Deltares

Terneuzen: Site evaluation

Geological and geotechnical characteristics and hazards

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Management Summary

This report describes the site evaluation for the possible Terneuzen nuclear power plant. This includes an evaluation of hazards associated with the build-up of the subsurface, subsidence, settlement, bearing capacity, seismicity and volcanism. No major hazards have been identified. It is a first-assessment desk study based on currently available data and does not provide sufficient information for the design phase. The main attention points are:

- Within the Terneuzen site few measurements (CPTs and boreholes) are present. With surrounding data and available geological models a general picture of the subsurface is constructed. However, for more certainty and local properties of the deposits new measurements are advised.
- In general, low subsidence rates (~1 mm/yr) are to be expected for this site, in the eastern part slightly higher rates can be expected due to a recent land reclamation where 3 to 4 m landfill material was added.
- Large settlements, in the order of 0.5 m to 0.8 m, are expected during and after constructing with the given loads of the reactor building. The Boom clay layer provides the largest contribution to the settlement. A lack of site specific information about the geotechnical properties of this layer causes large uncertainties around the expected settlements.
- Glauconite sands may cause an unexpected reduction of the bearing capacity of a foundation. It is therefore important to both better map the presence of glauconite sands and conduct lab tests
- From model simulations and surrounding monitoring wells, it appears that groundwater level might emerge to the surface within several tens of centimetres in wet periods and infiltrates mainly downwards into the subsurface. The freshwater lens is measured to be minimal 0 and maximal 10 meters thick. Monitoring should be installed and monitored for at least one year to capture seasonal effects.
- Based on preliminary assumptions it is concluded that the risk of full liquefaction of the subsurface due to earthquakes is low. These assumptions need further consideration once the full Probabilistic Seismic Hazard Analysis (PSHA) has been carried out.

From the above, the PSHA would be essential information when ranking the four proposed locations in terms of suitability. Although more field measurements (CPTs and/or boreholes) are not deemed necessary for the ranking of the four sites, it is advised to first further investigate the Terneuzen site with some additional measurements before planning a full field investigation. The other attention points can be addressed in a later phase.

Technical Summary

The Ministry of Economic Affairs and Climate Policy of the Netherlands requested Deltares to conduct a subsurface site evaluation for the possible Terneuzen nuclear power plant site in the province of Zeeland of The Netherlands. Within the scope of this study are the external hazards as described in chapter 5 of IAEA-SSR-1:

- Evaluation of fault capability.
- Evaluation of ground motion hazards (including human induced seismicity).
- Evaluation of volcanic hazards.
- Geotechnical characteristics and geological features of subsurface materials.
- Evaluation of geotechnical hazards and geological hazards.

The evaluation is based on currently available data and encompasses first-level assessments of the geological build-up and geotechnical properties of the subsurface, the geohydrological setting and hazards associated with subsidence, seismicity and volcanic activity. It does not provide sufficient information for the design phase.

Fault capability and Ground motion hazards
No major upfront constraints for the development of Terneuzen were identified. With respect to seismicity, this needs to be reevaluated after a full Probabilistic Seismic Hazard Analysis (PSHA) has been carried out.

Volcanic hazards
No major upfront constraints for the development of Terneuzen were identified.

Geotechnical characteristics and geological features of subsurface materials
The general build-up of the subsurface is a layer of sandy, Holocene, tidal deposits (Naaldwijk Formation) till approximately -20 m NAP, on top of almost 23 Myrs older thick and stiff clays of Oligocene age (Rupel Formation Boom Member). Below these clays an alternation of more clayey and more sandy units of Oligocene and Eocene age (Tongeren Formation and Dongen Formation). In the western part of the site some Pleistocene marine (Eem Formation) and fluviatile (Koewacht Formation) deposits can be present between the Naaldwijk and Rupel Formations. In the eastern part of the site a landfill of 3 to 4 m is located on top of the Naaldwijk Formation, possibly leading to slightly increased subsidence rates.

Evaluation of geotechnical hazards and geological hazards
As there are no public piezometric measurements at the Terneuzen site, groundwater levels were simulated using the Dutch Hydrological Model. In the west and south areas, levels range between 50–150 cm NAP, approaching surface level during wet periods and dropping to –20 cm NAP (~2 m depth) in dry summers. The east side is significantly higher in elevation, with groundwater levels reaching up to 450 cm NAP (just below surface) and falling to 150 cm NAP in dry periods. In all areas, groundwater discharges towards the lower surrounding polders and the Western Scheldt. It makes it vulnerable for contaminant transport. Overall there is a 0 to 10 m thick freshwater lens present, with brackish water near the surface in the east of the polder. Below the Boom clay layer, older deep freshwater is present, but industrial extraction is challenging due to induced saltwater intrusion from high groundwater flow velocities.

The properties described in this report are based on a limited data set. It is strongly advised to increase the density and depth of CPT measurements and lab testing, especially in the Paulinapolder. Non-typical behaviour can be expected in the Boom clay and glauconite sand layers, and site specific investigations should be compared against existing knowledge at neighbouring sites. For example, the glauconite content of the sand layer may reduce the

bearing capacity of the foundation. Significant settlements have been computed based on the derived settlement parameters for the Boom clay. Site specific investigation of the settlement is advised.

Need for additional data and analysis
Based on the current assessment of the subsurface at the Terneuzen site, the available information provides a good general overview of the site. Due to the lack of geological and geotechnical data within the site it is recommended to acquire additional data till depths of interest, to have site specific information.

For a proper characterization of the geohydrological setting more data is urgently needed. It is advised to install piezometric monitoring wells with filters at different depths as soon as possible. Monitoring should continue for at least one year to capture seasonal effects and should measure density as well.

With respect to seismic hazards a full Probabilistic Seismic Hazard Analysis according to the latest scientific standards and SSHAC guidelines is recommended.

Contents

1 Introduction

1.1 Aim of this study

This report provides a subsurface site evaluation for the Terneuzen locality in the Scheldt Delta region of the southwestern part of the Netherlands (Figure 1-1). This includes a data inventory, a geological desk study, a description of the geohydrological situation and the geotechnical parameters. Within the scope of this study are the external hazards as described in chapter 5 of IAEA-SSR-1:

- Evaluation of fault capability.
- Evaluation of ground motion hazards (including human induced seismicity).
- Evaluation of volcanic hazards.
- Geotechnical characteristics and geological features of subsurface materials.
- Evaluation of geotechnical hazards and geological hazards.

The geological, geohydrological and geotechnical models and profiles should all be regarded as first assessments to characterize the site, based on the currently available data. In addition, the report provides first assessments of expected rates of subsidence, seismic hazards and volcanic hazards. Hence, the report is not part of a Senior Seismic Hazard Analysis Committee procedure. All geological data and interpretations are available in a GIS project that is included as supplementary material to this report.

1.2 Content and structure of this report

This report is divided into 10 chapters and 3 appendices. The introduction (1) covers the aim of this study, while chapter 2 introduces the available datasets and the datasets specifically used for the geological and geotechnical desk study. In subsequent chapters first the regional geological background is given (3), while the geological interpretation and creation of the geological model are covered in chapter 4. Detailed descriptions of the relevant geological units are part of Appendix A. Chapter 5 uses, amongst others, the geological model to describe the geohydrological situation, including insights from existing groundwater-level monitoring systems. The geotechnical aspects of the site are described in chapter 6, that ends with proposed soil profile parameters for the initial design of the site. Chapters 7 to 9 give first assessments of expected rates of subsidence, seismic hazards and volcanic hazards. In a separate report, the Royal Netherlands Meteorological Institute (KNMI) describes the seismological and climatological data. The report finishes with conclusions and recommendations (10).

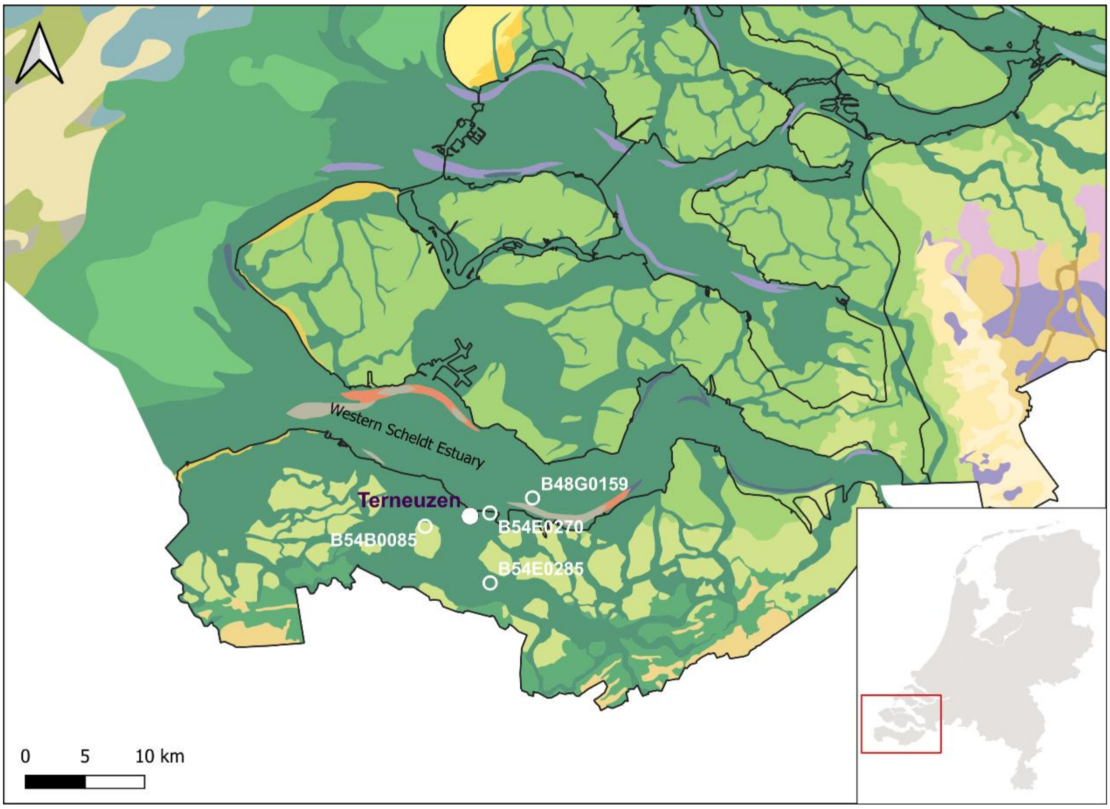


Figure 1-1 Geological location map for Scheldt Delta region surrounding the Terneuzen site, with key boreholes indicated. Geological units follow the geological map of the Netherlands (TNO-GDN, 2023). Note that the dark green color represents (tidally influenced) incised channel facies that were active in the past 500 years. These channels cover a significant part of the Scheldt Delta region, including the Terneuzen site locality. Light green areas are those where a relatively complete Holocene succession can be found.

2 Subsurface data sources

The geological subsurface model and lithological descriptions in the current report are based on several databases. The following sections will provide a more detailed description of the various datasets stored in these databases. Location of all datapoints is available in a GIS file (see Section 2.5) and are indicated in Figure 2-1.

The Netherlands has multiple open-source databases from which a wide range of subsurface data can be retrieved in standardized format. The ‘shallow subsurface’, in the Netherlands typically any data up to a depth of 500 m below Amsterdam Ordnance Datum zero or Normaal Amsterdams Peil (NAP) can be obtained from DINOloket (https://www.dinoloket.nl/en). This database is maintained by the Geological Survey of the Netherlands and is actively updated with both new data and digitized legacy data. For an explanation on how data can be retrieved from this database, see https://www.dinoloket.nl/en/help-subsurface-data.

A separate database, NLOG (https://www.nlog.nl/en/welcome-nlog) exists for subsurface data that falls under the Dutch Mining Act (e.g. 2D and 3D seismic surveys and deep boreholes) and provides data that extends below -500 m NAP depth. This database will not be described in detail in the current report because of the limited use within the scope of this report.

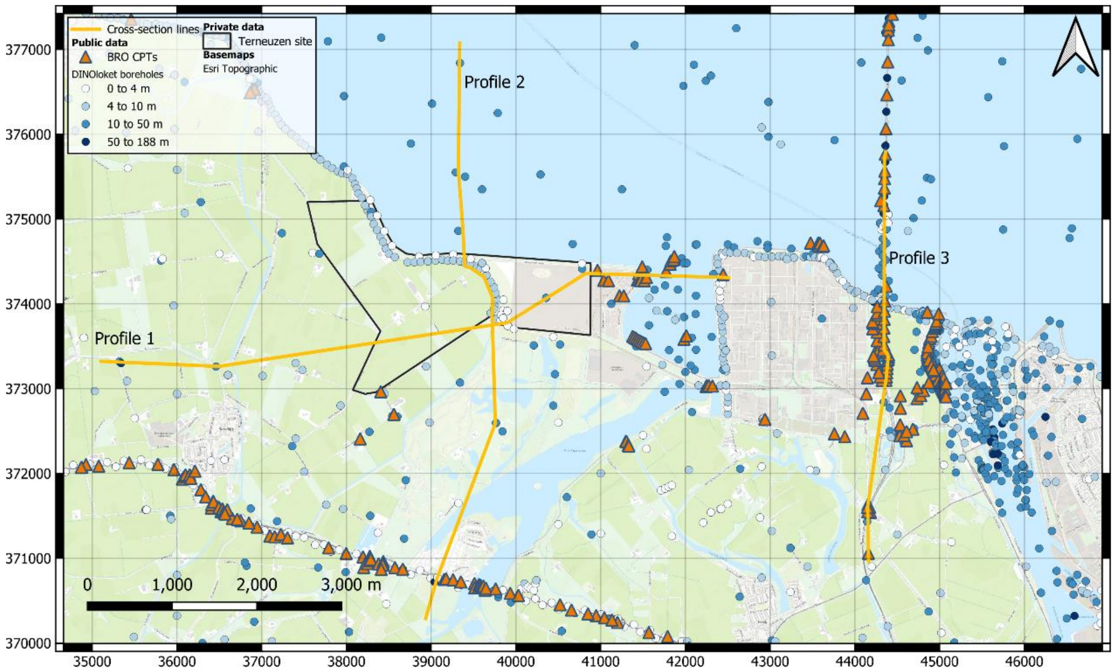


Figure 2-1 Location map of the Terneuzen site with locations of all publicly available data. Maximum depths of DINOloket boreholes are given in meter below surface level. All data within the Terneuzen site perimeter and a subset of the data outside this perimeter were used to describe the build-up of the subsurface.

