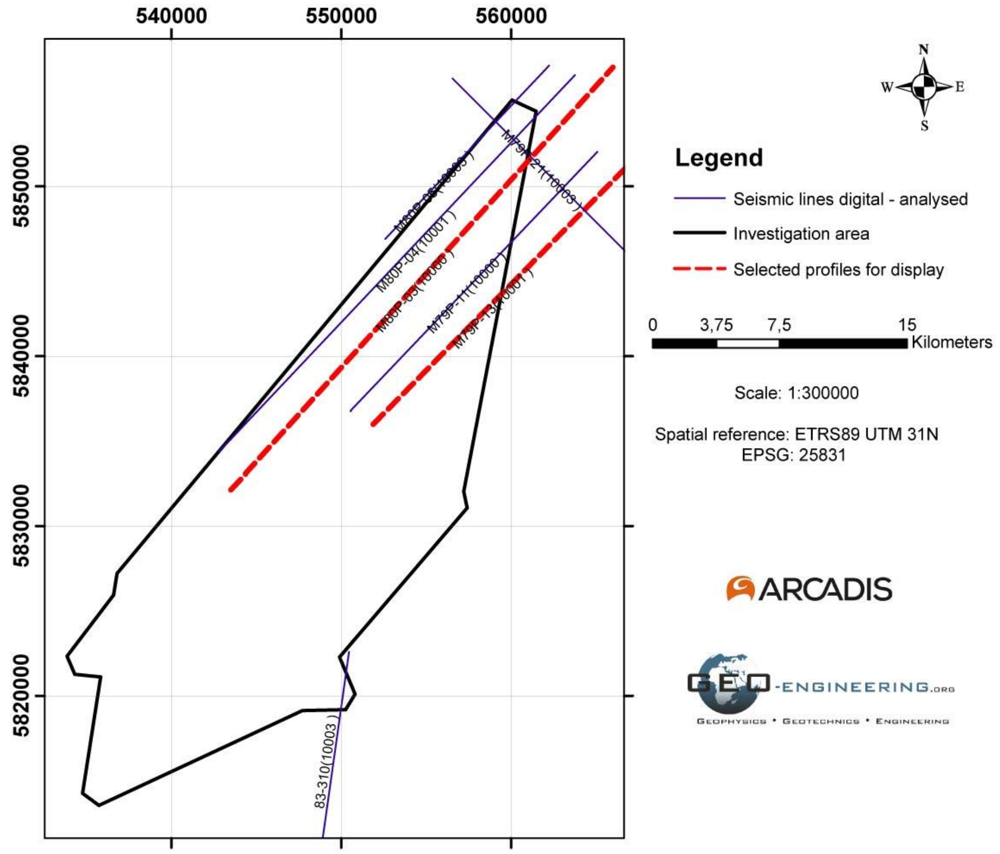

Figure 7. Digital seismic survey lines analysed in this study together with selected profiles for display in Figure 8 and Figure 9.

The following interpretation of seismic profiles reflects the author’s opinion solely.

Figure 8 and Figure 9 show seismic profiles (Line 921156_M80-P-03 and Line 919279_M79P-13) of the digital multi-channel seismic data from the northern part of the investigation area. The assumed velocity to estimate depth from time data is 1600 m/s.

These profiles show subsurface formations down to 1600 mbsl as the penetration is high but the vertical resolution low. Both profiles show similar structures. The lowest layer package from 1600 to ~900 mbsl is dominated by folded reflectors with several faults (black lines) and blurred sections. Tectonic stress caused this architecture and the blurred sections could indicate trapped gas.

An unconformity at around 900 mbsl (purple line) marks the beginning of the next section which shows horizontal layering up to ~700 mbsl.

The next layer package is defined from ~700 -400 mbsl with large scale oblique layering (pink lines). This structure is characteristic of deltaic foresets (regression and transgression cycles).

From 400 – 100 mbsl horizontal layering can be observed but the upper reflectors of this section are very weak and hard to follow.

The upper 100 m show strong horizontal reflectors, but the available data do not allow a detailed interpretation. However, the upper green line in Figure 8 and Figure 9 might represent the boundary of the Yarmouth Roads to the Winterton Shoal Formation at around 100 mbsf. In Figure 9, between shot point 75 to 200, a change in seismic character indicates a wide channel which might represent the glacial valley to the east of the investigation area.

In general, the change in impedance causing a reflector indicates a change in lithology but due to the low vertical resolution it is not possible to determine the top and bottom of each formation. A stratigraphic interpretation for the first 100 m is therefore discarded.

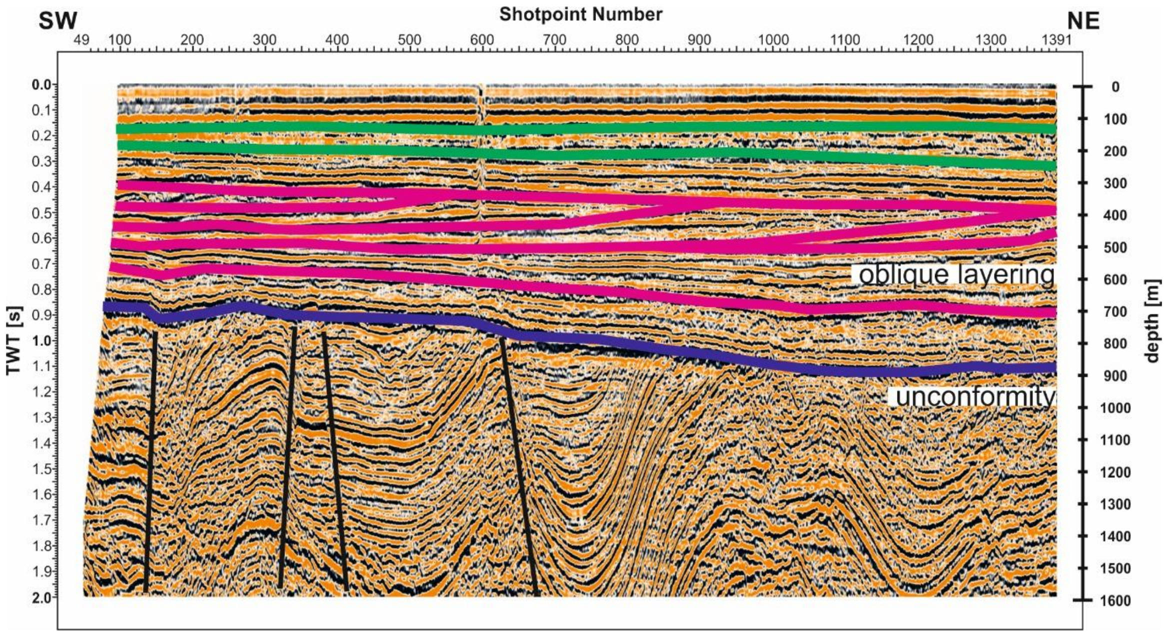

Figure 8. Example of multi-channel geophysical sections in the investigation area. (Line 921156_M80-P-03)

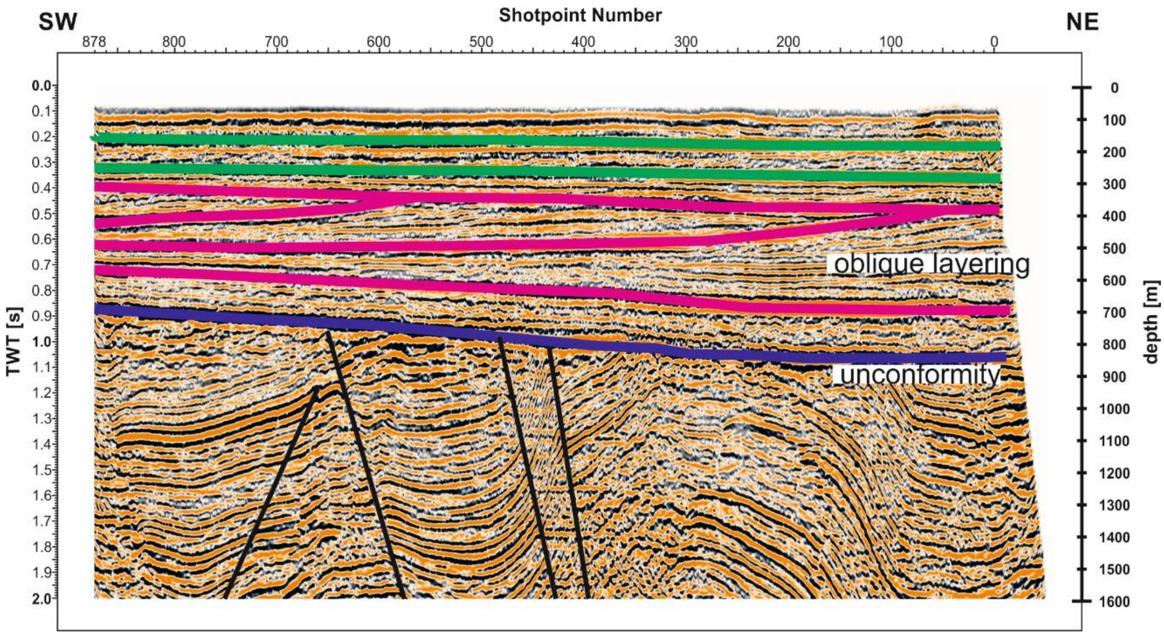

Figure 9. Example of multi-channel geophysical sections in the investigation area. (Line 919279_M79P-13).

2.5 Earthquake data

2.5.1 General information

Earthquakes are classified as geohazards and therefore addressed in this study. Several portals in the internet provide earthquake information. For the Netherlands the KMNI, the Koninklijk Nederlands Meteorologisch Instituut, provides such data. However, in the time of writing and researching for this study, the data portal of KMNI was malfunctioning which is why the data portal IRIS from the Incorporated Research Institutions for Seismology was used.

http://rdsa.knmi.nl/dataportal/

https://www.iris.edu/hq/

2.5.2 Available information

On the IRIS database all available information about seismicity along the western Dutch coast has been downloaded.

In total 30 events have been recorded in the time between 1975 and 2018 with a magnitude between 2 and 4 (Figure 10).

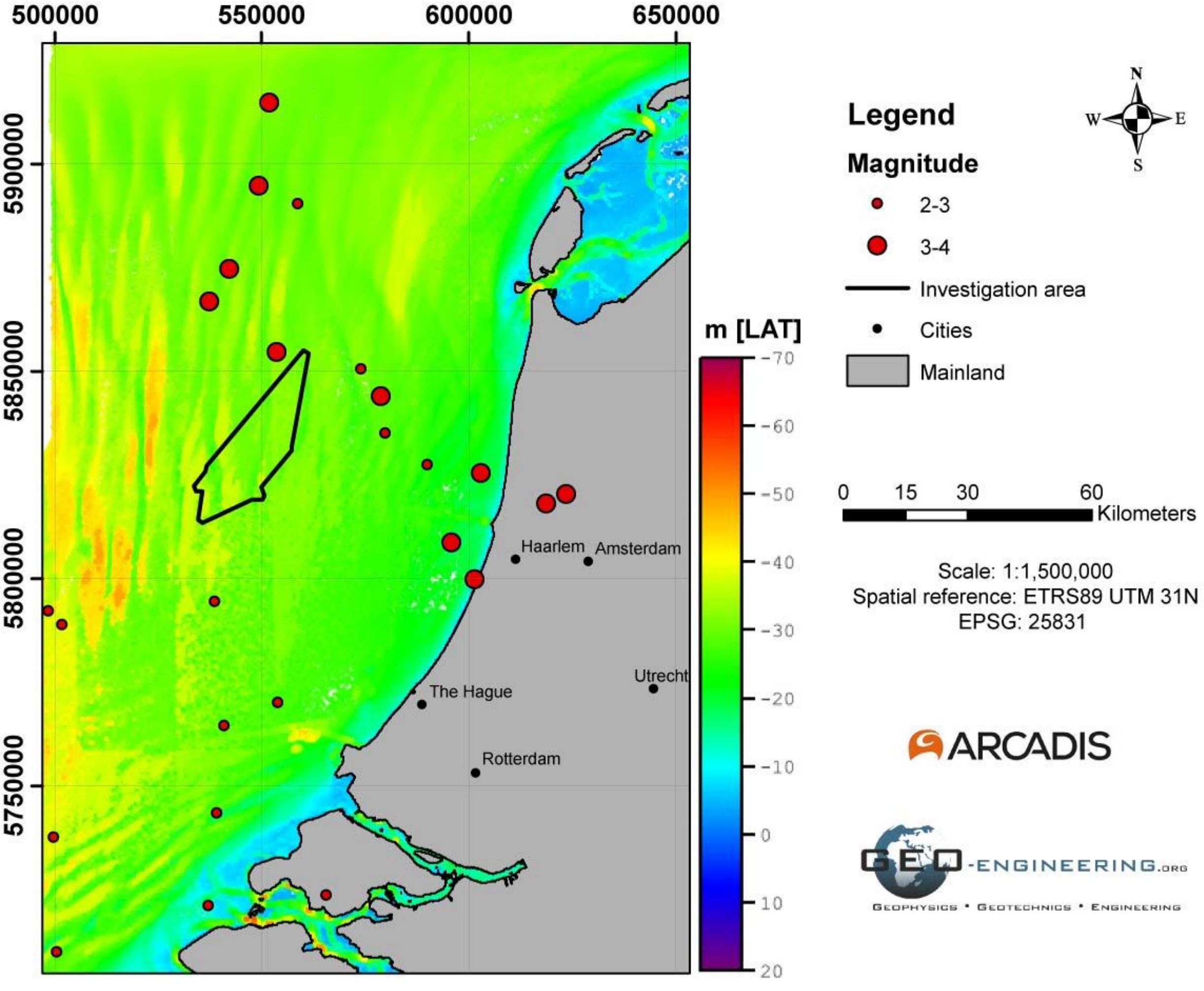

Figure 10. Epi centres for all recorded earth quakes from 1975 - 2018 extracted from IRIS database.

2.5.3 Assessment of data

The IRIS database lists all recorded earthquake events and the published data has been reviewed by the recording authorities.

The Figure 10 shows no historical events within the investigation area but in the vicinity. The magnitude has always been below 4.

An alignment of quakes striking NW-SE from Amsterdam into the offshore sector is obvious and might be correlated to the subsurface gas extraction. This topic will be further discussed in chapter Geohazard5.6.