2.1 Cone Penetration Tests

Geotechnical Cone Penetration Test (CPT) results for the surroundings of the Terneuzen site are available from several different sources. The main Dutch open access database from which subsurface data can be downloaded, DINOloket (https://www.dinoloket.nl/en/subsurface-data), provides .gef and .xml data files per CPT in a standardized format available through the Dutch National Key Registry of the Subsurface (BRO – https://basisregistratieondergrond.nl/english/). Within 500 m from the site there are only 6 CPTs available with a maximum penetration depth of 30 m, there are no CPT data within the site boundaries. There are 50 CPTs available within 2 km from the site with a maximum penetration depth of slightly more than 40 m. More CPTs are available along the regional road about 2.5 km south of the site with a penetration depth of 15 to 25 m. About 3.5 km to the east of the site many CPT's are available along the Western Scheldt tunnel trajectory, running north-south. Many of these CPTs have a penetration depth of more than 40 m, up to at least 60 m.

2.2 Borehole data

From DINOloket (https://www.dinoloket.nl/en/subsurface-data) well log descriptions, geophysical well logs, core photographs and supporting analytical data (e.g. chemical and grain size) can be downloaded. Well log descriptions are available as .gef and .xml data files and for some older localities also as scanned pictures of the hand-drawn logs. Since 2000 well log descriptions are performed throughout the Netherlands according to a standardized well description method (Standaard Boor Beschrijvingsmethode – SBB5.1; Bosch, 2000). Geophysical well log data are available as .las files and/or scanned pictures at DINOloket. While these data is provided in a standardized digital format, the type of analytical data that is provided may differ by location.

2.3 (Subsurface) Geological models

The data stored in the open-source databases feeds into geological mapping of the surface and subsurface. These models can be visualized using DINOloket (https://www.dinoloket.nl/en/subsurface-models/map), or can be requested to view and use outside DINOloket (https://www.dinoloket.nl/en/request-model-files). Multiple subsurface models designed for specific purposes are available at DINOloket, explanations on the intended uses and data underlying the various models can be found at https://www.dinoloket.nl/en/explanation-subsurface-models. Stratigraphic units used in these models are described in the Stratigraphic Nomenclature of the Netherlands (Figure 2-2; https://www.dinoloket.nl/en/stratigraphic-nomenclature).
The relevant models in the current context will be briefly discussed in the following paragraphs.

2.3.1 Geological map of the Netherlands

In 2023 an update was made to the Geological map of the Netherlands (TNO-GDN, 2023). For the onshore area, previous geological mapping at a scale of 1:50.000 and the regional 3D subsurface models were used as basis. For a full background on the geological map of the Netherlands, see https://www.dinoloket.nl/en/geological-map.

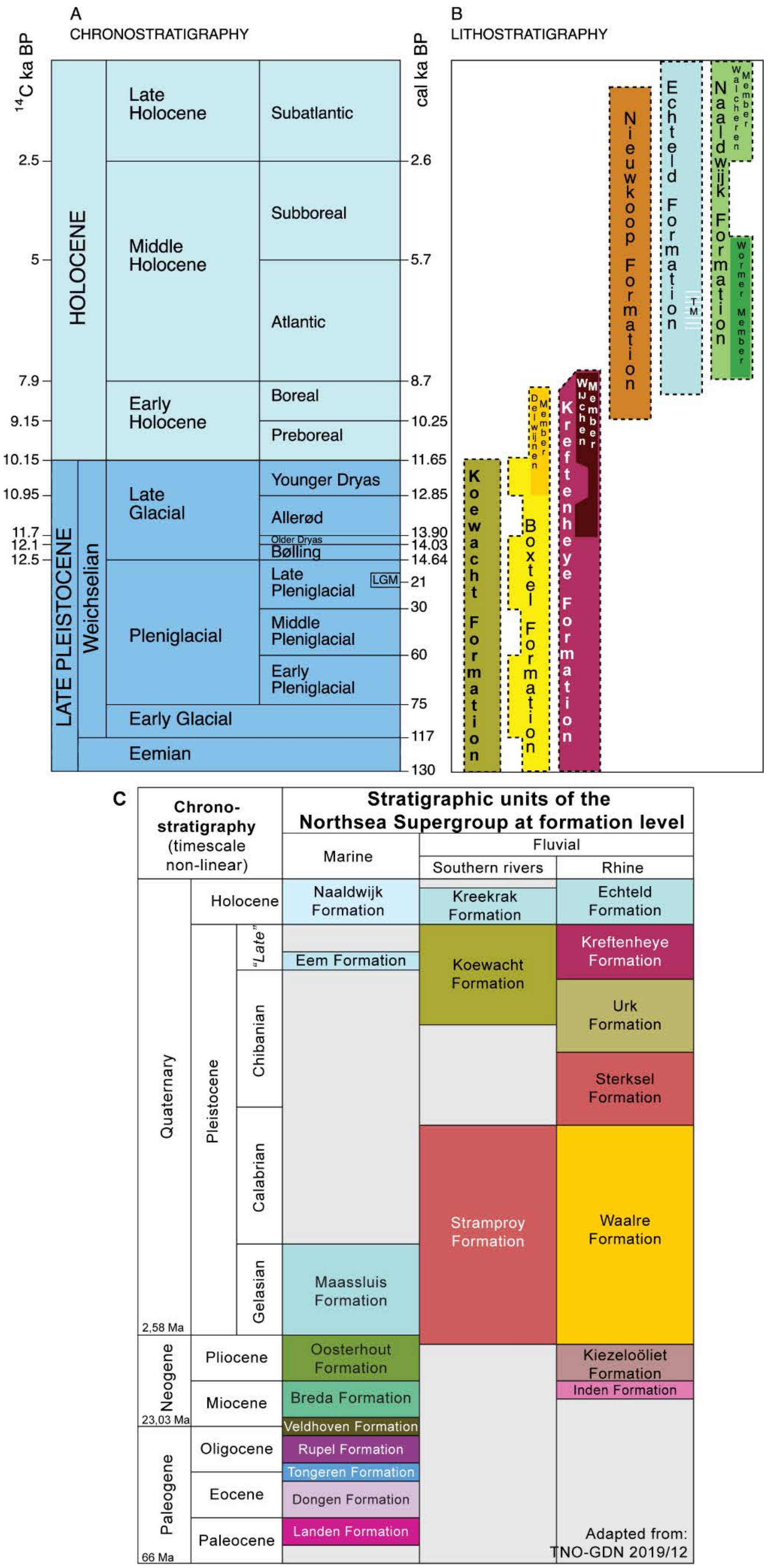


Figure 2-2 (previous page). Dutch stratigraphic nomenclature as used in this report. A) Adapted from Hijma et al. (2009), ¹⁴C ages and inferred calibrated ages for the Holocene follow Van Geel et al.

(1980/1981). Late Glacial ^{14}C ages follow Hoek (2001; 2008), while the Late Glacial calendar ages follow Rasmussen et al. (2006). Remaining Pleistocene chronostratigraphy according to Vandenberghe (1985) and Van Huissteden and Kasse (2001). B) Adapted from Hijma et al. (2009), lithostratigraphy for the southwestern coastal area of the Netherlands cf. Westerhoff et al. (2003); Wijchen Member cf. Törnqvist et al. (1994); TM = Terbregge Member (Hijma et al. 2009). C) Adapted from Van Adrichem Boogaert & Kouwe (1993), Lithostratigraphy of the North Sea Supergroup at formation level. Stratigraphic units are split in marine and fluvial facies, with the fluvial units further separated into units derived from the south (e.g. Paleo-Scheldt River) and from the east (e.g. Paleo-Rhine River). For a written description of these units at the scale of the Netherlands, see https://www.dinoloket.nl/en/stratigraphic-nomenclature.

2.3.2 GeoTOP

The GeoTOP model provides a detailed 3D model of the subsurface down to -50 m NAP to be used as a framework for groundwater management, (shallow) natural resources and infrastructure works. Voxels of 100 by 100 meters horizontally and 0.5 meter vertically provide lithology and lithostratigraphy including the probability of occurrence of each lithological class. The most recent version (v1.6) was released in 2023 and provides an updated subsurface characterization of the province of Zeeland and thereby the Terneuzen locality and site vicinity. For a full description see https://www.dinoloket.nl/en/detailing-the-upper-layers-with-geotop and/or https://www.dinoloket.nl/en/nieuws/geotop-v15-new-version-of-zeeland-and-goeree-overflakkee.

2.3.3 DGM/REGIS

The Digital Geological Model (DGM) and the regional geohydrological model (REGISII) that uses DGM as a framework provide regional-scale subsurface interpretations down to approximately -500 m NAP. DGM and REGIS are 3D layer models that classify lithostratigraphic units based on their lithology and other soil properties (hydraulic conductivity). These models do not cover the study area, but since also their boundaries lies just east of the study area, they still provide useful information. The horizontal and vertical resolution above NAP -50 m in DGM/REGIS is lower than that of GeoTOP, which therefore should be preferred for interpretations in that depth interval. For more information see https://www.dinoloket.nl/ondergrondmodellen/kaart and https://www.dinoloket.nl/en/regis-ii-the-hydrogeological-model.

2.3.4 NHI/LHM

The "Nederlands Hydrologisch Instrumentarium" (Hydrological Instrumentations of the Netherlands) or NHI is a collection of datasets, model codes, and tools to simulate the entire water cycle of the Netherlands. The instrumentation tools consider groundwater flow and surface runoff as well as the interaction between the atmosphere, vegetation, soil moisture and salinization, which all play a role in certain areas of the Netherlands. The hydrological instrumentation can model both dry and wet conditions to predict where any problems may arise and the effects of interventions. This helps policymakers and land managers make decisions that will limit damage from drought and flooding. Hydrological models explore the possible effects of climate change scenarios and can be used to substantiate and evaluate policy.

The website (https://nhi.nu/en/) provides access to models, code, data and tools. Brief documentation is available for the various datasets and instrumentation and references are provided for the data portal or other online locations where the models, code, data and tools are available. The resolution of the data is 250 x 250 meter and it serves mainly for regional effects of measures. It also creates an efficient starting point for more local geohydrological studies. The latest version (version 4.3.3) of the geohydrological model is described in Janssen (2025).

2.4 Surface elevation and bathymetry

The most recent publicly available digital terrain model (DTM) of the Algemeen Hoogtebestand Nederland (AHN5) at a resolution of 5x5 m was used for the surface elevation of onshore parts. For more information on the AHN, see https://www.ahn.nl/. Vaklodingen were used for bathymetric data in and around the Terneuzen port area. Vaklodingen are singlebeam surveys that are carried out every three to six years depending on the area by the Directorate General for Public Works and Water Management. For more information on vaklodingen, see https://waterinfo-extra.rws.nl/monitoring/morfologie/.

2.5 Hydraulic measurements and extractions

The data stored in the open-source databases for groundwater observations and licensed and/or registered groundwater extractions are available at DINOloket (https://www.dinoloket.nl/ondergrondgegevens/). Here data can be analysed, visualized and requested. Additional the temporal behaviour of groundwater can be examined at the Groundwater Head Viewer (https://www.grondwatertools.nl/gwsinbeeld/). Timeseries, average groundwater levels and isohypses can be derived from spatial interpolation with- or without results from the Dutch National Groundwater Model (LHM, see section 5). Another tool to derive extraction is the WKO-tool (https://wkotool.nl/?page=Bodemenergietool; only Dutch) where registered/licensed groundwater extractions can be inspected as well as Aquifer-Storage-Recovery systems. The local density distribution is mapped using airborne electromagnetic measurements. Interactive maps can be found and explored at the Freshem 2.0 Salt Distribution of the subsurface of Zeeland (https://kaarten.zeeland.nl/map/freshem#).

2.6 Explanation of the GIS project

A table containing the explanation of the data sources used in the GIS project file is provided. See the attached file data_sources_GIS.xlsx. The GIS data is provided as a QGIS project file (.qgs). It is advised to open and visualize this in QGIS version 3.32.2 ‘Lima’.

3 Regional geological background

3.1 Scheldt Delta sedimentary system

The subsurface geology of the Terneuzen locality should be considered within the context of the Scheldt Delta region sedimentary system on the western border between the Netherlands and Belgium. The region provides a record of millions of years of tidal influence on top of a gradual emerging trend from (shallow) marine to coastal and continental depositional environments. These environments were located in a tectonically quiet transitional setting between the uplifting London-Brabant Massif to the south and the subsiding southern West Netherlands Basin to the north (Figure 3-1). This edge-of-basin location resulted in a low accommodation space, meaning that during sea-level highstands relatively thin packages of sediment were deposited and that during sea-level lowstands these sediments could easily be eroded again. The position on the southern flank of the West Netherlands basin resulted in a northward dip of sediments. Tectonic movement is slow and hence the northward dip is especially clear for the older sediments, the younger sediments still lie more or less horizontally.

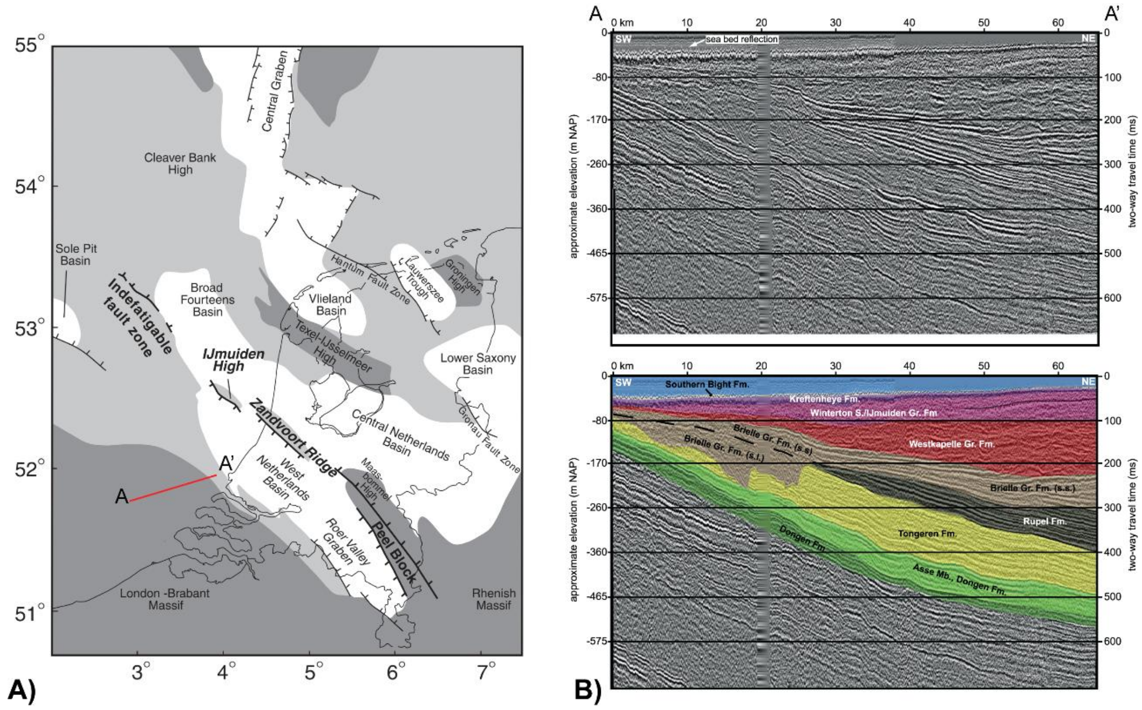


Figure 3-1 A) Generalized tectonic setting of the Netherlands (adapted from Michon et al., 2003). The Scheldt Delta region is located between the slowly uplifting London-Brabant Massif to the south and the subsiding West Netherlands Basin to the north. B) Seismic cross-section showing processed (upper) and interpreted (lower panel) data (Hijma et al., 2012). Location indicated in panel A).

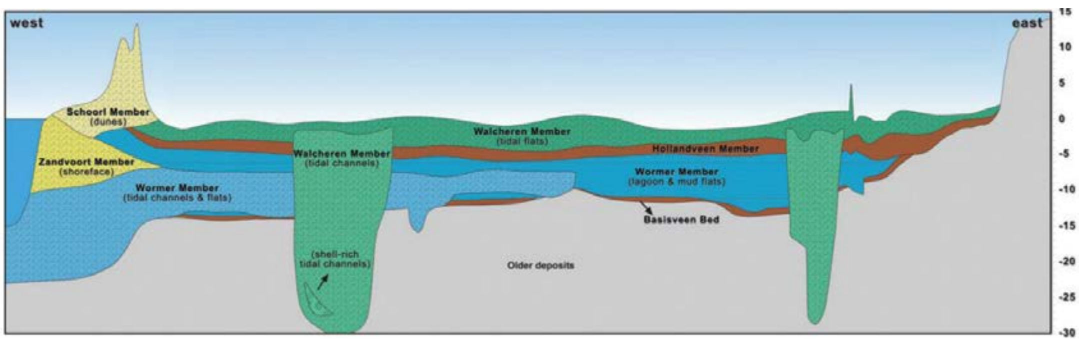


Figure 3-2 Schematic west – east cross-section showing complex cross-cutting relationships within the Holocene deposits in the Scheldt Delta region (after Stafleu et al., 2011). The horizontal distance is about 70 km.

The pattern of erosion varied through time. In the older, marine stages erosion resulted in regionally important unconformities that separate continuously deposited intervals of stratigraphy. For the younger coastal, estuarine and fluvial deposits, erosion became increasingly localized in channelized features and on a range of scales from small tidal creeks to inlets the size of the present-day Western Scheldt estuary (Figure 1-1). This resulted in complex cross-cutting relationships in the subsurface with non-eroded "islands" surrounded by younger sediments that were deposited after a preceding phase of erosion (e.g. Stafleu et al., 2011; Figure 3-2).

In southern direction the unconformities show a larger time hiatus, due to the proximity to the uplifting London-Brabant Massif. Here, Late Pleistocene and even Holocene deposits directly overly Oligocene or older deposits. The Late Pleistocene deposits are preserved in the 'non-eroded islands', while Miocene and Pliocene (and younger) deposits are fully eroded in later stages.

3.2 Description of depositional history

In the following paragraphs the geological record at Terneuzen will be briefly described for four time-intervals. In each section the focus will be on the type of sediment that was deposited at these times and the type of depositional environment that is associated with these sediments. Afterwards, key characteristics of the geological units will be described individually per unit. The chosen units follow the Stratigraphic Nomenclature of the Netherlands (https://www.dinoloket.nl/en/stratigraphic-nomenclature) to enable easy comparison with existing subsurface models such as GeoTOP.

Four boreholes at and nearby the Terneuzen site have been used to provide detail on the composition of the subsurface (see locations in Figure 1-1). These boreholes provide a full record of the sediments present at and nearby the Terneuzen site.
The oldest sediments are encountered in borehole B54E0285, about 3.5 km east of the site, reaching the early Eocene Ieper Member of the Dongen Formation (see also Figure 2-2). A well-log is also available for this borehole, but no other information. Borehole B54B0085 lies about 3 km east of the Terneuzen site, and provides a full record till the top of the Eocene Dongen Formation. For this borehole both a well-log and core photographs are available (selection presented in Figure 3-4). In this borehole the clay deposits from the Rupel Formation (Boom Member) are missing due to a hiatus, while they are a relevant unit for the Terneuzen site. Good photographs, grain size and chemical analysis are available from borehole B48G0159, located about 3.5 km east of the site along the Western Scheldt tunnel trajectory. The recent deposits of the tidal channels, belonging to the Naaldwijk Formation, are described in borehole B54E0270 which is located within the Terneuzen site. This borehole reaches into the top of the Rupel Formation and provides (low quality) photographs and grain size analyses.

Besides these four boreholes two CPTs, CPT000000020167 and CPT000000233287, are used to characterize the sediments of the different geological units. CPT000000020167 is located just east of the Terneuzen site and provides information of the Holocene deposits and the top of the Rupel Formation. CPT000000233287 is located about 3.5 km east of the site, and reaches into older formations, up to the top of the Ruisbroek Member (Tongeren Formation).

3.2.1 Paleozoic and Mesozoic

The oldest sedimentary rocks in the subsurface can be described using borehole KTG-01 (Figure 3-3). This well was drilled in 1982 approximately 23 km to the northeast of the Terneuzen locality down to a maximum depth of 1879 m (https://www.nlog.nl/nlog-mapviewer/brh/106507149?lang=en). It encountered 678 m of Neogene and Paleogene sediments and sedimentary rocks overlying multiple older units. These older units include Cretaceous chalk (approximately 265 m thick), Carboniferous limestone (100 m thick) and an 850 m thick, predominantly shaley Silurian to Devonian succession (Houben and Vis, 2021). These Paleozoic and Mesozoic rocks will not be discussed in detail given the great depths at which they are located. For more detailed information, we refer to the Middle Paleozoic chapter of the recently published “Geology of the Netherlands” (Veen et al., 2025).

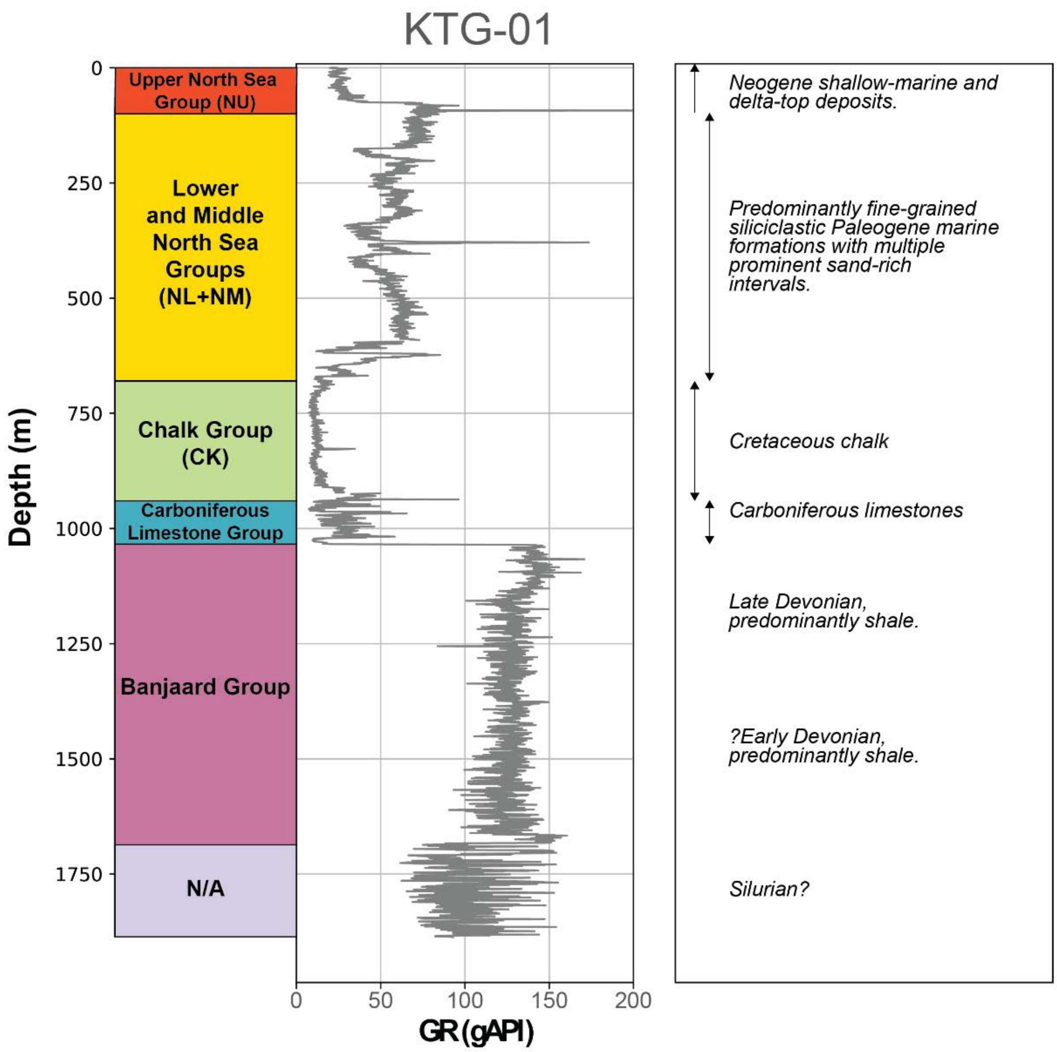


Figure 3-3 Stratigraphic reference well Kortgene-01 (KTG-01) for the deep subsurface. Stratigraphic units are given at group level.

3.2.2 Paleogene and Neogene

Most of the Paleogene and Neogene sediments in the Terneuzen site vicinity were deposited in marine conditions (Figure 2-2). This includes both sand-dominant and clay-dominant intervals that are regionally recognizable and often separated by unconformable surfaces.

The oldest deposit reached in borehole B54E0285 is the early Eocene Ieper Member of the Dongen Formation. According to the DGM, the top of the Dongen Formation lies around -80 m NAP at the Terneuzen site. The Ieper Member consists of clays, described as “generally soft, tough and sticky to hardened and friable" and it is encountered from a depth of -172 m NAP downward in borehole B54E0285. On top of the Ieper clays, the sandy Brussels Member (-105 till -172 m NAP) and the clay rich Asse Member (-58 till -105 m NAP) are found. The Brussels Member sands are composed of an alternation between glauconitic fine sand (with some gravel admixture) and hard, calcareous sandstone layers of decimetres thickness in the top part. In the lower part, also loam layers are observed. The Asse Member is composed predominantly of fat, grey greenish non-calcareous clay. In borehole B54B0085 the bottom of the Asse member is reached at a depth of -68 m NAP.

Overlying the Asse member is the late Eocene to early Oligocene marine Tongeren Formation (found at depths between -30 and -80 m NAP). It can be separated from bottom to top into the sandy Bassevelde Member, the clayey Watervliet Member and the sandy Ruisbroek Member (Ebbing et al., 2003; Figure 3-1 and Figure 3-4). Sandstones in this interval are up to 20 m thick and are poorly graded fine to medium weakly calcareous sandstone beds that contain phosphorite pebbles, little mica and up to 20 % glauconite.

The sandstone of the Ruisbroek Member is overlain by the marine clays of the Boom Member of the Rupel Formation (Vis et al., 2016, Figure 3-5). At Terneuzen the Boom Member is found at depths between -20 m NAP to -30 m (north) or -40 m (south), with a thickness of 10 to 20 m. These clays were deposited during the younger half of the Rupelian (early Oligocene) and are grey to dark greenish grey, poorly calcareous to calcareous fat and stiff clay (photographs available from borehole B48G0159, Figure 3-4). The top of the of the Boom Member is an important unconformity separating it from the Pleistocene or Holocene deposits, clearly visible in CPTs (Figure 3-6).