3 LITERATURE REVIEW

In the following a geological overview will be developed from peer-reviewed articles, reports, and maps as well as core and borehole data from the DINOloket-database. Since most of the borehole data does not exceed 10 m and seismic resolution is reduced with increasing depth, the level of knowledge and detail progressively diminishes with depth. For the development of an offshore wind farm the most relevant section are the uppermost 100 mbsf which consists of Pleistocene and Holocene deposits. The literature overview will be subdivided into three sections:

- Geotechnical prerequisites
- Glaciation and Pleistocene geomorphological development
- Holocene transgression

3.1 Geotechnical prerequisites

Pleistocene deposits of the southern North Sea often show a high grade of over consolidation and a high bulk density (Lesny et al., 2002). Non-cohesive Pleistocene sediments typically show good bearing capacities and are usually suitable as building ground for offshore pile foundations (Lesny et al., 2002). Within Pleistocene valleys the sediments are often very heterogeneous with varying thicknesses. Typical glacial valley sediments are sands but also clays, silts and organic material within mudflat sediments and peats, as well as varved clays and silts. The valley slope may be very steep which often puts dense sands with good bearing capacities next to heterogeneous cohesive material of large thicknesses. Glacial valleys are a main target for geophysical site investigations for offshore wind farms. They should be localised precisely to reduce risks and will be in focus for this overview as well. Appendix 3 shows the typical geotechnical parameters from the soil units found in HKZWFZ in the southeast of the investigation area together with a table (Appendix 2) that connects the soil units with the formation names.

3.2 Glaciation and Pleistocene geomorphological development

During the Pleistocene the North Sea basin has been reorganized repeatedly due to sequences of glaciation and deglaciation. During glacial periods sea level was low while in interglacial periods sea level could reach levels similar to the present-day level. During the early Middle Pleistocene between 1 and 0.5 Ma the Dover Strait was closed and England was connected to the European continent via a chalk land bridge (Hijma et al., 2012). Several river systems as Thames, Rhine, Meuse and the Baltic River System provided sediment to the Southern North Sea. Sediments from these river systems can be found in the investigation area from depth between 5 mbsf and 30 LAT and have their base well below 100 mbsf. These sediments consist in the upper 60-70 mbsf of fine to medium sand with occasionally clay laminae or reworked peat (Yarmouth Roads Formation) (Forzoni et al., 2017). At high sea level the river outlet characteristics were estuarine/deltaic whereas during low sea level the river outlet characteristics were deltaic. Figure 11 shows an interglacial highstand situation during the early Middle Pleistocene as repeatedly occurred. On average the sea level was ~50 m lower than present (Cameron et al. 1993).

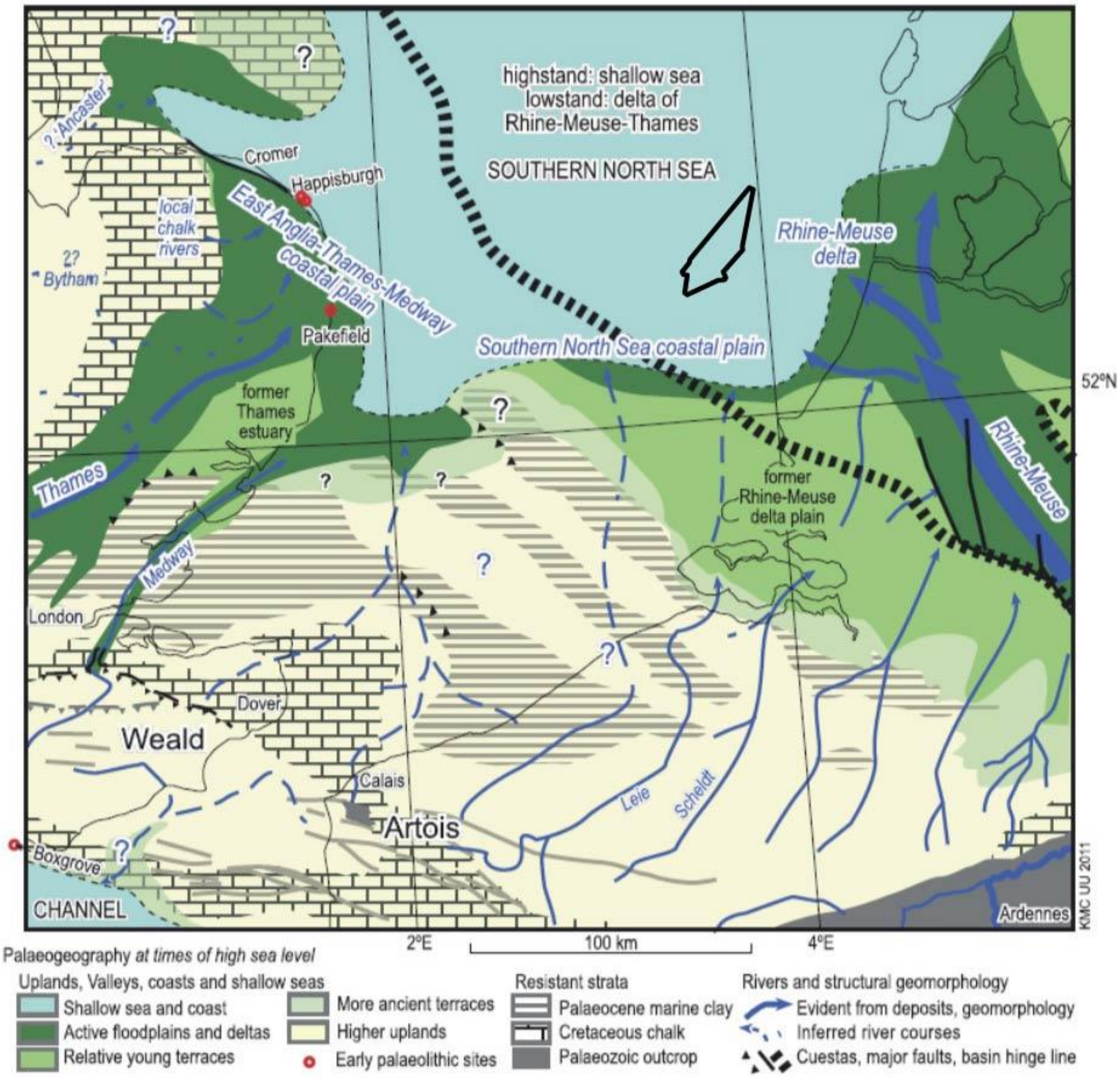

Figure 11. An interglacial high stand situation during the early Middle Pleistocene as repeatedly occurring between 1 and 0.5 Ma. (Hijma et al., 2011). Approximate location of HKWWFZ in black.

Between 500 ka and 140 ka the landscape of the investigation area and around have been influenced heavily by extensive glaciation. Table 3 shows the nomenclature of glacial and interglacial phases. During Elsterian glaciation the first of three wide spread invasions of ice across the North Sea basin took place.

Table 3: Glacial-interglacial phases nomenclature in the North Sea region

	Netherlands	Britain
Glacial	Weichselian	Devensian
Interglacial	Eemian	Ipswichian
Glacial	Saalian	Wolstonian
Interglacial	Holsteinian	Hoxnian
Glacial	Elsterian	Anglian

The ice covered most of northern Europe including the eastern North Sea (Ehlers, 1990; Ehlers et al., 1984) but did not reach the investigation area. The ice cover however blocked the northern drainage path of Rhine and Meuse. This forced the river outflow to migrate southwards (Figure 12) resulting in erosion of the chalk bridge and subsequently caused the creation of the Dover Strait (Laban & Van der Meer, 2004 Hijma et al., 2012). Following each of the glaciations sea level rise led to the development of strongly tidal, marine environments similar to those of the present day (Cameron et al., 1993).

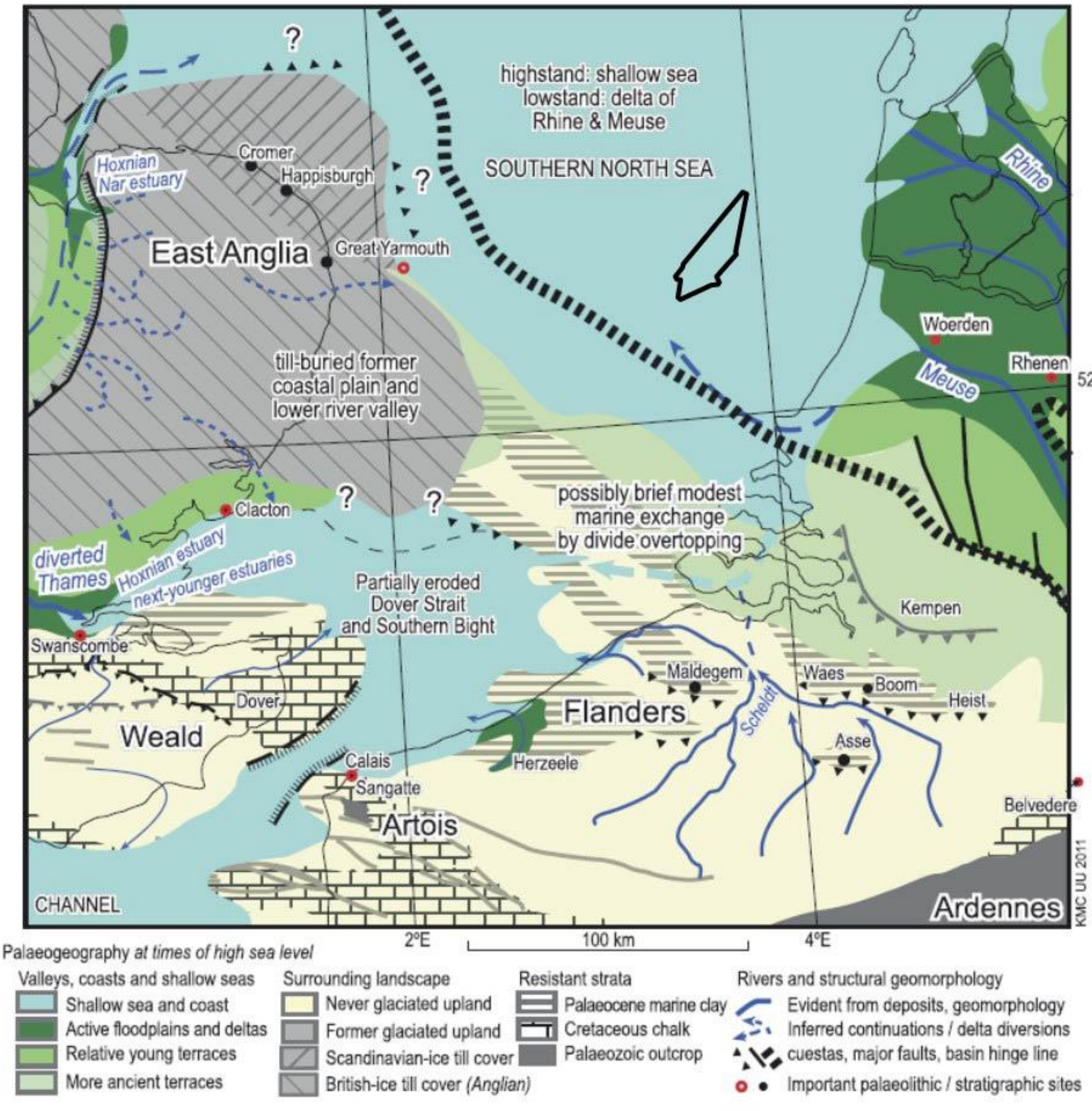

Figure 12. An interglacial high stand situation during late Middle Pleistocene as repeatedly occurring between ~0.4 and 0.13 Ma (i.e. Holsteinian, from Hijma et al., 2011). Approximate location of HKWWFZ in black.

During Saalian glaciation the northern part of the investigation area was covered by ice (Graham et al., 2011), documented by several ice-pushed ridges, which form a line right in the south east of Hollandse Kust (west) (Peeters et al, 2015). A glacial basin lies right to the east of Hollandse Kust (west) (Figure 13) and is charted by Cameron et al. (1984a) (Figure 18). Proglacial lacustrine clays, outwash sands and wind-blown sands were deposited in a periglacial environment beyond the ice margin further south in the investigation area.

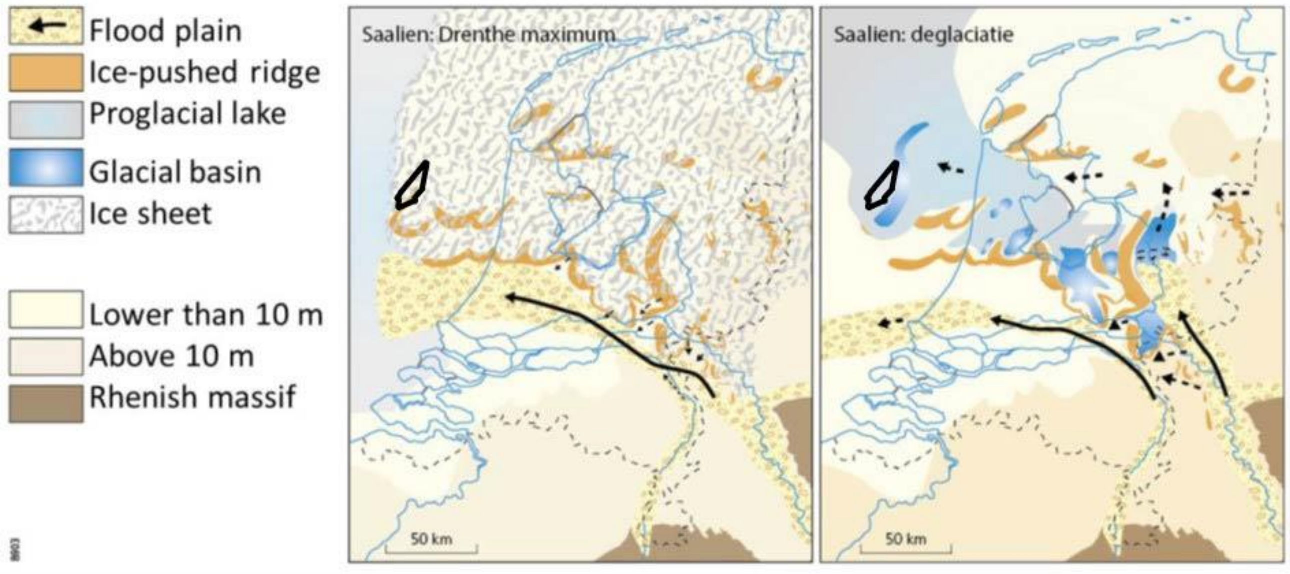

Figure 13. Ice sheet coverage and glacial basins during Saalian. Modified after Stouthamer et al., 2015. Approximate location of HKWWFZ in black.