The Breda Formation is likely absent at the Terneuzen site, but does occur on top of the Rupel Formation north of the site and locally east of the site. It is characterized by greenish black fine to medium sand with abundant glauconite. These sands are marine in origin with the glauconite indicating subtidal offshore low energy environments below storm wave base (Slupik & Janse, 2008).

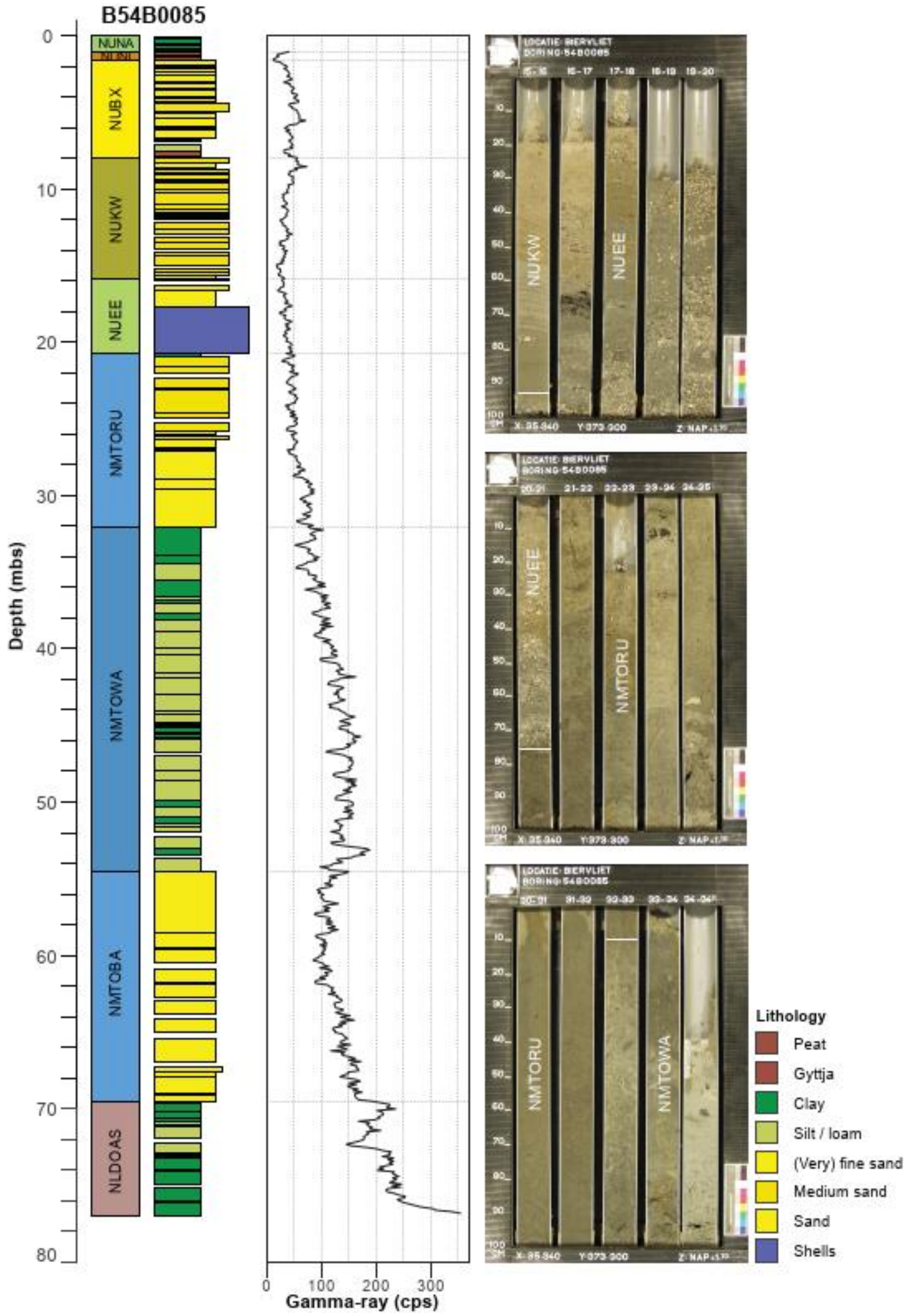


Figure 3-4 Lithological overview figure of well B54B0085 including selected core photographs highlighting the different members of the Eocene Tongeren Formation (units NUTOWA and NUTORU) and the sharp boundary with the marine deposits from the Eem Formation (NUEE) in which the fluviatile Koewacht Formation (NUKW) is incised. At this location the estuarine channels did not incise deep, preserving a local patch of Weichselien cover sand (Boxtel Formation, NUBX) with on top peat (Nieuwkoop Formation, Hollandveen Member, NIHO) and a thin layer of tidal marsh deposits (Naaldwijk Formation, NUNA). The gamma ray graph shows the higher amounts of glauconite present in the Tongeren Formation. Depths are given in meters below surface-level (MBS). All data and photographs can be obtained through DINOloket. The location of B54B0085 is indicated in Figure 1-1.

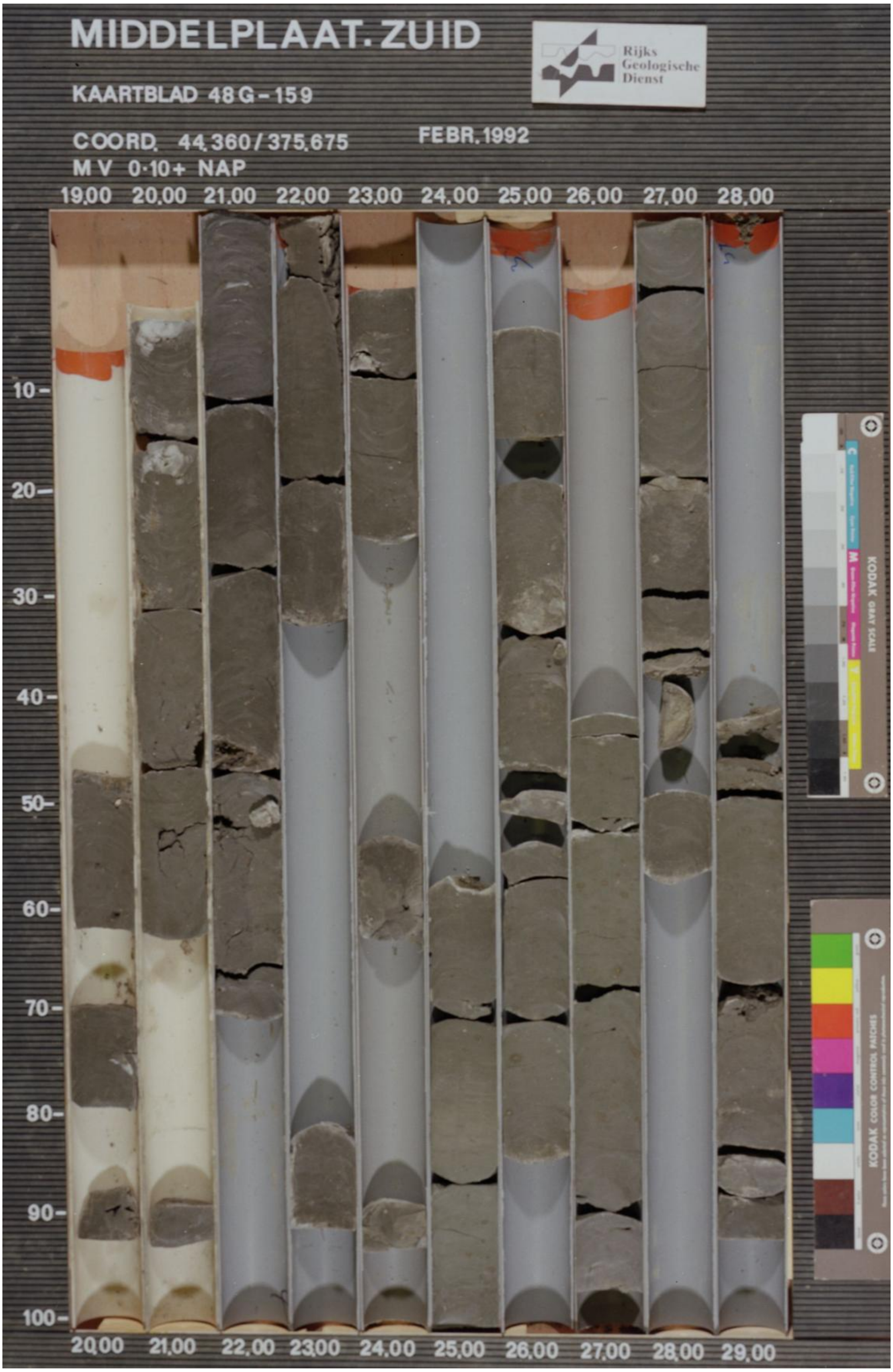


Figure 3-5 Picture of borehole B48G0159 displaying the Rupelian (Boom Member) clay

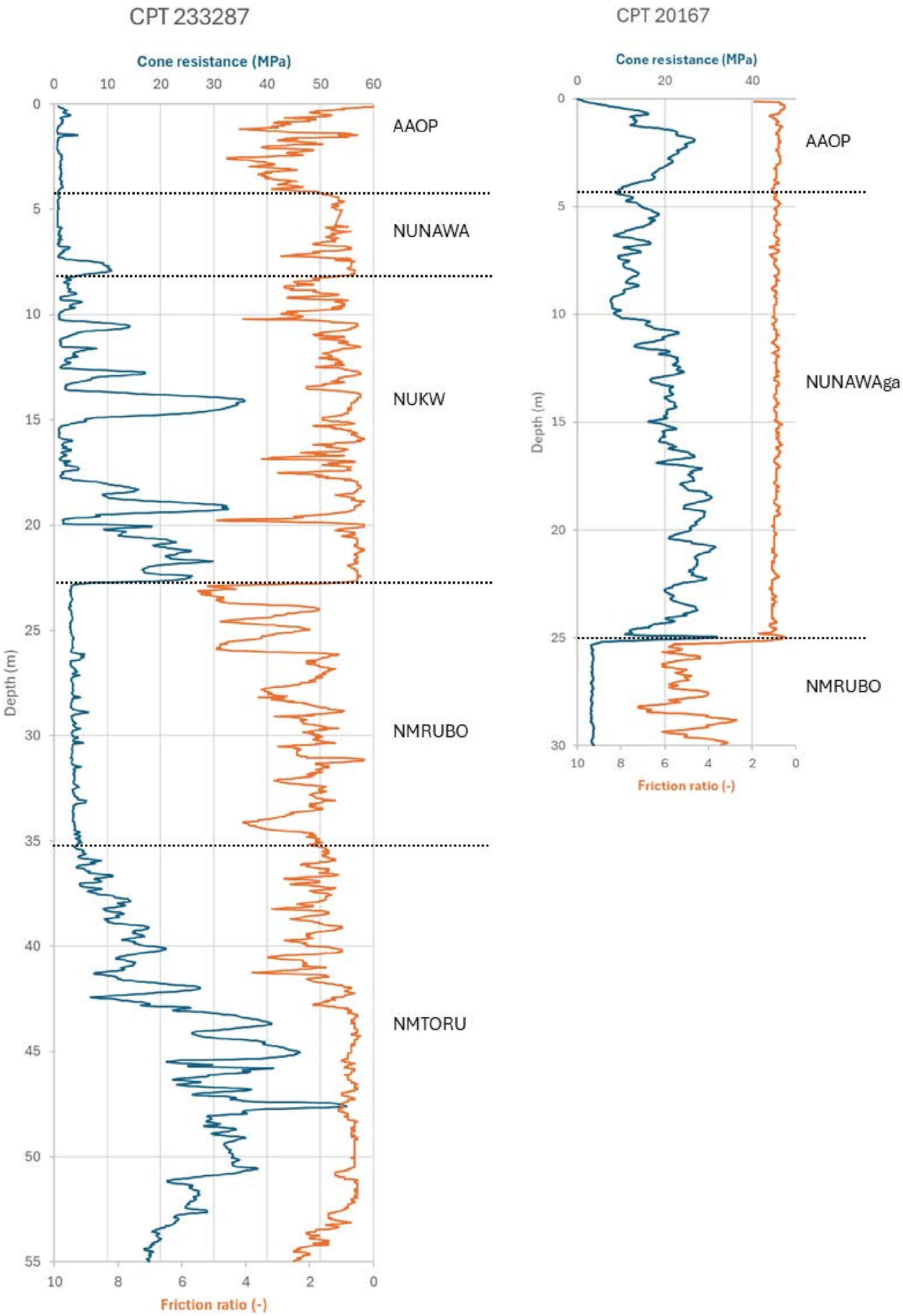


Figure 3-6 Cone penetration test for CPT000000020167 and CPT000000233287 with indicated stratigraphical units. The Eocene clay from the Rupel Formation is clearly recognizable by its low resistivity and relative high friction ratio. The relative sandy deposits from the incised fluviatile (NUKW) or tidal (NUNAWAga) units cause a sharp upper boundary of the Rupel clays. Data can be obtained through DINOloket.

3.2.3 Late Pleistocene

A major hiatus of almost 23 Myrs exists between the preceding Oligocene Rupel Formation clays and the overlying sediments. Sea-level lowstands during Pleistocene glaciations transitioned the Palaeo-Scheldt Delta region into a delta-top environment in which the Palaeo-Scheldt River and its tributaries incised into the older deposits (Kiden, 2010). Marine flooding during interglacial highstands allowed the incised valleys to be filled with estuarine sand.

During the sea-level highstand of the Eemian interglacial, the area of the *Flemish Valley* (see Figure 3-7) was inundated transitioning the area to an estuarine environment. The deposits formed at the time belong to the Eem Formation and can consist of sandy and clayey sediments and also contain shells – partly reworked older shells.