During the Eemian warm period sea level rose again and the transgression deposited estuarine and shallow marine sediments (Eem Formation) in the investigation area and wider surroundings. In the late Eemian and the Weichselian glaciation the water level dropped about 40m (Cameron et al. 1993). The investigation area became part of the deltaic plain of the Rhine. Much of the Southern Bight was dominated by brackish water lagoonal setting (Cameron et al., 1993). Deltaic sediments with significant amounts of clay and peat are classified as the Brown Bank Member of the Eem Formation. Sandy sediments with fluvial characteristics are classified as part of the Kreftenheye or with more tidal characteristics as Eem Formation. With further drop of the sea level during the Weichselian glaciation the Rhine incised into the deltaic plain and fluvial sediments of the Kreftenheye Formation were deposited. This was followed by deposition of the Boxtel Formation, which includes different types of deposits like sand, sandy loam, peat, thaw-lake deposits and eolian deposits.

3.3 Holocene transgression

The seabed sediment map from Cameron et al. 1984b is the most valuable source for information about the Holocene sediments within and around the investigation area. During the late Weichselian glaciation into the early Holocene the investigation area prevailed in a terrestrial periglacial environment. Under influence of rising ground water as a result of the sea level rise peat beds developed and may be preserved in the investigation area as the Nieuwkoop Formation. With continuous sea level rise, tidal flat sedimentation extended over the area between 8000 and 7000 BP. Within the investigation area, sediments from this period belong to the Elbow Formation which is nowadays classified as a part of the Naaldwijk Formation (Figure 15). Those sediments consist of fine sands interbedded with clay. Within the tidal flat sediments shallow tidal channels, possibly filled with cohesive sediments, can occur (Figure 14). During continued sea level rise, sandy deposits were shaped into sand banks and sand waves (Van Dijk and Kleinhans, 2005) which are part of the Southern Bight Formation. The Southern Bight Formation and its Bligh Bank Member is expected to cover the whole investigation area.

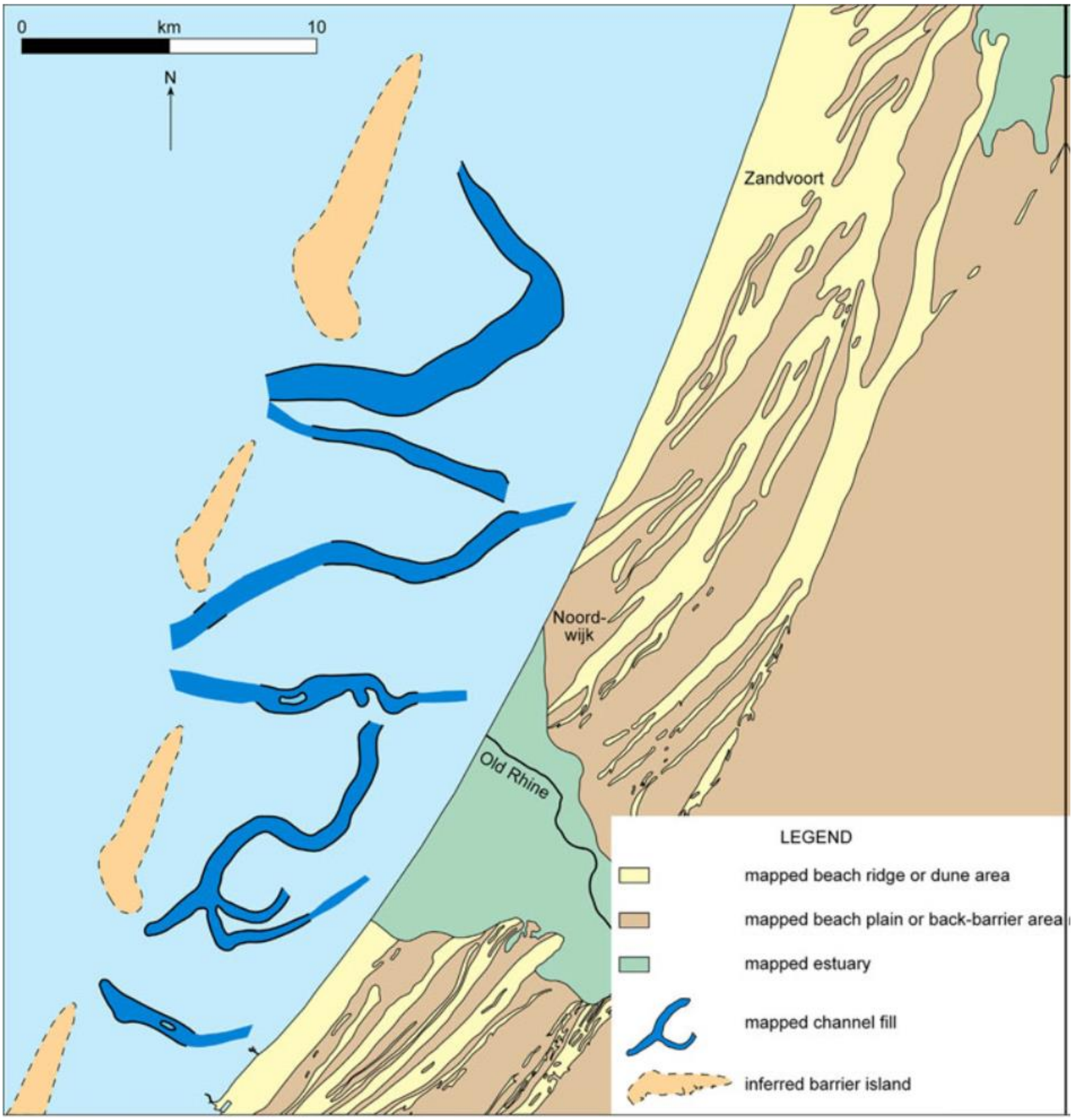

Figure 14. Inference of possible position of former barrier islands offshore from the western Netherland using information on the positions and extents of tidal-channel fills. (van Heteren et al., 2014)

4 STRATIGRAPHY

4.1 General information

This chapter focuses on the Holocene and Pleistocene stratigraphy. No older sediments are expected to be part of the first 100 m below sea floor (see Figure 17 for the base of Pleistocene).

The stratigraphic framework in the following is based on borehole logs from DINOloket, the scientific work of Rijsdijk et al. (2005), geological maps from 1984 by the British Geological Survey (BGS) and the Netherlands Geological Survey (Cameron et al., 1984a + b) as well as recent studies done by Deltares (de Bruijn et al., 2015; Forzoni et al., 2017) and FUGRO ENGINEERS B.V (2016) for the Wind Farm Site II Hollandse Kust (zuid) in the south of the investigation area.

We follow the stratigraphic framework of Rijswijk et al. (2005) with a few exceptions: for the older Pleistocene formations the older names Yarmouth Roads Formation and Winterton Shoal Formation are used. The Yarmouth Roads Formation is considered as the offshore equivalent of the Sterksel Formation. The Winterton Shoal Formation is considered as the offshore equivalent of the Waalre Formation and Peize Formation.

Without detailed palynological analysis, the stratigraphic interpretation of boreholes of the investigation area remains an approximation. This is underlined by the fact that at the same area similar depositional environments repeatedly occurred over time and created similar lithologies. Therefore, a correlation of onshore borehole stratigraphy with offshore borehole logs is difficult and needs to be handled with caution. For example, the distinction of the fluvial formations of the Middle to Late Pleistocene and the underlying Early Pleistocene Yarmouth Roads Formation is difficult (FUGRO ENGINEERS B.V., 2016; Bosch et al., 2003; Busschers and Weerts, 2003).

Maps showing the distribution and thickness of single geological formations throughout the investigation area are not provided within this study. This is due to the lack of detailed information necessary to produce reliable maps. The authors like to point out that such maps would be rather misleading than beneficial to the following work in HKZWFZ.

4.2 Expected formations

Within the investigation area the following formations are expected and shown in Table 4 and Table 5:

Southern Bight Formation – Blight Bank Member (Holocene)

This is the upper sand unit that covers the entire investigation area. Its thickness varies south of the investigation area (at HKZWFZ) between 2 m and 6 m. Within the investigation area of Hollandse Kust (west) the thickness at sand banks may be up to 10 m. The material is medium- or fine-to medium grained, clean yellow-brown sand with local mud laminae. Gravel contents of 1-5 % are common towards the base, shell fragments are sparsely present. The sands of the Southern Bight Formation are mostly mobile and deposited in the Holocene marine environment.

This unit does not have a clear seismostratigraphical character and the differentiation with the underlying soil unit is not always possible. The boundary is considered to be an undulating surface semi-parallel to the seafloor (FUGRO ENGINEERS B.V., 2016).

Naaldwijk Formation (Holocene)

Naaldwijk Formation can be 0 to 5 m thick in large parts of the investigation area (Figure 15) where it has been charted by Cameron et al. 1984b as Elbow Formation. It lies discordant with sharp transition on top of the underlying deposits. It consists of fine- or fine grained bluish-grey muddy sands with interbedded clay and was deposited in a brackish marine and tidal-flat environment. Where a basal peat layer exists directly underlying the Naaldwijk Formation it is classified as Nieuwkoop Formation, but this layer is expected to be existent more to the East of the investigation area.

Boxtel Formation (Middle Pleistocene to Holocene)

In the investigation area it is built up by well-sorted, fine grained, wind-blown periglacial sands and is mostly less than 1 m thick which formerly were classified as Twente Formation. Based on the geological map (Cameron et al., 1984a) it is expected in the southeast of the investigation area to directly underlie the Holocene sediments as a patch (see Figure 18) and is described in the borehole BP090014.

The seismic character of the Boxtel Formation within the study area is predominantly homogeneous with locally subparallel reflectors. Mostly it occurs sheet like, but as channel infill prograding reflectors are observed (Laban, 1995).

Kreftenheye Formation (late Weichselian)

It was deposited by Rhine and Meuse rivers as fluviatile fine-to medium-grained sands occasionally with shells and fine to coarse gravel. South of the investigation area (HKZWFZ) the thickness ranges from 6.6 m to 16.2 m. FUGRO ENGINEERS B.V. (2016) also describe a calcareous clay with laminae of sand and with organic matter, peat and wood fragments as part of the Kreftenheye Formation with thicknesses from 5.5 m to 11.7 m. Those are deposited in a fluvial to coastal plain setting and in the area of HKZWFZ locally present as channel infill deposits. In HKWWFZ the Kreftenheye Formation is not described explicitly but it may be present nonetheless and is therefore mentioned.

This unit can be seismostratigraphicaly differentiated into two units within HKZWFZ defined by a change in seismic character. The base of the upper unit represents an erosional boundary (FUGRO ENGINEERS B.V., 2016).

Eem Formation – Brown Bank Member (late Eemian to early Weichselian)

These sediments are described as partly consolidated grey brown silty clays and fine sands that occur in patches with thicknesses of 2 to 6 m. The sediments are extensively bioturbated and locally cryoturbated. The Brown Bank Member is deposited in a lagoon-delta plain brackish environment. Fluviatile current-bedded silts and finely laminate clays can fill late Eemian or early Weichselian channels up to 20m deep.

Brown Bank Formation often shows parallel seismic lamination (Laban, 1995).

Eem Formation (Eemian)

In a coastal environment the Eem Formation was deposited as medium coarse sands, silt and silty sands with around 5 % shells and locally 1 – 5 % of gravel. Eemian sediments are expected to underlie the Holocene directly in large parts of the investigation area.

The seismic character is described in FUGRO ENGINEERS B.V. (2016) as unit C2 and may be predominantly chaotic, locally showing inclined reflectors. The inclined reflectors have slope angles of less than 5°. The base is considered to be represented by very high amplitude seismic reflections. Channelling is locally observed at the base.

Egmond Ground Formation (Holsteinian)

This formation consists of shelly fine sands with locally present peat deposited in a fluvio-deltaic environment. It can be up to 10 m thick.

Yarmouth Roads Formation (Waalian to early Elsterian)

The manly fluviatile sediments of Yarmouth Roads Formation attain a maximum thickness of up to c. 200 m in the Southern Bight of the North Sea. It consists of fine- or medium-grained non-calcareous sands with variable clay lamination. There are local intercalations of reworked peat. In HKZWFZ the unit is of high special variability with alternating sands (with clay laminae) and clays (with sand laminae). The units may also be disturbed by ice-pushing during Saalian glaciation.

The seismic character of the Yarmouth Roads Formation is difficult to differentiate from the one of the Eem Formation and the Egmond Ground Formation, especially if the clear high amplitude seismic reflector, which marks the base for the overlaying unit, is missing (FUGRO ENGINEERS B.V. (2016). Generally it is characterized by chaotic reflector configuration (British Geological Survey).

Winterton Shoal Formation (Eburonian to Waalian)

The Winterton Shoal Formation is difficult to differentiate from the YRF in boreholes but are seismostratigraphic distinguished. The sediments are fine- or medium-grained sands with minor clay intercalations of fluvio-deltaic origin. The Winterton Shoal Formation is expected to be present below 100 and 200 mbsf in the investigation area. Winterton Shoal Formation is mainly structureless in seismic profiles, but in some sections gently dipping reflectors prograde westwards onto erosional base (British Geological Survey).

The Drente Formation and the Drachten Formation are not expected to be present within the investigation area.

4.3 Geological model

A geological model has been developed from the sources mentioned in chapter 4.1. Figure 18 displays the Holocene subcrop map according to the geological map (Cameron et al., 1984a). With the geotechnical investigation of Hollandse Kust (zuid) there is a recent study near the investigation area, but for the investigation area itself the data from this geological map is considered as best data base. The applicability of the HKZWFZ geological model is limited due to the differences in glacial influences between HKWWFZ and HKZWFZ.