In the vicinity of the Terneuzen site only thin parts of the Eemian deposits are preserved, because the following Weichselian glacial period, the Belgian rivers (Leie, Schelde and Rupel) eroded the major part of the Eem Formation. The Eemian deposits that were eroded have largely been replaced by fluvial deposits, which are part of the Koewacht Formation, from the prior mentioned Belgian rivers. The Koewacht Formation predominantly consists of fine to coarse sand with quartz and flint pebbles (Kiden, 2010). The Koewacht Formation is heterogeneous, both laterally and vertically, and also contains silt and clay layers. Reworked marine shells from the Eem Formation can be found in these fluvial deposits as well, particularly in coarse basal lags. The Eem and Koewacht Formations can occur interfingered.

During the Pleniglacial, the Belgian rivers were draining in northward direction, through the Flemish Valley (Vos & De Vries, 2015, Kiden & Verbruggen, 2001; Figure 3-7), forming the youngest deposits of the Koewacht Formation. At the end of the Pleniglacial, aeolian coversands caused the rivers to shift to the east towards the present-day Scheldt river valley (Figure 3-7). The cover sands continued to build up forming a west-east oriented sand ridge just south of the Dutch-Belgian border, closing off the northward drainage direction completely. Without the northward flowing rivers, the input of fluvial sediments ceased at the surroundings of Terneuzen. Therefore, only deposition of very fine grained periglacial aeolian sands remained during the Late Glacial. These aeolian sands belong to the Boxtel Formation.

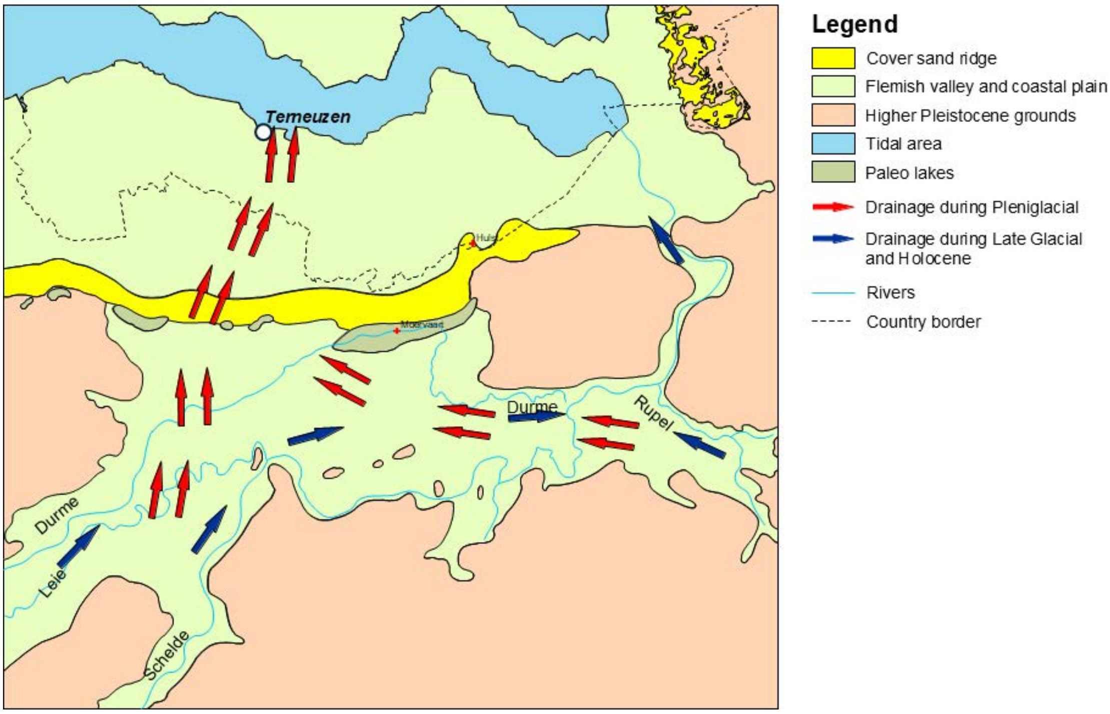


Figure 3-7 Paleolandscape changes of the Flemish Valley during the Weichselian. After: Vos & De Vries (2015), based on Kiden (1991) and Crombé et al. (2013)

3.2.4 Holocene

The geological development during the Holocene was strongly influenced by the sea-level rise after the Last Glacial Maximum (Hijma et al., 2009; Hijma & Cohen, 2019). Rising sea-levels progressively drowned the previously exposed areas (Vos & Van Heeringen, 1997). Initial drowning in the early Holocene is commonly characterized by a thin peat layer known as the Basal Peat Bed of the Nieuwkoop Formation. The overlying clastic tidal deposits of the Wormer Member of the Naaldwijk Formation indicate further drowning of the area due to relative sea-level rise. More peat, in the form of the Hollandveen Member occurs higher in the sequence and is typically overlain by clastic tidal deposits of the Walcheren Member of the Naaldwijk Formation.

At the Terneuzen site tidal channels incised into the older deposits up to about -20 m NAP around 1500 AD (Figure 3-8). The channels deposited relative sandy sediment, with possible thin clay layers. The early Holocene (Basal Peat), and older deposits (Koewacht and Eem Formations) were eroded. To the west of the site an island was present (Figure 3-8), where a more complete Holocene sequence is still present. Borehole B54B0085 (Figure 3-4) is located at the location of this former island. The peat layer here is present directly on top of the Pleistocene aeolian sands (Boxtel Formation). However, due to its high elevation it is not classified as Basal Peat but as Hollandveen in the GeoTOP model. The peat is also less compacted than Basal Peat would be, due to the smaller overburden.

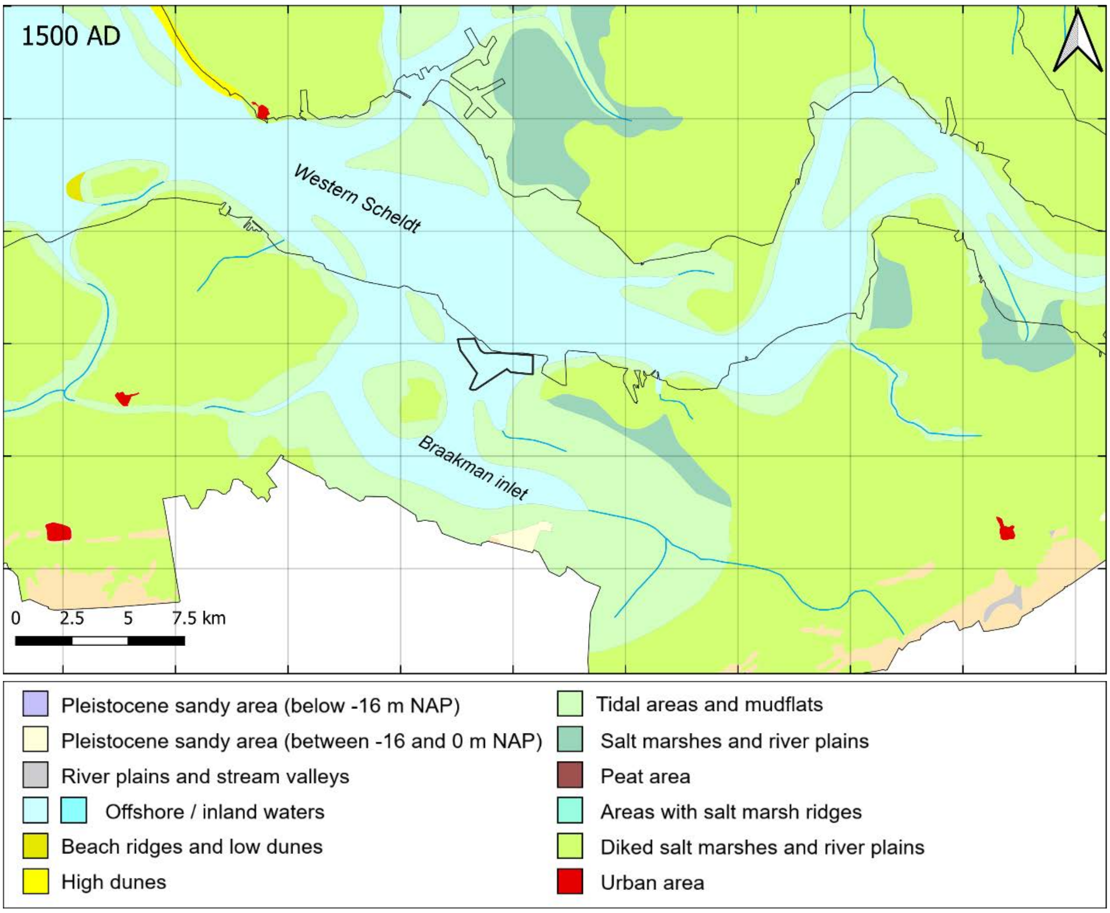


Figure 3-8 Paleogeographical reconstruction (Vos et al., 2020) showing the landscape around 1500 AD. The Terneuzen site lies fully in the then active tidal channels. At the locations of islands to the west of the site, some Pleistocene sands are preserved, as visible in borehole B54B0085 (Figure 3-4).

3.2.5 Anthropogenic influence

The Braakman tidal channel (Figure 3-8) running south from the Western Scheldt was formed by storm surges in the 14th and 15th centuries. The development of this inlet is highly influenced by human activities, off which the recent events can be seen in historical maps (Figure 3-9). The Braakman was still present at the beginning of the 19th century, although its size was decreased, partly due to land reclamation. In 1845 another land reclamation was made, creating the *Paulina* polder, being first drawn on the 1850 map. This polder, consisting of former salt marshes, forms the western part of the Terneuzen site. The eastern part of the site remained a tidal inlet untill 1952 (Figure 3-9: 1950). When a dam was constructed to close off the inlet (see 1961 map), the salt marshes and remnants of tidal channels initially are still present in the eastern part of the Terneuzen site. This part was reclaimed between 1975 and 1977, forming an industrial area and small harbour and the land was raised with 3 to 4 m landfill (mainly sand).

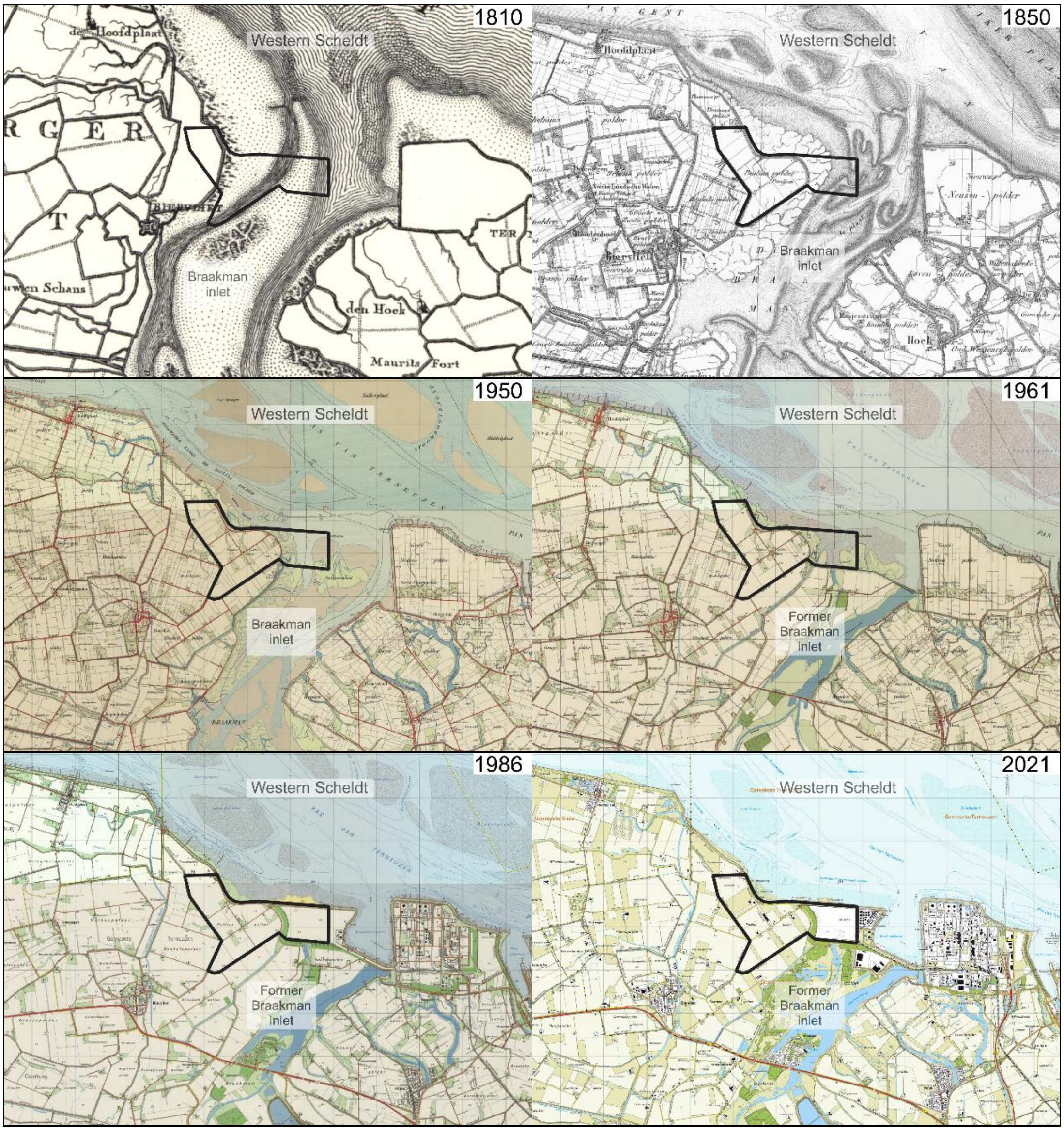


Figure 3-9 Historical maps of the province of Zeeland from 1810 till 2021

4 Geological cross sections

Three geological cross-section were produced to illustrate and understand the build-up of the shallow subsurface down to a depth of 80 m below the surface.