The Eem Formation and the Brown Bank Member are the most prominent Pleistocene sediments directly underlying the Holocene sediments. With a significant amount of clay content and a known unit for channel infill, those units are also geotechnically relevant. As a patch the Boxtel Formation is present in the southeast of the investigation area. The borehole BP090014 gives a local stratigraphic insight. Apart from that the Yarmouth Roads Formation crops out underneath the Holocene sediments in the north of the investigation area. In the east, the border of the investigation area directly follows the border of a charted glacial valley. This valley may be filled with cohesive sediments and/or peat and may be represented by the deep boreholes P09-01 and P06-02. The deep borehole P09-09 (Appendix 7) shows in the upper 50 m firm grey clay followed by 3 m of fibrous organic material. This also may represent valley infill material which indicates an extension of the charted valley towards the south. The borders of this valley may not be as sharp as seen in the chart and should be investigated closely within the geophysical survey. Also, the depth of the valley is not clear. In the investigation area the Kreftenheye Formation is not expected to play a major role as it certainly does in the southeast of the area (namely at HKZWFZ). This is in line with the geological map (Cameron et al., 1984a) as it indicates Kreftenheye Formation directly underlying the Holocene sediments in the southeast of its coverage. The geological model for HKWWFZ is presented in two profiles shown in Figure 19 (SW-NE) and Figure 20 (W-E).

Table 4. Stratigraphic table for the expected geological units within the survey area and in the closer surroundings. Colours represent the corresponding geological formations for the geological model of this study.

Formation	Member	Age	Epoch
Southern Bight	Bligh Bank	Holocene	Holocene
Naaldwijk		Holocene	
Boxtel			Middle/Late Pleistocene to Holocene
Kreftenheye		Late Weichselian	Late Pleistocene
Eem	Brown Bank	Late Eemian to early Weichselian	
Eem		Eemian	
Egmond Ground		Holsteinian	Middle Pleistocene
Yarmouth Roads		Waalian to Elsterian	Early to Middle Pleistocene
Winterton Shoal		Eburonian to Waalian	

Table 5. Characteristics of expected geological formations within the investigation area and in the closer surroundings.

Stratigraphic Unit	Thickness	Lithology
Southern Bight Formation, Bligh Bank Member	2-6 m	medium- or fine-to medium grained, clean yellow-brown SAND with local mud laminae. Gravel contents of 1-5 % are common towards the base, shell fragments are sparsely present.
Naaldwijk Formation	0-5 m	fine- or fine grained bluish-grey muddy SANDs with interbedded clay
Boxtel Formation	0-5 m	well-sorted, fine grained, wind-blown periglacial SANDs
Kreftenheye Formation	0-15 m	fluviatile fine-to medium-grained SANDs occasionally with shells and fine to coarse gravel
Eem Formation, Brown Bank Member	0-15 m	partly consolidated grey brown silty CLAYs and fine SANDs
Eem Formation	3-15 m	medium coarse SANDs, SILT and silty SANDS with around 5 % shells and locally 1 – 5 % of gravel
Egmond Ground Formation	0-10 m	shelly fine SANDs with locally present peat
Yarmouth Roads Formation	60 -100 m	fine- or medium-grained non-calcareous SANDs with variable clay lamination, locally reworked peat
Winterton Shoal Formation	60 – 130 m	fine- or medium-grained SANDs with minor clay intercalations

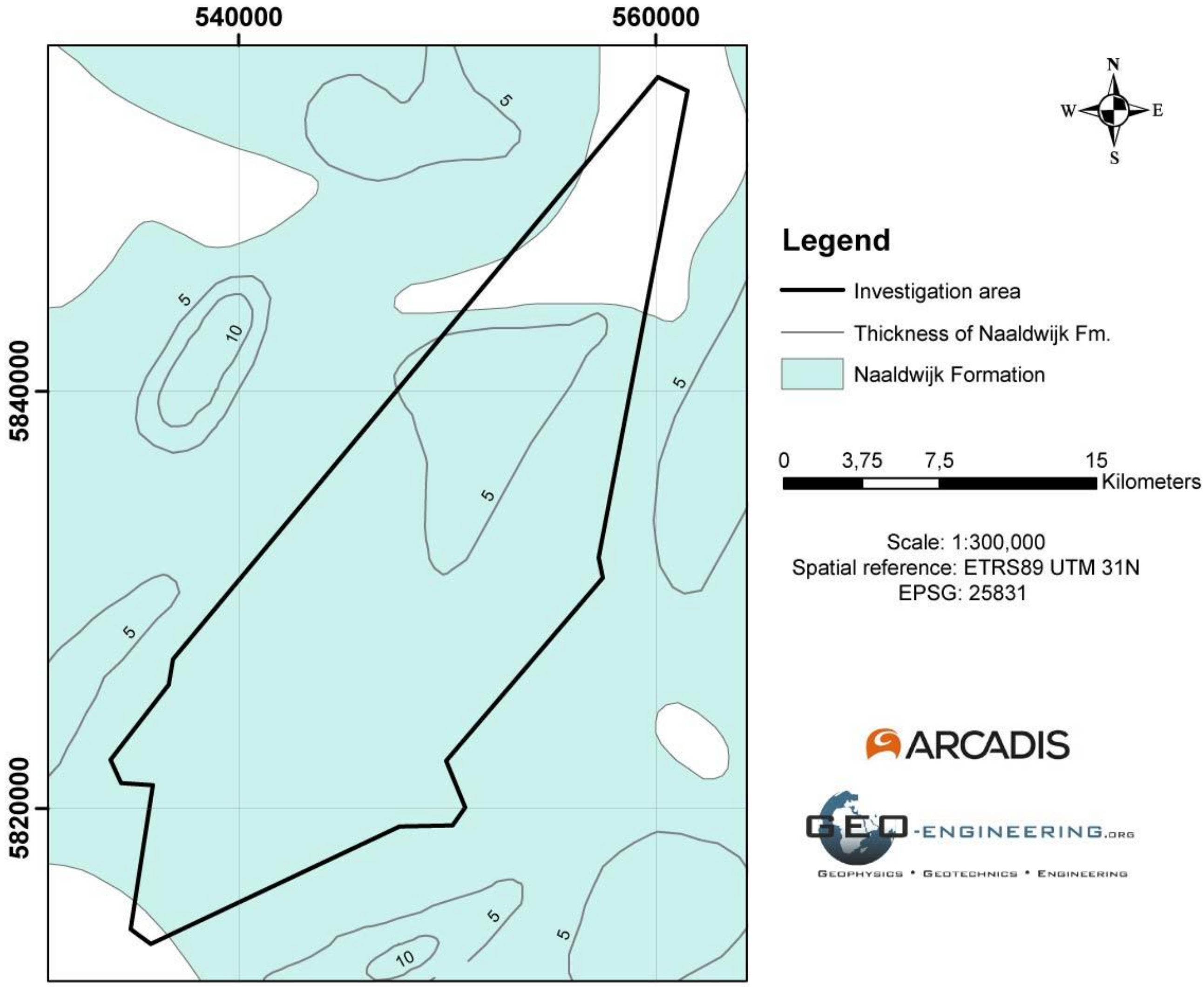

Figure 15. Map showing the thickness of the Naaldwijk Formation. White areas have no coverage. There, the Bligh Bank Member is directly overlaying Quaternary formations. After Cameron et al. 1984b.

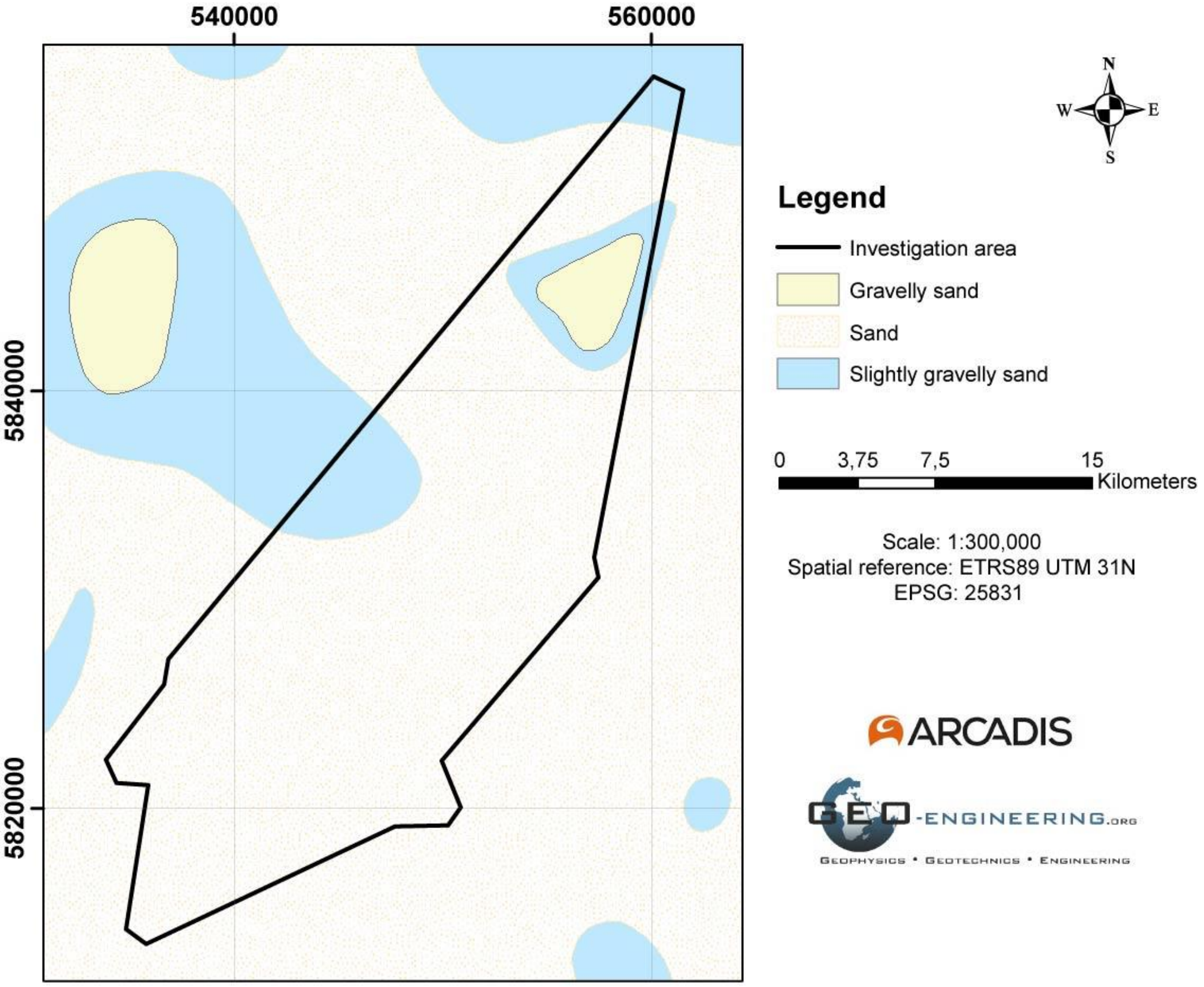

Figure 16. Map showing the seabed sediment characteristics after Cameron et al. 1984b.

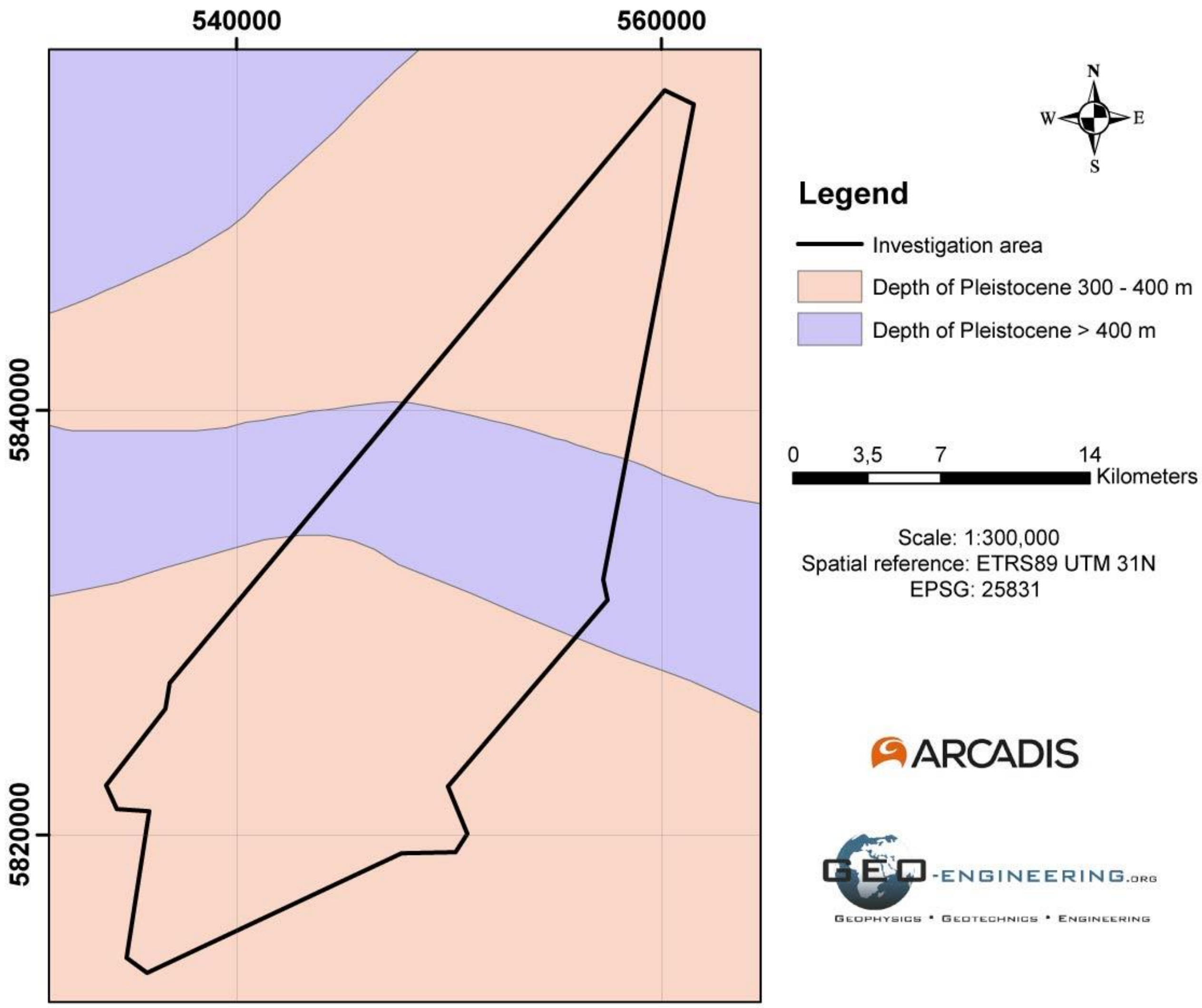

Figure 17. Estimated depth to the base of Pleistocene after Cameron et al. (1984a).