The proximity of the Terneuzen site to the London-Brabant Massif has resulted in a relative shallow occurrence of older, pre-Pleistocene deposits. These show a dip in northern and in eastern direction (Figure 4-1 and Figure 4-2), due to the uplifting of the massif in the south and the tectonic lowering of the area towards the north. This has the following implications: 1) erosion at a later stage causes the large hiatus with the more recent deposits; 2) the further south, the older the deposits below the recent sediments and 3) in general, the thickness of Holocene units decreases in southern direction.

The Eocene Dongen Formation and Eocene to Oligocene Tongeren Formation show an alternation of more sandy and more clayey units (e.g. B54B0046 in Figure 4-2). Due to the low data density in these depth ranges, the geological models are relatively uncertain. Along the Western Scheldt Tunnel trajectory the data density is higher (Figure 4-3), with multiple boreholes and CPT’s reaching into the Tongeren Formation. Note that CPT data was not included in the creation of the geological models, leading to local mismatches where only CPT data is available.

A good reference and recognizable unit at the Terneuzen site are the fat and stiff clays of the Oligocene Rupel Formation (Boom Member), which are present throughout the entire area. The top is eroded, by Pleistocene rivers (Koewacht Formation) and Holocene tidal channels (Naaldwijk Formation). In the western part of the site some Eemian marine deposits may be present on top of the Rupel clay. Outside the site, on the western side, a patch of Pleistocene cover sand and Holocene peat is preserved (visible on the west-east section, Figure 4-1).

In the entire Terneuzen site the top of the Pleistocene deposits have been reworked by the Holocene tidal channels. In the western part, some of the Pleistocene deposits are expected to be preserved. This part was reclaimed in 1845, creating the *Paulina polder*. In the most eastern part of the site the (relatively sandy) Holocene tidal deposits have eroded into the Rupel clay. After closure of the tidal channel with a dam, part of the tidal marshes have been reclaimed and a layer of 3 to 4 m landfill was placed (*Mosselbanken* NUAAOP in west-east section, Figure 4-1).

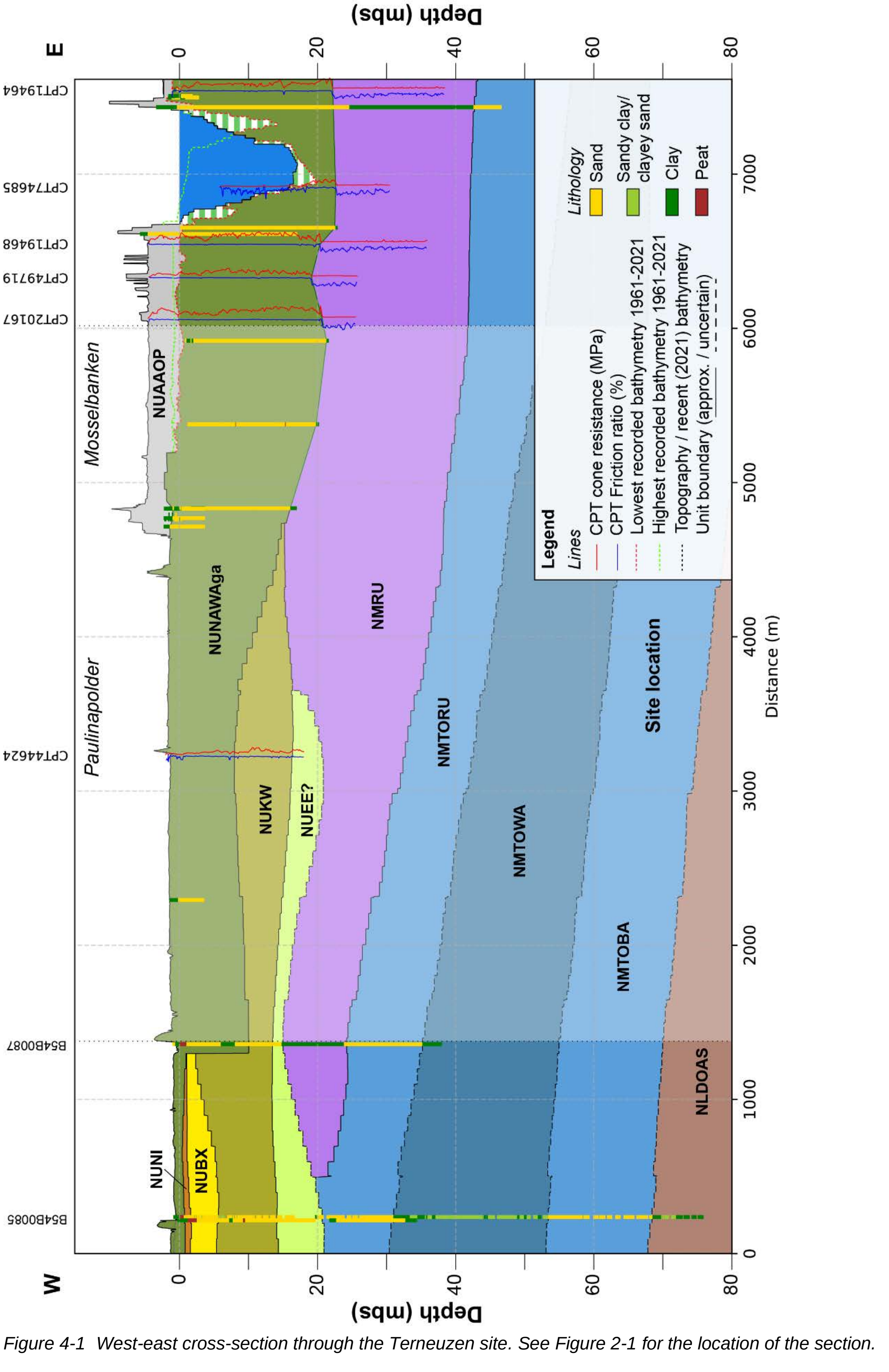


Figure 4-1 West-east cross-section through the Terneuzen site. See Figure 2-1 for the location of the section.

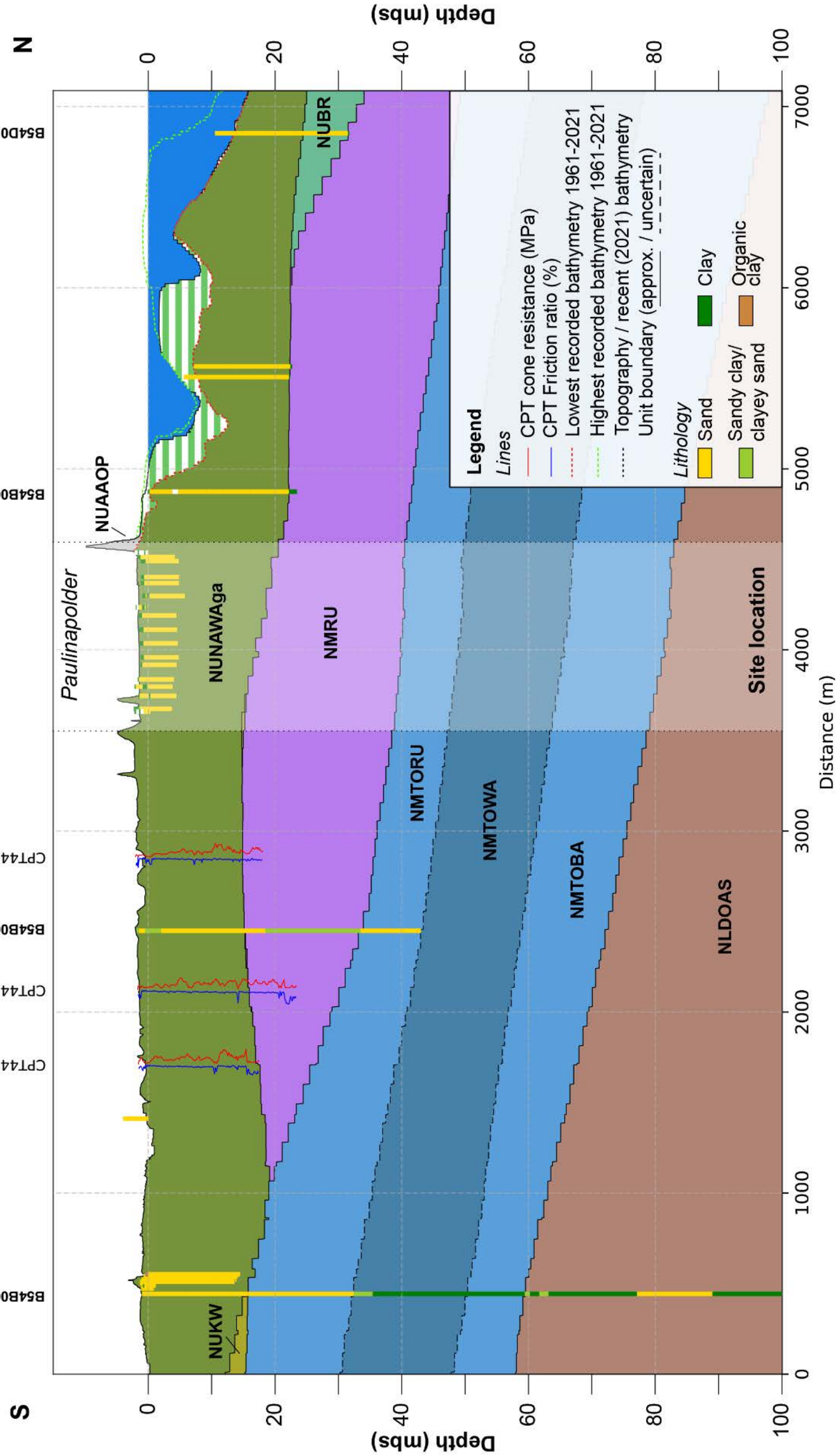


Figure 4-2 North-south cross-section through the Terneuzen site. See Figure 2-1 for the location of the section.

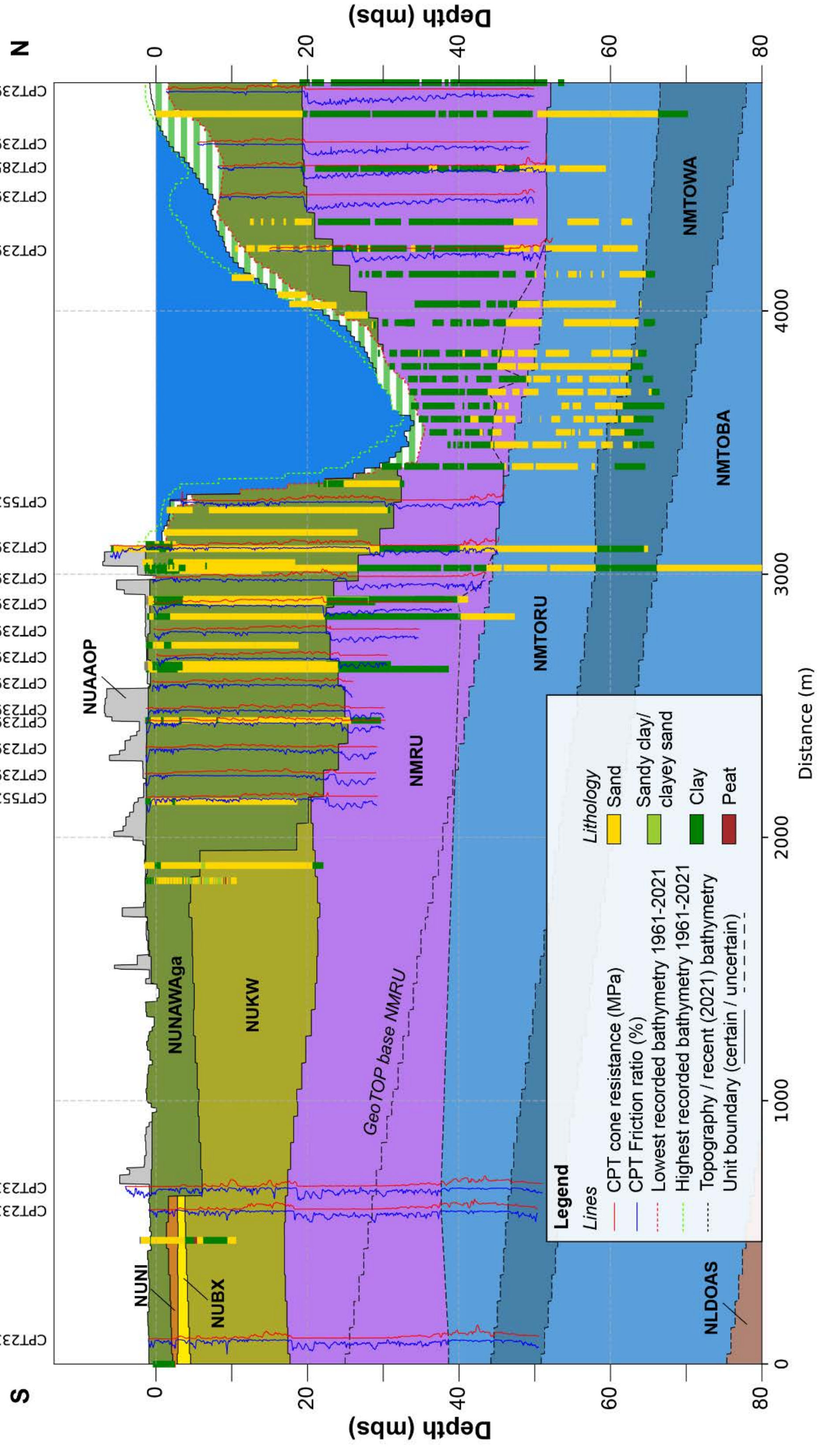


Figure 4-3 North-south cross-section about 3.5 km east of the Terneuzen site, at the nearby tunnel trajectory were data density is much higher. See Figure 2-1 for the location of the section.