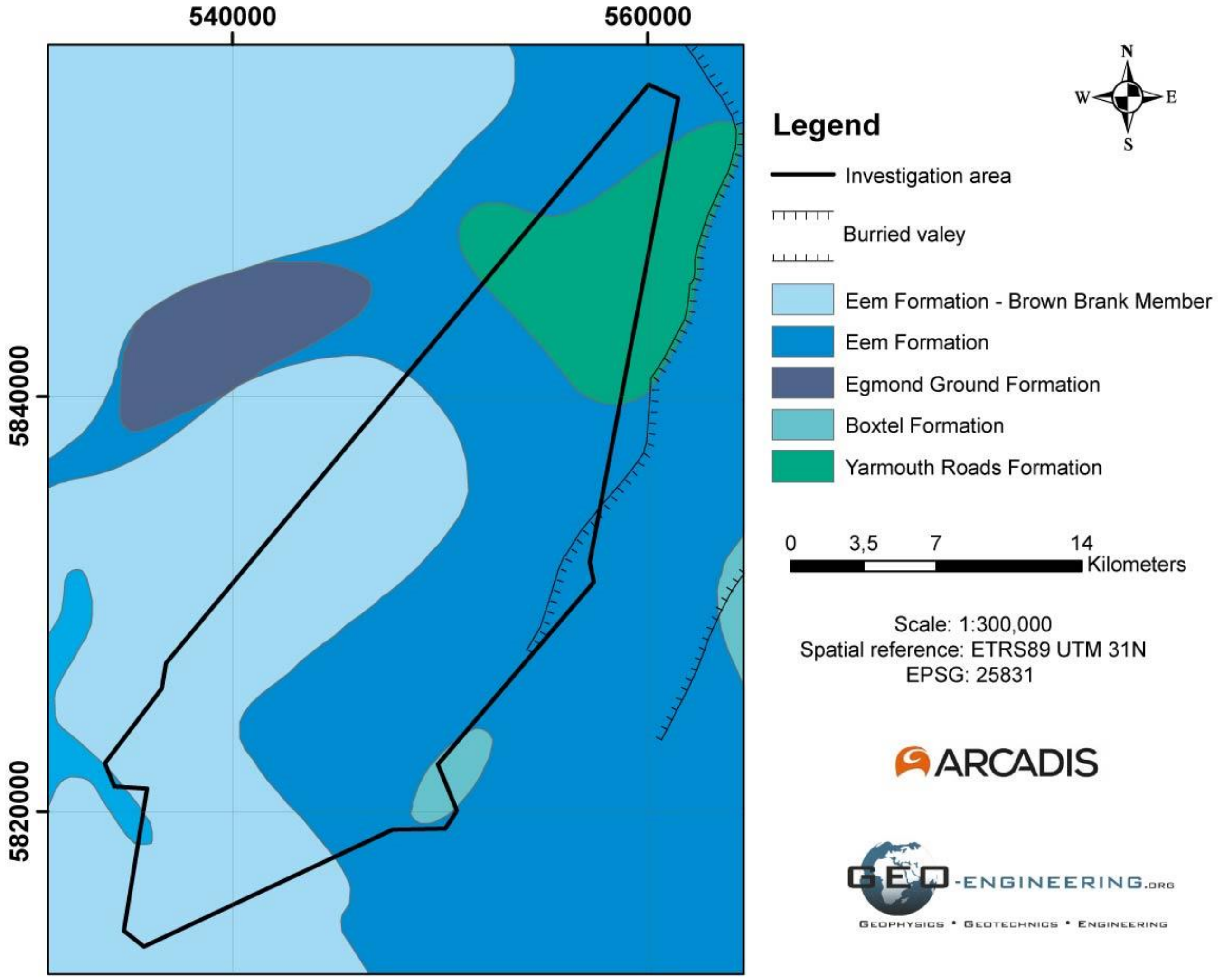

Figure 18. Holocene subcrop map after Cameron et al. (1984a).

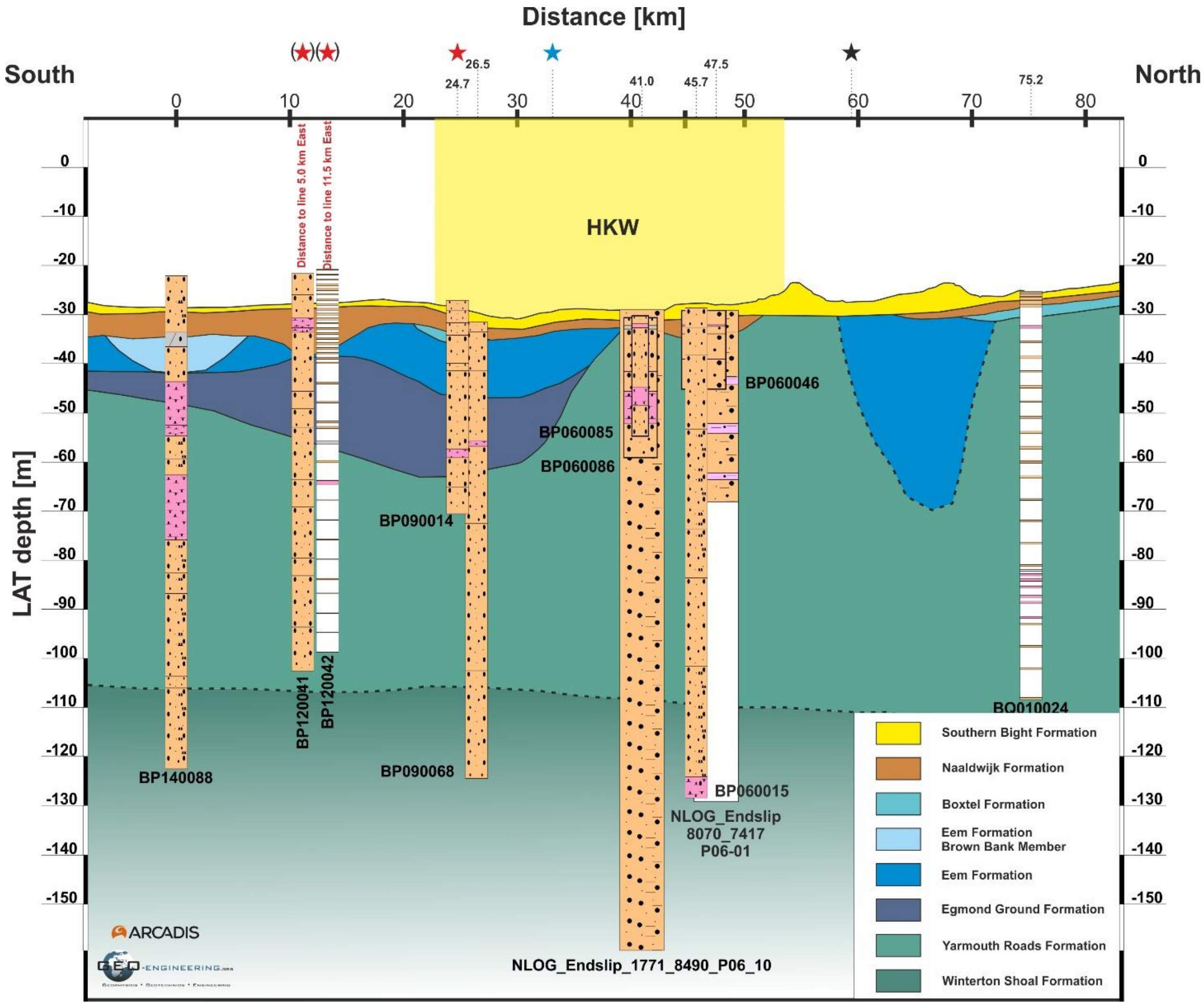

Figure 19. Idealized geological model for the Hollandse Kust (west) Wind Farm Zone as south-north profile with smoothed bathymetry. The profile line is shown in Figure 4. Red stars mark boreholes with stratigraphic information. Stars in brackets indicate that these profiles are projected on the profile line. The blue star marks the intersection with section 3 of Cameron et al. 1984b. The black star marks the intersection with section 2 of Cameron et al. 1984a. This geological model is developed after Cameron et al. 1984a, b.

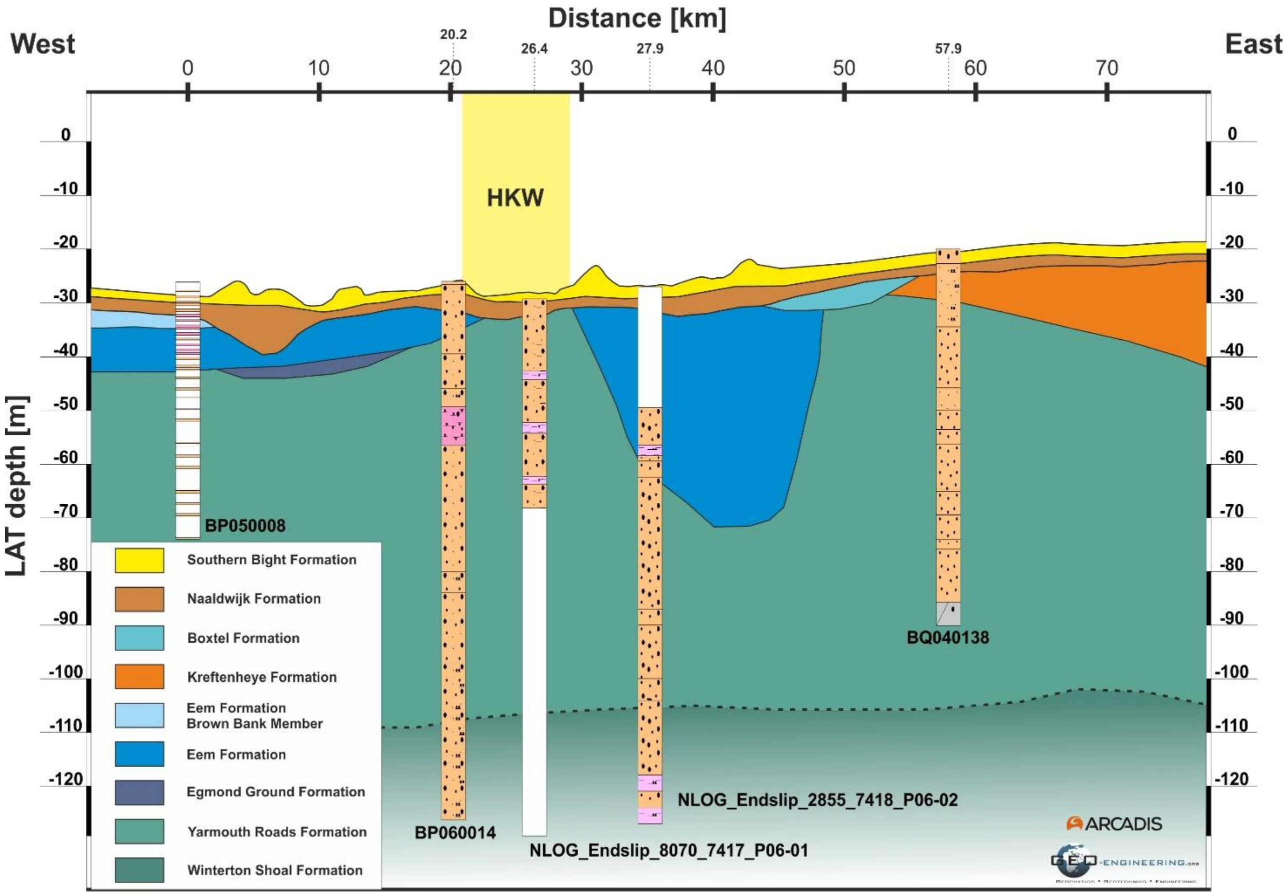

Figure 20. Idealized geological model for the Hollandse Kust (west) Wind Farm Zone as east-west profile with smoothed bathymetry. The profile line is shown Figure 4. This geological model is developed after Cameron et al. 1984a, b.

5 INSTALLATION CONSIDERATIONS

In this chapter the possible constraints are mentioned regarding the installation of an offshore wind farm in the investigation area of this study.

5.1 Seabed morphology

The seafloor morphology is typical for a high energy environment with constant sediment transport. Different migration speeds are known which vary between 0 – 1 m/year for sand banks and 1-10 m/year for sand waves. In the Prinses Amalia Wind Farm migration speeds of 4 m/year have been observed in a study conducted by Deltares (de Bruijn et al., 2015).

The migration of sand waves and banks can cause several problems regarding the installation and operation of an offshore wind farm. Free span sections can occur when the underlying sediment is removed. The free span creates stress on the cable and in addition local scour can cause vibrations which adds further mechanical stress to the structure of the cable. A moving sand wave can also increase the overlying sediment thickness and cause a temperature increase to the cable.

The variable Holocene sediment thickness has to be considered as well when assessing the pile fixation level.

Further needs to be addressed that in such high energy environment a high risk for scour around foundations can be expected.

5.2 Peat

Peat layers can obstruct the jetting procedure for offshore cable trenching and cause increased seafloor heating as peat acts as a heat accumulator. Various formations (Yarmouth Roads Fm., Eem Fm., Boxtel Fm., and Nieuwkoop Fm.) mapped in the subsurface of the investigation area can contain peat occasionally. The geotechnical site investigation should address this topic accordingly.

A suitable survey design is required to image the peat. Depending on the foundation design, peat layers with a thickness greater than one decimetre can be relevant. It is expected that most of such geotechnically relevant layers should have a lateral extent of tens to hundreds of metres at least.

5.3 Archaeology

The archaeological aspect within the investigation area will be addressed in a separate study and is therefore mentioned within this study only briefly.

Archaeological constraints can be wrecks, air planes (especially from World War II) and settlements from the ancient human civilisations.

The very mobile Bligh Bank Member of the Southern Bight Fm. can host ship and aeroplane wrecks. However, due to the mobility of this member remnants are expected to be found at its base. Hunter gatherer camps, flint and bone artefacts, burnt nuts and seeds, charcoal, and hunting gear might be found within the Boxtel Formation. The Eem Fm. might contain remnants of Neanderthal camp sites, flint and bone artefacts.

5.4 Boulders

Boulders are a well-known obstacle within the shallow subsurface of the North Sea. The number of boulders within the sediment or at the seafloor decreases with distance to the Scandinavian and British ice shields and the location of the investigation area is just near the maximum glacial extent. It is therefore possible to come across boulders during further investigation or installation work.

5.5 Glacial valleys and Holocene channels

The investigation area has been in a deltaic and tide-influenced environment repeatedly in the geological past. In such environments glacial valleys and channels are common which can have a different lithology than the surrounding area.

Within Pleistocene valleys the sediments are often very heterogeneous with varying thicknesses. Typical glacial valley sediments are sands but also clays, silts and organic material within watt sediments and peats, as well as varved clays and silts. The valley slopes may be very steep which often puts dense sands with good bearing capacities next to heterogeneous binding material of large thicknesses. Glacial valleys and channel identification within the subsurface should be addressed accordingly in the geophysical and geotechnical survey.

The investigation area has only once been covered with land ice, only during the Saalian glaciation. Along the eastern border of the investigation area a large and deep glacial valley has been mapped during the reconnaissance mapping of the Dutch sector of the North Sea. There are no indications of Saalian glacial valleys west of this valley. As suggested in this report, additional seismic surveys can improve the boundaries of this valley.

Shallow Holocene channels can occur throughout the investigation area because of the tide influence in the geological past. The channels can be of high geotechnical significance due to their potential for spudcan failure. These channels have a much smaller lateral extent (tens of metres wide and hundreds of metres long) than the glacial valley mentioned above and are much shallower. However, their influence on seafloor installation shouldn't be underestimated.

5.6 Geohazards

5.6.1 Natural earthquakes

The risk of natural earthquakes to happen in the Dutch North Sea and cause damage to the structural health of offshore wind farms is very low. Regional risk assessments for natural seismicity calculated a peak ground acceleration of 0.1 – 0.2 m/s for the investigation area of this study with a 10% chance of being exceeded in 50 years for stiff soil conditions (see Figure 21; Grünthal et al., 1999, Panza et al. 2003, Jimenez et al., 2003, European Seismological Commission, 2003).

In Figure 10 the recorded earthquakes for the time span between 1975 and 2018 are shown. Only one event with a magnitude of 3.5 plots very close to the investigation area and is dated to 2001.

5.6.2 Cables and pipelines

Three active and three inactive cables cross the investigation area. Together with pipelines connected to the oil and gas installations several corridors exist which obstruct the planning of wind farm installations (Figure 22).

5.6.3 Induced seismicity

Induced seismicity are seismic events cause by human activities. On the Dutch continental shelf the only cause is related to resource extraction (i.e. oil and gas). Reservoir exploitation through fracking is known to cause seismic activity. Figure 23 shows the position of oil and gas fields in and around the investigation area. Three active gas fields and one oil field in production are located at least partly within the area of Hollandse Kust (west) Wind Farm Zone. One gas field is already out of production and one oil field is not developed yet. This implies an active change of conditions in the deeper subsurface and below the planned wind farm zone and should therefore carefully addressed in further assessments. Even after active resource exploitation subsidence can occur which could be of danger to a wind farm.

Regular seismic events can be a threat to the structural health of offshore foundations.

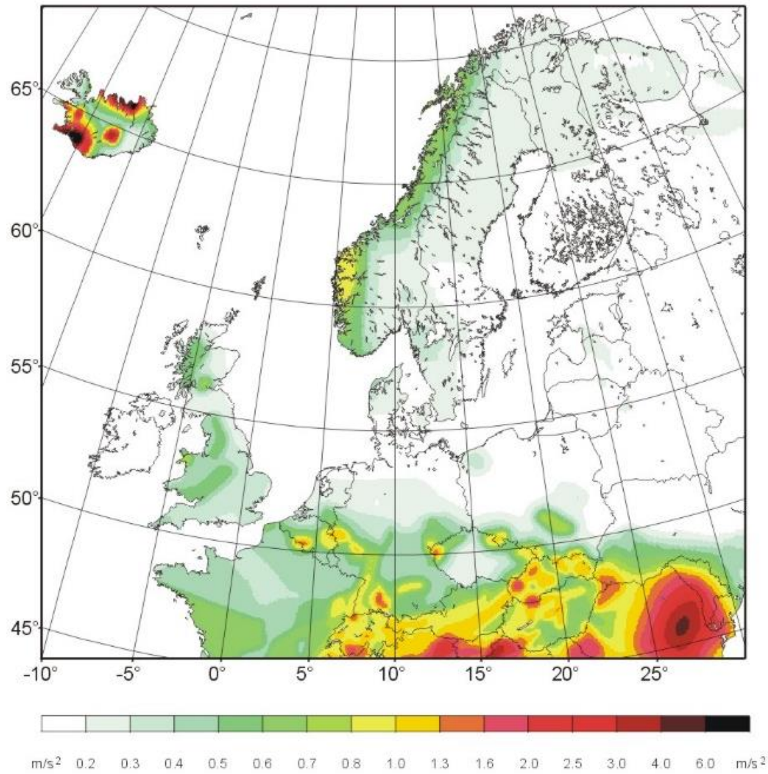

Figure 21. Peak ground acceleration values with a 10% chance of being exceeded in 50 years for stiff soil conditions (Grünthal, 1999)

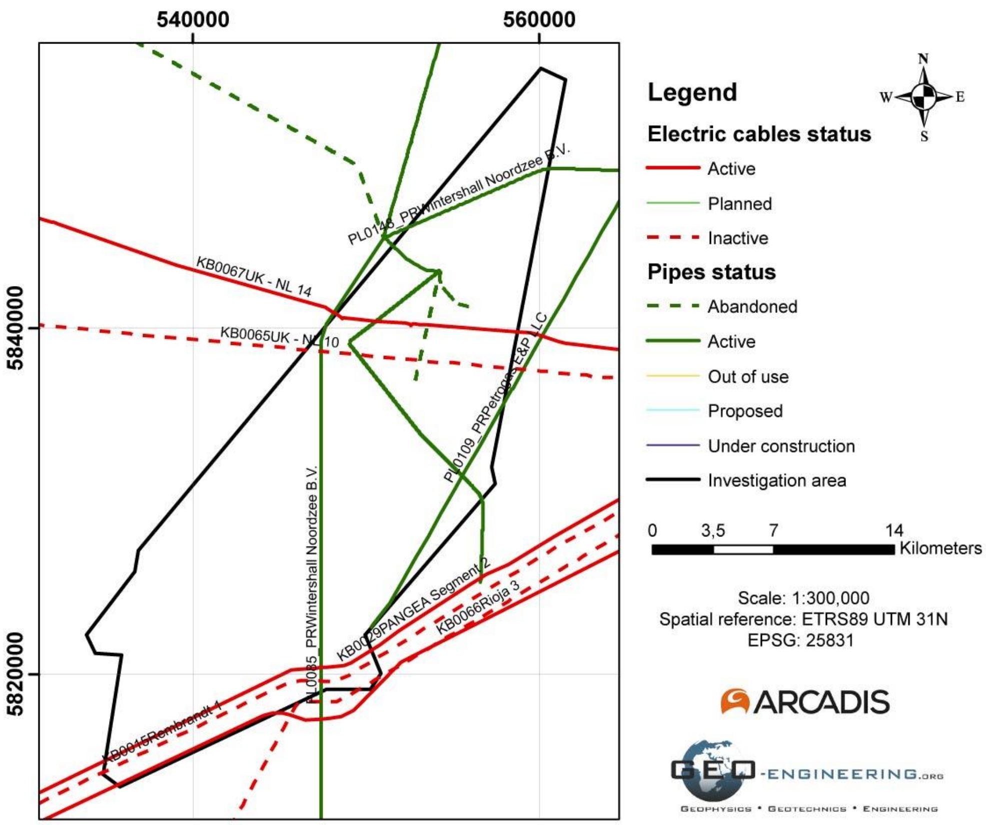

Figure 22. Overview of all pipes and cables charted for the Hollandse Kust (west) Wind Farm Zone.

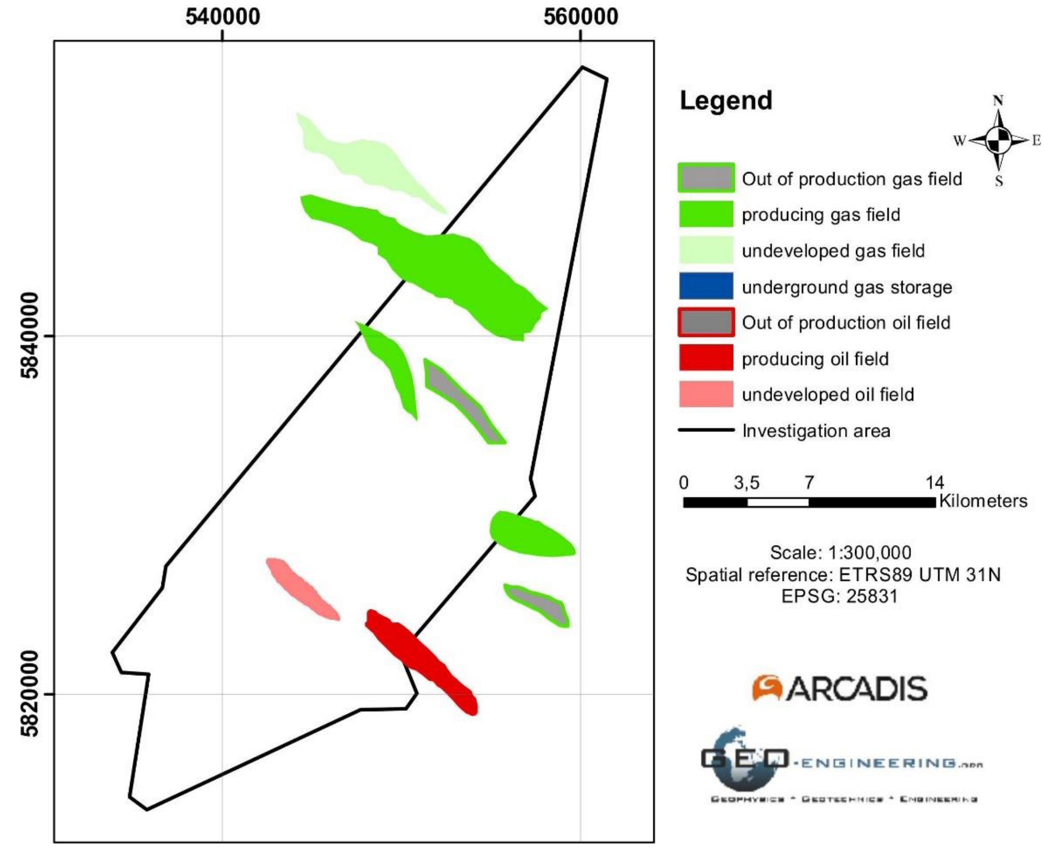

Figure 23. Location and status of oil and gas fields in and around the investigation area. Data extracted from NLOG database.

5.6.4 Shallow gas pockets

Shallow gas pockets can have a serious effect on foundation behaviour because the patches in the subsurface with gas in the pore water have a much lower bearing capacity than the gas free zones around. Besides the danger for foundations these pockets can cause a threat to human health when inhaled during geotechnical survey work.

Two sources are common for gas pockets. Biogenic gases originate from bacterial decay of organic matter in the shallow subsurface and don't migrate much. Petrogenic gases source from much deeper and migrate upwards along cracks and through permeable soils until trapped. In the case that no trap stops the uprising gas it will eventually enter the ocean and cause pockmarks to develop around the discharge site (Schroot et al. 2005).

As indicated at the Quaternary Geology map Flemish Bight (Cameron, et.al., 1984a), in and below the Brown Bank Member at several locations, west of the investigation area, shallow gas has been observed in the single channel seismic records. The clay layers within the Brown Bank Member act as a trap and therefore shallow gas can occur within the investigation area as well.

This topic should be addressed accordingly in the geophysical survey to minimize the risk for the geotechnical survey and the later installation of foundations. Shallow gas also provides a risk of other serious events such as spudcan penetration and potentially gas blowout during drilling (with potential for rig/vessel destabilisation, explosions, and loss of life).

It should be further noted that gas rich sediments sampled from cores on deck of research vessels do not necessarily represent the in-situ condition.

6 CONCLUSION

This geological desk study assessed all publicly available data to analyse the geology for the Hollandse Kust (west) Wind Farm Zone within the Dutch Exclusive Economic Zone.

The available bathymetric data covers the investigation area entirely and the most of it is covered by recent surveys from 2014 and 2015. The bathymetry from today is therefore similar to the morphology in Figure 2. The water depth varies between 21 and 33 m (LAT). The bathymetric data set from NLHO and Deltares has a grid resolution of 25x25 m. This resolution is sufficient to analyse the major morphological characteristics of the area.

Remarkable are the sand banks striking N-S with an elevation change of up to 10 m from top to bottom. These banks are approximately 10-30 km long, 1-3 km wide and around 4-8 km apart from each other. Further noticeable are the smaller scale sand waves that create a relief with up to 5 m in height difference from crest to surrounding lows. They are between several hundreds to ~3 km long and oriented in a NW-SE direction, more or less perpendicular to the sand banks.

No Cone Penetration Test data (CPT) is available for the Hollandse Kust (west) Wind Farm Zone on the web portal of TNO, the Geological Survey of the Netherlands.

A total of 673 shallow boreholes and cores were extracted from the DINOloket database for analyses. These include 197 within the investigation area and 476 within the vicinity (Figure 3). The seafloor penetration depth of the majority of cores is less than 10 mbsf and therefore discarded from further analyses. Only 6 cores within the investigation area have a sufficient depth and core description.

Within the investigation area 5 deep boreholes (from NLOG) give insights into the deep subsurface. For completeness 5 additional boreholes have been selected from the vicinity.

The cores mainly consist of fine to medium sand with a grain size median between 150 and 350 µm. These sandy deposits are in parts highly calcareous and include shell fragments. Occasionally the sand is interbedded by marine clay or loam with a thickness of several centimetres to metres.

However, due to the similar lithologies a stratigraphic identification and correlation of layers in different boreholes is only possible with detailed palynological analysis.