5 Geohydrological site characterization

5.1 Introduction

Geohydrological investigations are essential for assessing groundwater conditions in various contexts. They support construction projects by evaluating groundwater levels and pressures that can affect foundations or cause uplift. They help determine the suitability of sites for water extraction and to understand how groundwater moves through the subsurface that might be important for contaminant transport. For spatial planning and permitting, such studies assess the impact of land-use changes on groundwater. Lastly, they are vital in understanding how groundwater influences subsidence, especially in clay or peat soils. The next sections give an overview of data relevant to the above mentioned topics.

5.2 Geohydrological characterization based on REGISII and GeoTOP

The Dutch national geohydrological model REGISII and the national subsurface model for the top 50 m of the subsurface, GeoTop v1.6.1, are used to provide a basic overview of the geohydrological conditions at the project area for Terneuzen. Both are also used in the construction of the Dutch National Groundwater flow model (LHM, Janssen, 2025). REGISII is mainly used to delineate between the sequence of aquifers and aquitards and GeoTOP is mainly applied to derive permeability values for the uppermost Holocene layer. These are not supplied with REGISII.

Two cross sections over the Terneuzen site are created along the same transects as discussed in Chapter 4. The locations of these lines are given in Figure 2-1. The geohydrological parameters of those cross sections are described in detail in the following subsections. In general it is worth to mention that the GeoTOP model, as well as the detailed mapping in Chapter 4 provide a slightly different interpretation of the geological succession, particularly in the uppermost 25 m, both compared to REGISII. Also worthwhile to acknowledge is that REGISII and GeoTOP are both intended for use at a regional-scale level, which in both cases forced simplifications of subsurface conditions. Therefore, studies at a local scale may use these 3D models as starting point but require adjustments to account for higher resolution variability encountered when comparing to our local interpretation of the subsurface. This influences depth and lateral continuity of aquifer and/or aquitard layers.

5.2.1 Cross section W - E (Profile 1)

A west-east cross section over the Terneuzen site is given in Figure 5-1. In the uppermost subfigure a cross-section is given from a REGISII schematization. It distinguishes a single Holocene unit of ~2-meters thickness in the west of the site and up to 20 meters thickness at the east of the site. In the west it covers the sands of the Boxtel Formation (NMBX, 0-5 meter) on top of the upper sandy deposits of the Koewacht Formation (NMKWz1, 0-10 meters). Underneath, a thin layer (0-5 meters) of the Eem Formation (NMEEz1) are present. Below this, the clayey sediments of the Rupel Formation (NMRUBOk1) are present that is present under the entire site. In the east, because all fluvial sediments are absent, it is directly below the Holocene deposits. Finally, a clay-rich layer of sands, belonging to the Tongeren Formation lies underneath with a thickness of 40-50 meters.

In the more detailed geological model for the uppermost 25 m of GeoTOP (see mid figure in Figure 5-1), the Holocene sequence is divided into a landfill layer of maximally 5 meter thick. This is laid on top of the Naaldwijk Formation (NUNAWA2) and/or the recent tidal channel fill (NUNAWAga). Deeper in the succession, another difference in aquitard presence may be noticed between the models (REGISII and GeoTOP). The sandy deposit of the Boxtel

Formation (NMBX) is assigned to the Koewacht Formation (NMKW). The other formations underneath are similar.

In the lithology model for the uppermost 25 m of GeoTOP (see lowest figure in Figure 5-1), the lithology is presented. From a geohydrological point of view it is important to notice that all geological layers on top of the NMRUBOk1 are all members of fine to coarse sands. Local distortions of clay exits but are irrelevant for groundwater flow. Important to observe is the high presence of clayey-sand and clay of the NMRUBOk1 Formation, as it disconnects the drainage towards the Western Scheldt from the deeper layers. Further to the west, the NMRUBOk1 declines which introduces interaction between shallow and deeper groundwater.

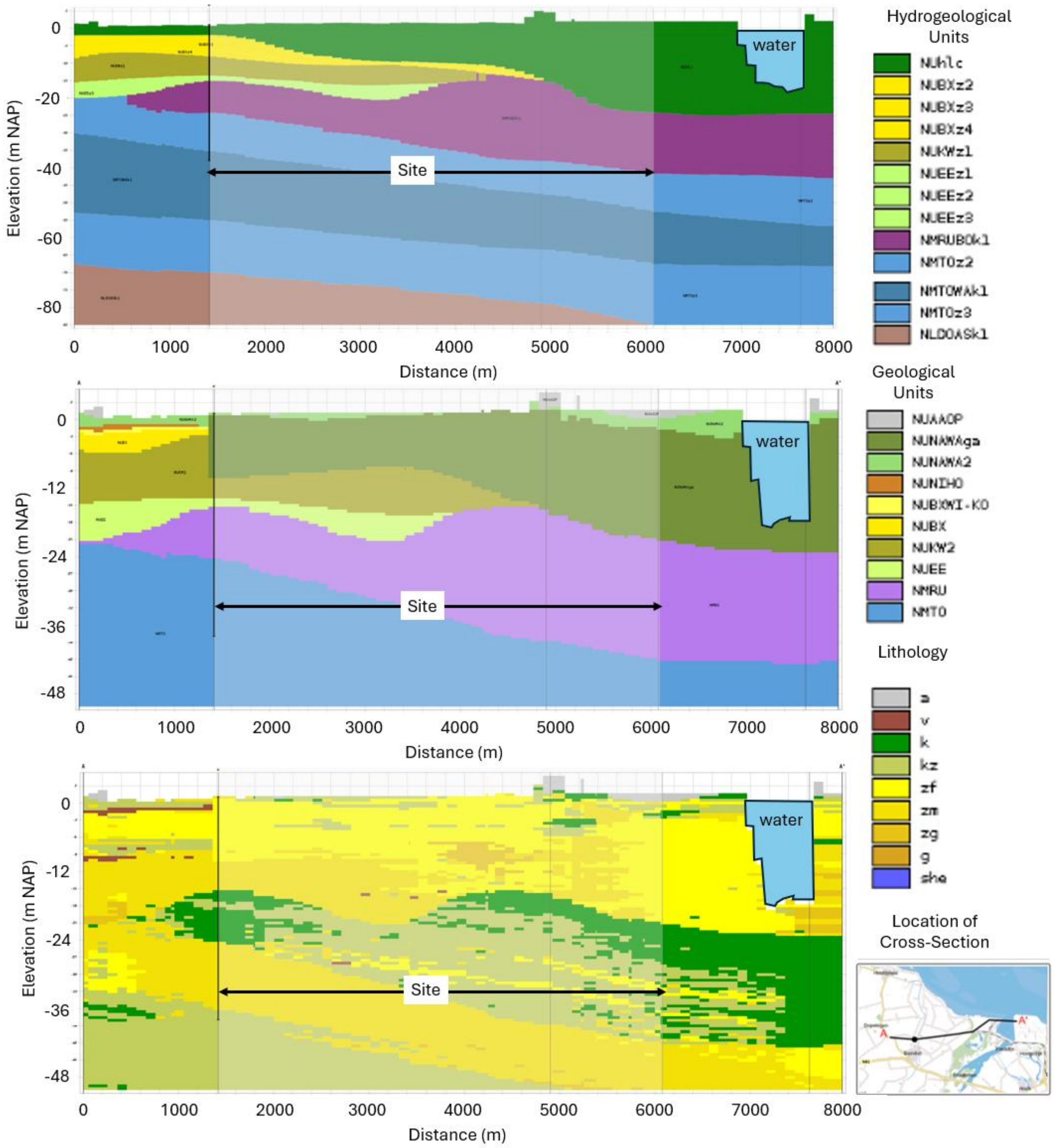


Figure 5-1 West – East REGISII (top) and GeoTOP v1.6.1 (mid geological units and bottom lithology) cross section across the Terneuzen site. The location of the cross section is similar are used in Figure 4-1. Note that the vertical scale of the first and the second/third cross sections is different, with the top panel showing the situation down to -80 m NAP and the lower panel showing the situation down to -50 m NAP.

5.2.2 Cross section S - N (Profile 2)

A south-north cross section over the Terneuzen site is given in Figure 5-2. South of the Terneuzen site, REGISII characterizes the first 15 – 30 meters of the subsurface as Holocene deposits (NUHlc Formation). Only a thin layer of the Boxtel Formation appears underneath the Holocene. From GeoTOP this layer is absent. The Holocene deposits (NUhlc) are further discretized into a thin layer of Antropogene (NUAAOP) sediments on top of thin layer (1-3 meter) of sediments of Naaldwijk Formation (NUNAWA2) on top of the Walcheren Formation (NUNAWAga). The thickness of this last layer varies in between 5 up to 15 meters. This layer connects to three different formations. First, north of the site of Terneuzen it connects to the Breda Formation (NMBR-VI) with fine sands. At the site itself, it connects to the Boom Clay of the Rupel Formation (NMRUBOk1) and south of the site it connects to the fine sands of the Tongeren Formation (NMTO). Underneath the clayey sands of the Dongen Formation exist.

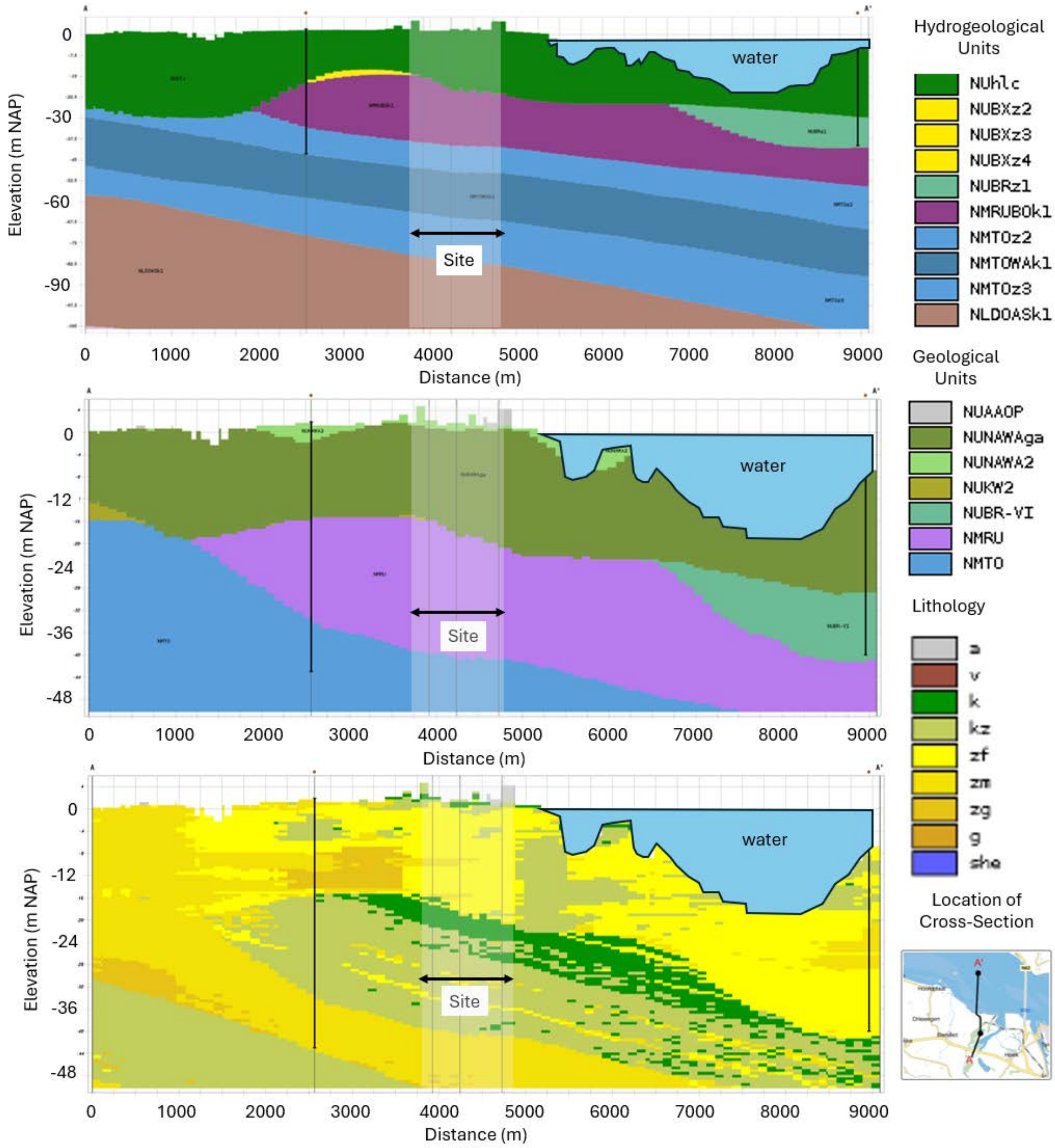


Figure 5-2 South – North REGISII (top) and GeoTOP v1.6.1 (mid geological units and bottom lithology) cross section across the Terneuzen site. The location of the cross section is similar are used in Figure 4-2. Note that the vertical scale of the first and the second/third cross sections is different, with the top panel showing the situation down to -80 m NAP and the lower panel showing the situation down to -50 m NAP.

5.3 Available data for geohydrological site characterization

There is no publicly available pumping test data available in DINOloket. From the REGISII 3D model an interpolation is provided with estimated values for permeability and layer thicknesses. For three representative locations in the Terneuzen site, these are listed in Table 5-1,

Table 5-2, and Table 5-3.