Only 7 seismic lines of digital multi-channel seismic data cover parts of the HKWWFZ. All available digital seismic data were performed for deep exploration with high penetration depth (hundreds of metres to kilometres) but with a low vertical resolution. Therefore, the data are suitable to analyse large scale geological structures but lack the small features and heterogeneities which are important for this study. Due to the low resolution, these surveys are not useful for any interpretation of the first 100 m of subsoil which is the vertical section of interest regarding the planning of offshore wind farms.

The stratigraphic framework from Rijswijk et al. (2005) was applied with a few exceptions: For the older Pleistocene formations the older names Yarmouth Roads Formation and Winterton Shoal Formation are used. The Yarmouth Roads Formation is considered as the offshore equivalent of the Sterksel Formation. The Winterton Shoal Formation is considered as the offshore equivalent of the Waalre Formation and Peize Formation.

The HKWWFZ is geologically characterized by repeatedly occurring cycles of glaciation and deglaciation and the connected sea level changes. Fluviatile, deltaic, estuarine and shallow marine sediments were deposited from the Middle Pleistocene to the Holocene and build up the upper 100 m of sediment that are most significant for the foundations of the offshore wind farm. This sediment consists mainly of sands and silty sands with clay intercalation. Major cohesive sediment thicknesses may be present as infill of channels or glacial valleys.

No major constraints could be identified that would obstruct the development of an offshore wind farm in the investigation area. A map showing pipelines and cables is presented in Figure 22. Selected minor constraints are the following:

Peat

Peat layers can obstruct the jetting procedure for offshore cable trenching and cause increased seafloor heating as peat acts as a heat accumulator. Various formations (Yarmouth Roads Fm, Eem Fm, Boxtel Fm, and Naaldwijk Fm) mapped in the subsurface of the investigation area can contain peat occasionally. The geotechnical site investigation should address this topic accordingly.

Glacial valley and shallow channels

During the reconnaissance survey of the Dutch continental shelf a glacial valley has been detected in the north east of the investigation area.

No shallow channels within the upper metres below the seafloor have been detected yet, but their occurrence is possible due to the tidal influence of the area in the geological past.

Both features are of high geotechnical significance due to their potential to spudcan failure. In general, the filled channels and valleys have different geotechnical parameters than the surrounding environment. An identification and mapping of such structures is a high priority for the upcoming surveys.

Seabed mobility

The seafloor morphology is typical for a high energy environment with high seabed mobility. The migration of sand waves and banks can cause several problems regarding the installation and operation of an offshore wind farm. Free span sections can occur when the underlying sediment is removed. The free span creates stress on the cable and in addition local scour can cause vibrations which adds further mechanical stress to the structure of the cable. A moving sand wave can also increase the overlying sediment thickness and cause a temperature increase to the cable.

The variable Holocene sediment thickness has to be considered as well when assessing the pile fixation level.

Further needs to be addressed that in such high energy environment a high risk for scour around foundations can be expected.

A comprehensive geophysical and geotechnical survey is suggested to follow this study prior to further development of the wind farm area.

7 REFERENCES

British Geological Survey. http://www.bgs.ac.uk. Accessed on 30. April 2018.

Bosch, J.H.A., Weerts, H.J.T. and Busschers, F.S. 2003. Formatie van Urk. In: Lithostratigrafische Nomenclator van de Ondiepe Ondergrond. Retrieved 28 March 2018 from https://www.dinoloket.nl/formatie-van-urk.

Busschers, F.S. and Weerts, H.J.T. 2003. Formatie van Kreftenheye. In: Lithostratigrafische Nomenclator van de Ondiepe Ondergrond. Retrieved 28 March 2018 from https://www.dinoloket.nl/formatie-van-kreftenheye.

Cameron, T. D. J., Laban, C. and Schüttenhelm, R. T. E. (1984a). Flemish Bight Sheet 52°N-02°E, Quaternary Geology, Scale 1:250 000. British Geological Survey and Rijks Geologische Dienst.

Cameron, T. D. J., Laban, C. and Schüttenhelm, R. T. E. (1984b). Flemish Bight Sheet 52°N-02°E, Seabed Sediments, Scale 1:250 000. British Geological Survey and Rijks Geologische Dienst.

Cameron, D., Van Doorn, D., Laban, C., & Streif, H. J. (1993). Geology of the southern North Sea basin. In Coastlines of the southern North Sea (pp. 14-26). ASCE.

de Bruijn, R., Forzoni, A., Vermaas, T., Mesdag, C., de Lange, G., de Kleine, M. (2015). Geological study Hollandse Kust (Zuid) Wind Farm Zone. Deltares.

Ehlers, J. (1990). Reconstructing the dynamics of the north-west European Pleistocene ice sheets. Quaternary Science Reviews, 9(1), 71-83.

Ehlers, J., Meyer, K. D., & Stephan, H. J. (1984). The pre-Weichselian glaciations of north-west Europe. Quaternary Science Reviews, 3(1), 1-40.

Ehlers, J., & Linke, G. (1989). The origin of deep buried channels of Elsterian age in Northwest Germany. Journal of Quaternary Science, 4(3), 255-265.

Erkens, G., Peeters, J. H. M., van Heteren, S., Marges, V. C., Vonhögen-Peeters, L. M., & de Kleine, M. P. E. (2014). Proef Indicatieve Kaart Archeologische Waarden (IKAW) Noordzee. Deltares (Utrecht).

Forzoni, A., Vermaas, T., Mesdag, C., Hijma, M., de Lange, G., & de Kleine, M. (2017). Geological study Hollandse Kust (noord) Wind Farm Zone. Deltares, 73.

Fugro Engineers B.V., (2016). Geological Ground Model Wind Farm Site II, Hollandse Kust (zuid) Wind Farm Zone - Dutch Sector, North Sea. Fugro Report no. N6196/10. Revision 3 dated 14.11.2016.

Graham, A. G., Stoker, M. S., Lonergan, L., Bradwell, T., & Stewart, M. A. (2011). The Pleistocene glaciations of the North Sea basin. In Developments in Quaternary Sciences (Vol. 15, pp. 261-278). Elsevier.

Grünthal, G., GSHAP Region 3 Working Group (1999). Seismic Hazard Assessment for Central, North and Northwest Europe: GSHAP Region 3. - Annali di Geofisica, 42, 6, p. 999-1011.

Hijma, M. P., Cohen, K. M. (2011). Holocene transgression of the Rhine river mouth area, The Netherlands/Southern North Sea: palaeogeography and sequence stratigraphy. Sedimentology, 58(6), 1453-1485.

Hijma, M. P., Cohen, K. M., Roebroeks, W., Westerhoff, W. E., & Busschers, F. S. (2012). Pleistocene Rhine–Thames landscapes: geological background for hominin occupation of the southern North Sea region. Journal of Quaternary Science, 27(1), 17-39.

Jimenez, M. J., Giardini, D., Grünthal, G. (2003). The ESC-SESAME Unified Hazard Model for the European-Mediterranean region. - EMSC/CSEM Newsletter, 19, 2-4.

Laban, C., & van der Meer, J. J. (2004). Pleistocene glaciation in the Netherlands. Developments in Quaternary Science. Elsevier, 251-260.

Laban, C. (1995). The Pleistocene glaciations in the Dutch sector of the North Sea. A synthesis of sedimentary and seismic data.

Lesny, K., Richwien, W., & Wiemann, J. (2002). HAUPTAUFSATZE-Grundungstechnische Randbedingungen fur den Bau von Offshore-Windenergieanlagen in der Deutschen Bucht. Bauingenieur, 77(9), 431-437.

Panza, G. F., Romanelli, F., Vaccari, F., Decanini, L., & Mollaioli, F. (2003, May). Perspectives of innovative approaches in seismic hazard evaluation. In SEE4 Fourth International Conference of Earthquake Engineering and Seismology (pp. 12-14).

Peeters, J., Busschers, F. S., & Stouthamer, E. (2015). Fluvial evolution of the Rhine during the last interglacial-glacial cycle in the southern North Sea basin: a review and look forward. Quaternary International, 357, 176-188.

Righolt, R. H., Schaap, J., Dorst, L. L., & Vos, E. M. (2010). Needle in a haystack. NCG KNAW, 1.

Rijsdijk, K. F., Passchier, S., Weerts, H. J. T., Laban, C., Van Leeuwen, R. J. W., & Ebbing, J. H. J. (2005). Revised Upper Cenozoic stratigraphy of the Dutch sector of the North Sea Basin: towards an integrated lithostratigraphic, seismostratigraphic and allostratigraphic approach. Netherlands Journal of Geosciences, 84(2), 129-146.

Schroot, B. M., Klaver, G. T. & Schüttenhelm, R. T. E. Surface and subsurface expressions of gas seepage to the seabed: Examples from the Southern North Sea. Marine and Petroleum Geology 22, 499–515 (2005).

Seismic Hazard Map (2003). European Seismological Commission. (http://preventionweb.net/go/10049 accessed on March 29 2018)

Stouthamer, E., Cohen, K., & Hoek, W. (2015). De vorming van het land. Geologie en geomorfologie, Perspectief Uitgevers, ISBN 978 94 91269 11 0. Website: http://www.geovorming.nl/

Van Dijk, T. A., & Kleinhans, M. G. (2005). Processes controlling the dynamics of compound sand waves in the North Sea, Netherlands. Journal of Geophysical Research: Earth Surface, 110(F4).

Van Heteren, S., Meekes, J. A. C., Bakker, M. A. J., Gaffney, V., Fitch, S., Gearey, B. R., & Paap, B. F. (2014). Reconstructing North Sea palaeolandscapes from 3D and high-density 2D seismic data: An overview. Netherlands Journal of Geosciences, 93(1-2), 31-42.

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DE0117.000819.0100

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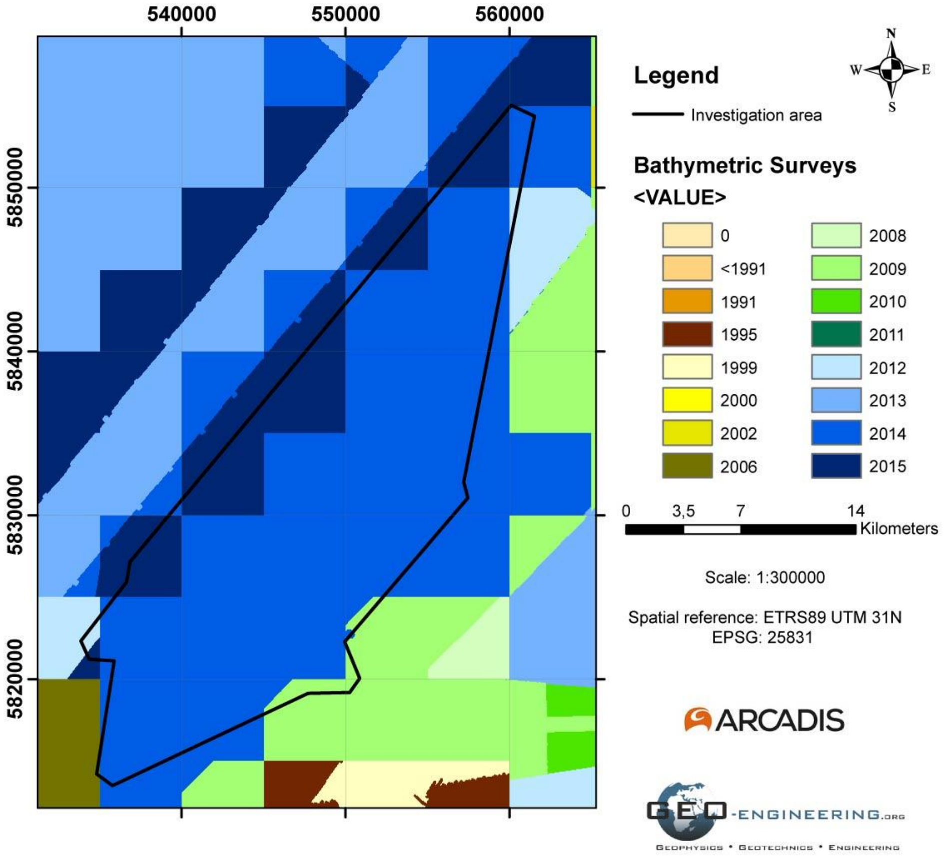
8 APPENDIX



Appendix 1. Map showing the year of survey used to calculate the most recent bathymetry for the investigation area. The sharp boundaries mark the borders of single tiles. Some survey data is truncated at the end of single tiles which creates the blocky texture in the graphic.

Soil Unit		Rijsdijk et al. 2005			
Unit	**Sub-unit**	**Formation**	**Member**	**Age**	**Epoch**
A		Southern Bight	Bligh Bank	Holocene	Holocene
B	**B1**	Kreftenheye		Weichselian Eemian (Saalian)	Upper Pleistocene Holocene
	B2				
C	**C1**	Eem Drente Egmond Ground Urk	Brown Bank	Eemian Saalian Holsteinian	Middle to Upper Pleistocene
	C2				
D		Yarmouth Roads (possibly Winterton Shoal, Ijmuiden Ground)		Elsterian Waalian	Lower Pleistocene

Appendix 2. This table is supposed to be used only for a better understanding of Appendix 4. (source: "Geological Ground Model – Wind Farm Site II – Hollandse Kust (zuid) Wind Farm Zone" authored by Fugro Engineers B.V.)

Soil Unit	Value Type	Sample Rec.	Sample Micro	Thermal Conductivity(1) k (at low. $\gamma_{d;i}$)	Thermal Conductivity(1) k (at hig. $\gamma_{d;i}$)	w	γ_1	γ_2	ρ_s	Atterberg Limits w_p	Atterberg Limits w_L	Atterberg Limits I_p	Carb. Cont.	Org. Cont.	Particle Size Distribution(2) <0.002	Particle Size Distribution(2) <0.063	Particle Size Distribution(2) <2.000	UU s_u	UUr $s_{u,r}$	CIUc s_u	CIUc+BE v_s	CIUc+BE G_{max}	CIDc φ'	CIDc+BE v_s	CIDc+BE G_{max}	RS(3) (SO-SO) fast sh. φ'_R	RS(3) (SO-SO) slow sh. φ'_R	RS (SO-ST) δ	OED IL σ'_p	OED CRS σ'_p
		[m]	[-]	[W/(m.K)]	[W/(m.K)]	[%]	[kN/m³]	[kN/m³]	[Mg/m³]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[kPa]	[kPa]	[kPa]	[m/s]	[MPa]	[°]	[m/s]	[MPa]	[°]	[°]	[°]	[kPa]	[kPa]
A	1	18	15	9	9	49	49	36	6	-	-	-	5	-	1	16	16	-	-	-	-	-	2	2	2	1	1	2	-	-
	2			2.070	2.503	27.2	20.4	20.1	2.67	-	-	-	10	-	3.3	25.1	100.0	-	-	-	-	-	39	144.5	41.2	25.3	33.2	27.4	-	-
	3			1.705	1.800	20.2	19.2	17.2	2.65	-	-	-	2	-	3.3	0.9	98.0	-	-	-	-	-	32	129.3	33.9	25.3	33.2	25.7	-	-
	4			1.946	2.218	22.9	19.9	18.9	2.66	-	-	-	4		3.3	3.4	99.4	-	-	-	-	-	36	136.9	37.6	25.3	33.2	26.6	-	-
B1	1	58	9	3	3	154	154	125	6	-	-	-	5	4	1	25	25	-	-	-	-	-	6	4	4	1	1	6	1	1
	2			2.023	2.701	29.4	20.9	21.0	2.66	-	-	-	12	1	49.7	98.3	100.0	-	-	-	-	-	38	226.7	105.7	29.9	30.7	28.4	757	576
	3			1.807	2.116	17.3	18.9	17.4	2.63	-	-	-	2	0	49.7	1.7	96.2	-	-	-	-	-	32	149.9	44.4	29.9	30.7	24.8	757	576
	4			1.942	2.431	22.7	19.9	19.1	2.65	-	-	-	7	1	49.7	7.4	99.2	-	-	-	-	-	35	191.5	76.5	29.9	30.7	26.9	757	576
B2	1	13	-	-	-	33	33	35	3	6	6	6	2	3	3	3	3	4	4	1	1	1	-	-	-	1	1	-	-	-
	2			-	-	39.5	20.7	20.3	2.74	28	58	33	19	21	23.7	97.2	100.0	142	121	104	174.7	59.4	-	-	-	11.0	20.0	-	-	-
	3			-	-	19.6	17.7	18.4	2.63	22	35	13	13	1	13.4	82.3	100.0	58	15	104	174.7	59.4	-	-	-	11.0	20.0	-	-	-
	4			-	-	29.1	19.1	19.2	2.69	25	49	24	16	8	17.2	88.4	100.0	102.5	72	104	174.7	59.4	-	-	-	11.0	20.0	-	-	-
C1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2			-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	3			-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	4			-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C2	1	115	3	-	-	274	267	237	17	27	27	27	14	14	29	47	47	9	9	11	6	6	8	2	2	3	3	5	5	7
	2			-	-	63.4	22.8	21.1	2.73	38	71	33	15	5	44.0	99.0	100.0	93	57	224	264.3	143.2	33	225.7	101.4	29.2	31.0	28.3	757	866
	3			-	-	10.4	16.0	16.5	2.64	16	21	5	2	0	3.0	2.5	99.0	34	25	104	217.4	98.1	30	214.6	91.1	15.2	17.6	24.2	531	384
	4			-	-	26.7	19.4	19.3	2.68	21	38	17	6	1	17.8	41.4	99.9	60	36	153	236.5	115.4	31	220.2	96.3	23.8	26.2	26.0	597	554
D	1	73	-	-	-	130	127	99	10	11	11	11	5	5	15	31	31	1	1	2	2	2	8	2	2	2	2	2	1	-
	2			-	-	36.7	22.6	20.8	2.69	25	49	24	8	1	38.2	92.5	100.0	147	139	253	247.6	119.7	33	244.6	121.1	31.0	33.4	27.8	1174	-
	3			-	-	11.1	18.0	15.7	2.64	16	27	6	2	0	4.9	3.0	96.7	147	139	154	221.1	102.3	30	206.7	84.5	30.5	30.9	27.5	1174	-
	4			-	-	26.3	19.4	19.0	2.66	21	35	14	3	0	14.0	30.3	99.8	147	139	204	234.4	111.0	31	227.3	103.8	30.8	32.2	27.7	1174	-

Key:
Sample Rec. : sample recovery
Sample Micro : sample micro photography
w : water content
k : thermal conductivity
γ_1 : unit weight derived from water content
γ_2 : unit weight derived from volume mass calculation
ρ_s : density of solid particles
w_P : plastic limit
w_L : liquid limit
I_P : plasticity index
Carb. Cont. : carbonate content
Org. Cont. : organic content
<0.002 : mass percentage of material smaller than 2 µm
<0.060 : mass percentage of material smaller than 60 µm
<2.000 : mass percentage of material smaller than 2 mm
UU(r) : unconsolidated undrained triaxial compression (on remoulded test specimen)
CIUc : isotropically consolidated undrained triaxial compression
CIDc : isotropically consolidated drained triaxial compression
$s_{u(r)}$: undrained shear strength (of remoulded soil)
BE : with piezoceramic bender elements
v_s : shear wave velocity immediately before shearing stage
G_{max} : shear modulus at small strain immediately before shearing stage
RS : ring shear (slow and fast shear)
SO-SO : soil-soil
SO-ST : soil-steel
φ' : effective angle of internal friction
φ_R : angle of residual shear resistance
δ : angle of interface friction
OED IL : incremental loading oedometer
OED CRS : constant rate of strain oedometer
σ'_p : effective preconsolidation pressure

Value Type:
1) number of laboratory tests per soil unit
2) highest value per soil unit
3) lowest value per soil unit
4) calculated average value per soil unit

Note:
(1) Thermal conductivity is presented for the lowest initial dry density and the highest initial dry density tested
(2) Values presented can be from different tests
(3) Values presented are derived from specimen consolidated to estimated effective vertical stress

Appendix 3. Geotechnical parameters from Hollandse Kust (zuid) (source: "Geological Ground Model – Wind Farm Site II – Hollandse Kust (zuid) Wind Farm Zone" authored by Fugro Engineers B.V.)

Location	Name	Type	ETRS89/UTM31		Water depth (msl/nap)	Year	Δ(NAP - LAT)	Depth from most recent bathymetry	From Kelly Bushing		Start depth	End depth	Logging within first 100 mbsf	Lithology
			X	Y					Seabed	Start depth				
			[m]	[m]	[m]		[m]	[m]	[m]	[m]	[m]	[m]	[m]	
Inside HKW	BP060014	Shallow borehole	551017.82	5845235.68	-	1980	0.75	-26			0	100.3	100.3	Alternating sequence of sand and silty sand interbedded with horizon of marine clay - loam (23.3 to 30.5 mbsf)
Inside HKW	BP060015	Shallow borehole	555339.79	5841158.47	-	1980	0.75	-28.6			0	99.8	99.8	Sand, occasional silty sand, horizon of marine clay - loam at 95.5 - 99.8 mbsf
Inside HKW	BP060046	Shallow borehole	555961.80	5841298.41	-	1984	0.75	-29.2			0	16.6	16.6	Sand, horizon with marine clay at 2.9 to 3.2 mbsf
Inside HKW	BP060085	Shallow borehole	552828.80	5836925.45	-	1995	0.71	-30.2			0	24.5	24.5	Sand with interbedded horizons of marine clay at 1.60 to 2.4 & 14.50 to 18.3 mbsf
Inside HKW	BP060086	Shallow borehole	552799.80	5836956.54	-	1995	0.71	30.6			0	28.5	28.5	Sand, horizon of loam at 1.60 bis 2.30 mbsf
Inside HKW	BP090068	Shallow borehole	550262.82	5822761.53	-	1991	0.59	-31.5			0	93	93	Sand, marine clay at 24.10 to 25.30
Inside HKW	NLOG_Endslip_1771_8490_P06_10	Deep borehole	552921.79	5837020.56	-30.50	2000	0.71	-29	73	73	0	3480	100	0 - 100 m sand, silt
Inside HKW	NLOG_Endslip_8070_7417_P06-01	Deep borehole	556448.24	5842313.82	-29.60	1968	0.76	-29.2	55	55	0	3680	100	0 - 40 m sand / 40 - 100 m no samples
Inside HKW	NLOG_Endslip_4850_7781_P09-P09-HORIZON-A-01-S1	Deep borehole	550326.03	5822847.71	-30.80	1987	0.59	-31	72	72	0	2519	100	0 - 50 m sand / 50 - 58 m coal / 58 - 100 m sand
East of HKW	NLOG_Endslip_2855_7418_P06-02	Deep borehole	565174.61	5843445.84	-29.60	1969	0.79	-27	54	75	0	3145	79	0 - 21 m no samples / 21 - 100 m sand
East of HKW	BQ040138	Shallow borehole	587816.59	5841526.51	-	2000	0.97				0	70.1	70.1	
Northeast of HKW	BQ010024	Shallow borehole	573758.91	5864009.98	-	1980	0.98				0	83.2	83.2	
South of HKW	BP140088	Shallow borehole	543674.83	5797320.64	-	unknown	0.58				0	100.4	100.4	
Southeast of HKW	BP120041	Shallow borehole	551623.78	5806528.90	-	1989	0.6				0	81	81	
Southeast of HKW	BP120042	Shallow borehole	558485.75	5806886.63	-	1989	0.67				0	82	82	
West of HKW	BP090014	Shallow borehole	550664.31	5821121.71	-	1969	0.59	-27.1			0	43.46	43.46	Sand, marine clay at 30.20 to 32.00 mbsf
West of HKW	BP050008	Shallow borehole	531646.04	5851059.73	-	1968	0.78				0	48.5	48.5	

Appendix 4. List of selected boreholes used in this study.

Year	Month	Day	Time UTC	Mag	Lat	Lon	Depth km	Region	IRIS ID	Timestamp
2014	12	31	0.10048611	2	51.65	5.45	10	THE NETHERLANDS	10520934	1419992682
2014	12	25	0.37011574	3	51.88	5.51	6.1	THE NETHERLANDS	10515088	1419497578
2013	9	25	0.87478009	2.9	51.84	3.57	1.7	THE NETHERLANDS	9223799	1380142781
2013	1	5	0.96872685	2.7	52.8	4.1	13.8	THE NETHERLANDS	8963678	1357427698
2011	10	9	0.19008102	2.7	53.16	3.88	17.8	NORTH SEA	4652410	1318134823
2011	10	4	0.82824074	2.9	52.66	4.18	11.9	THE NETHERLANDS	4646505	1317757960
2011	8	14	0.28751157	2.9	51.75	2.74	1	NORTH SEA	4574675	1313304841
2011	4	19	0.78665509	2.3	51.79	3	1	NORTH SEA	4401837	1303239167
2011	3	24	0.87773148	2.1	52.25	3.03	0	NORTH SEA	4353521	1301000636
2010	11	18	0.67600694	2.3	51.54	3.01	1	THE NETHERLANDS	4200414	1290096807
2009	7	1	0.8084375	2.1	52.28	2.98	8.4	NORTH SEA	3742401	1246476249
2008	10	11	0.34699074	2.9	52.59	4.33	12	THE NETHERLANDS	2857218	1223713180
2002	7	31	0.50409722	3.1	53.38	3.78	10	NORTH SEA	1419933	1028117154
2001	9	12	0.03302083	3.5	52.84	3.8	14.3	NORTH SEA	1094850	1000255653
2001	9	10	0.18769676	3.4	52.34	4.49	14	THE NETHERLANDS	1082137	1000096217
2001	9	9	0.29040509	3.8	52.42	4.41	3.9	THE NETHERLANDS	1076516	1000018691
1999	9	11	0.5228125	3.4	51.57	5.42	14.2	THE NETHERLANDS	819907	937053171
1999	8	25	0.78208333	2.8	52.03	3.6	2	NORTH SEA	807191	935606772
1998	12	4	0.93623843	3.2	53.2	3.74	10	NORTH SEA	694503	912810491
1997	9	10	0.76564815	2.7	52.3	3.57	0	NORTH SEA	604649	873915752
1995	11	24	0.02576389	2.2	51.83	5.45	10	THE NETHERLANDS	464172	817173426
1995	7	28	0.80883102	4	52.74	4.17	10	THE NETHERLANDS	463066	806959483
1994	9	21	0.05063657	3.4	52.57	4.52	5	THE NETHERLANDS	398661	780109975
1994	8	6	0.7516088	3	52.52	4.82	3.7	THE NETHERLANDS	365150	776196139
1993	7	27	0.25527778	3.5	53.02	3.63	10	NORTH SEA	342202	743753256
1993	1	26	0.12741898	3.1	52.95	3.56	10	NORTH SEA	307193	728017409
1992	6	25	0.89678241	2.8	52.08	3.79	10	NORTH SEA	256248	709507882
1990	5	15	0.88163194	2.7	51.64	3.54	10	THE NETHERLANDS	2813899	642805773
1989	12	1	0.83975694	3.1	52.5	4.75	10	THE NETHERLANDS	3109715	628546155
1975	10	16	0.42688657	2.8	51.66	3.95	0	THE NETHERLANDS	150983	182686483

Appendix 5. Table of recorded seismic events from IRIS database.

Litho- and seismostratigraphic units	Lithology	Un-drained shear strength S_ukN/m²	Plasticity index %I_p	Moisture content %	Bulk density kg/m³	Triaxial test Φ	Porosity %	Cone resistance MN/m²
Boxtel Fm.	Fine sand			24	1900	35-37°	39-41	
Kreftenheye Fm.	Medium-grained sand							32-41
Brown Bank Fm.	Firm to stiff clay	30-80	18-23	25-30	1900		39-44	
Eem Fm./ Egmond Ground Fm.	Fine to medium grained sand			15-23	1900	30-43°	36-42	
Yarmouth Roads Fm.	Fine to medium-grained sand			22	1900		40	
Winterton Shoal Fm.	Clay with sand intercalations			27	1900		43	

Appendix 6. Geotechnical properties measured from boreholes in Dutch waters for the geological formations expected in the investigation area and in the closer surroundings after Cameron et al. (1984a).

Appendix 7. Geological borehole logs.

This investigation was carried out by Arcadis Germany GmbH & Geo-Engineering.org GmbH, commissioned by RVO.nl, an agency of the Ministry of Economic Affairs and Climate Policy.

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Netherlands Enterprise Agency (RVO.nl) | June 2018