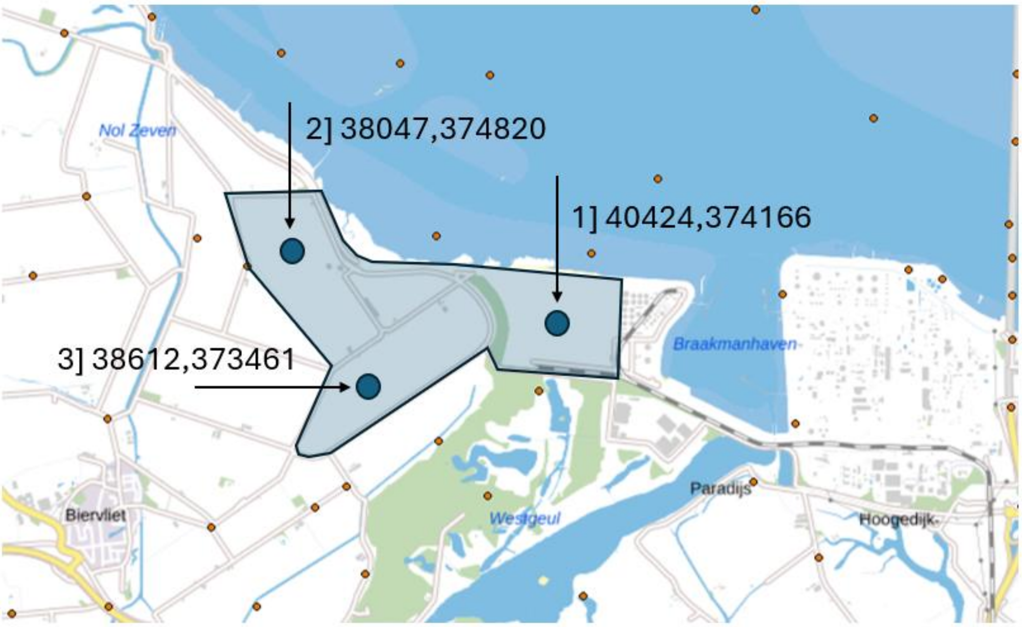


Figure 5-3 Location of three arbitrary location on the Terneuzen site to identify a geohydrological interpretation.

Table 5-1 Overall geohydrological representation of the eastern Terneuzen site at 1] x=40424; y=374166 (RD). Kh=horizontal permeability and Kv=vertical permeability.

Layer	Geohydrological unit	Lithology	Formation name	Top [m NAP]	Bottom [m NAP]	Kh [m/d]	Kv [m/d]
1	Phreatic aquifer	Variable	NUHlc	2	-24	1*	0.1*
2	Aquifer1	absent	absent				
3	Aquitard1	Clay	NMRUBOk1	-24	-41		5E-5
4	Aquifer2	Sand	NMTOz2	-41	-51	2.5-5	
5	Aquitard2	Clay	NMTOk1	-51	-66		1E-4-5E-4
6	Aquifer3	Sand	NMTOz3	-66	-83	1-2.5	
7	Aquitard3	Clay	NMDOASk1	-83	-133		5E-5

** estimated from LHM*

Table 5-2 Overall geohydrological representation of the western Terneuzen site at 2] x=38047; y=374820 (RD). Kh=horizontal permeability and Kv=vertical permeability.

Layer	Geohydrological unit	Lithology	Formation name	Top [m NAP]	Bottom [m NAP]	Kh [m/d]	Kv [m/d]
1	Phreatic aquifer	Variable	NUHlc	2	-12.5	1*	0.1*
2	Aquifer1	Fluvial sand	NUBXz2	-12.5	-13	2.5-5	
		Fluvial sand	NUBXz3	-13	-14.5	2.5-5	
		Fluvial sand	NUBXz4	-14.5	-15	2.5-5	
		Fluvial sand	NUKWz1	-15	-17	10-25	
		Sand	NUEEz2	-17	-17.25	10-25	
		Sandy	NUEEz3	-17.25	-17.5	10-25	
3	Aquitard1	Clay	NMNUBOk1	-17.5	-39		5E-5
4	Aquifer 2	Sand	NMTOz2	-39	-47	2.5-5	
5	Aquitard2	Clay	NMTOk1	-47	-66		1E-4-5E-4
6	Aquifer3	Sand	NMTOz3	-66	-82	1-2.5	
7	Aquitard3	Clay	NMDOASk1	-82	-129		5E-5

** estimated from LHM*

Table 5-3 Overall geohydrological representation of the southern Terneuzen site at 3] x=38612; y=373461 (RD). Kh=horizontal permeability and Kv=vertical permeability.

Layer	Geohydrological unit	Lithology	Formation name	Top [m NAP]	Bottom [m NAP]	Kh [m/d]	Kv [m/d]
1	Phreatic aquifer	Variable	NUHlc	1.5	-10	1*	0.1*
2	Aquifer1	Sand	NUBXz2	-10	-10.3	2.5-5	
			NUBXz3	-10.3	-10.5	2.5-5	
			NUBXz4	-10.5	-10.8	2.5-5	
			NUKWz1	-10.8	-16	10-25	
			NUEEz1	-16	-16.2	10-25	
			NUEEz2	-16.2	-16.9	10-25	
			NUEEz3	-16.9	-18.4	10-25	
3	Aquitard1	Clay	NMRUBOk1	-18.4	-33.5		5E-5
4	Aquifer2	Sand	NMTOz1	-33.5	-43	2.5-5	
5	Aquitard2	Clay	NMTOk1	-43	-61		1E-4-5E-4

6	Aquifer3	Sand	NMTOz2	-61	-75	1-2.5	
7	Aquitard3	Clay	NMDOASk1	-75	-130		5E-5

** estimated from LHM*

The hydraulic conductivity for the phreatic aquifer is not given in REGISII. The Dutch Hydrological Model estimated this to be 1 m/d in a horizontal direction and 0.1 m/d in a vertical direction. This is mainly derived from the lithology distribution from GeoTOP and the associated permeability values per lithology. The phreatic aquifer has a transmissivity of 10-25 m^2/day whereas the vertical resistance is estimated to be 100-250 days.

A first aquifer is present at the west and south side of the Terneuzen site. It contains permeability values of 2.5 – 25 m/d and the transmissivity of this aquifer is in between 30 and 200 m^2/day. The first aquitard (average thickness of 20 meter) has an average vertical resistance 300.00-450.000 days. This aquitard is a major barrier for groundwater flow and can be often used as a hydrological base as it separates superimposed layers.

The second aquifer and third aquifer are both sand from the Tongeren Formation for which the third aquifer is slightly less permeable (1-2.5 m/d) than the second (2.5-5 m/d). It yields transmissivities values of 25-50 m^2/d and 35-75 m^2/d for the third and third aquifer, respectively. In between the second and third aquifer there is a second aquitard with an average vertical resistance of 30.000-150.000 days. The lowest aquitard is formed by the clays of the Dongen Formation (45-55 meter thickness) which have a vertical resistance of 950.000-1.100.000 days.

Altogether, the Terneuzen site is characterized by aquifers with a relatively low transmissivity which are vertically separated by aquitards with an enormous vertical resistance. The phreatic aquifer and the first aquifer are connected with the second aquifer further south of the Terneuzen site.

5.4 Hydraulic conductivities based on the pumping- and slug tests

As part of a study (Meerten van and Lambert, 1992) into the feasibility of tunnel construction, two pumping and recovery tests were conducted to investigate the permeability of the "Zanden van Berg" sand layer along the route of the Westerschelde Oeververbinding (Western Scheldt Tunnel). The so-called “Zanden van Berg” are nowadays called sands from the Formation of Tongeren. At the Middelplaat (borehole B48G0160), the Formation of Tongeren is found between approximately -61.30 m NAP and -73.20 m NAP and at borehole location B54E0269 near Terneuzen, the Formation of Tongeren is present between approximately -44 m NAP and -59 m NAP, see Figure 5-4.

Based on test analyses, the transmissivity of the Formation of Tongeren for horizontal groundwater flow is estimated at 40 to 45 m^2/day for B48G0160 and 70 to 90 m^2/day for B54E0269. Considering an effective thickness of about 10 m (B48G0160) and 15 m (B54E0269), the hydraulic conductivity at these borehole locations are estimated at around 4.0-4.5 m/day. The determined values for the hydraulic conductivity of the Formation of Tongeren sand deposits are within the typical range for fine sand. Nevertheless, they are slightly higher than the estimated (interpolated) conductivity values (1-2 m/day) by REGISII at the Terneuzen site, which is ~4000 meter more to the west. The range of transmissivity values from REGISII (25-75 m^2/d, see section 5.3) do match the results from this pumping test very well.

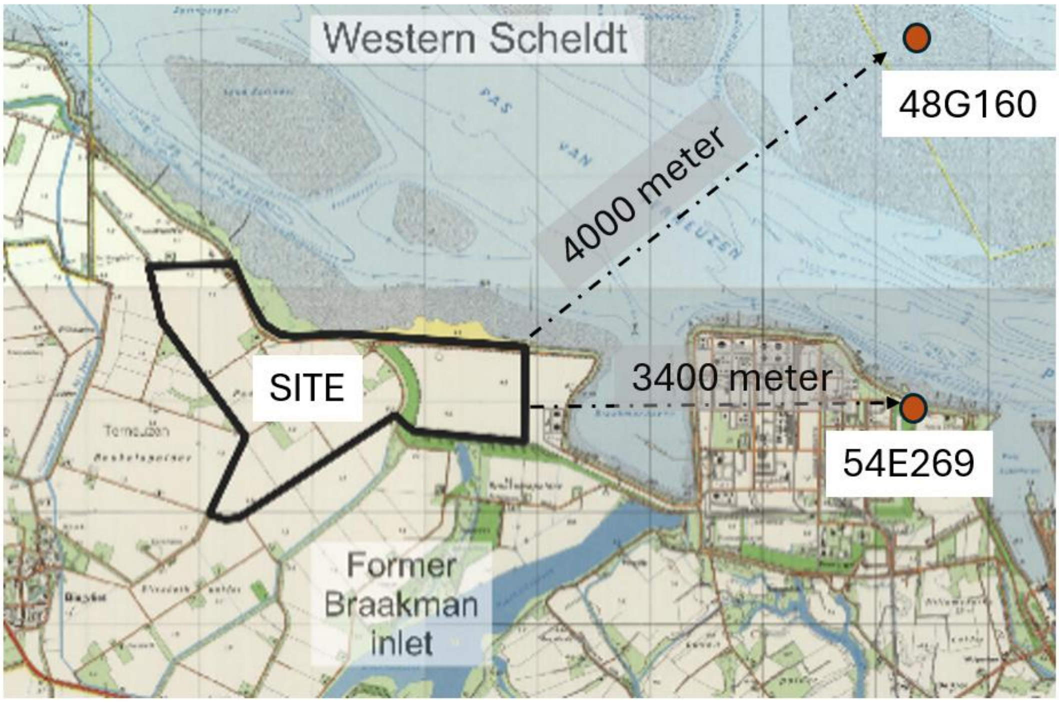


Figure 5-4 Location of pump tests (B48G0160 and B54E0269) to analyze the conductivity in the Formation of Tongeren.

5.5 Groundwater Extraction

Due to the shallow interface of brackish and/or salt water in the subsurface (see section 5.8) groundwater extraction is limited at the Terneuzen site. Only a few wells are registered for extracting groundwater. It is unknown whether these are actually active and if so, how much groundwater they extract. According to the Province of Zeeland (n.d.) up to a maximal rate of 60 m^3/hour (limited to 8,000 m^3/year) a farmer can extract groundwater without having a license.

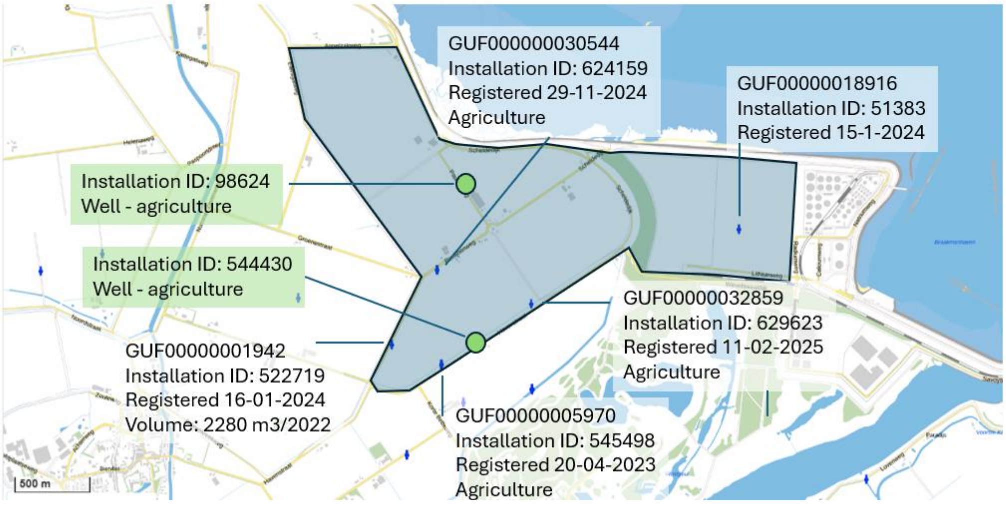


Figure 5-5 Overview of extractions for agricultural extractions in the Terneuzen site, in blue derived from dinoloket.nl; green additional installations derived from wkotool.nl.

Further south of the Terneuzen site, the Braakman inlet serves as an important source of drinking water, managed by Evides Waterbedrijf. Water is extracted from the Braakman and its reservoirs, purified at facilities such as the Braakman treatment plant, and supplied to both households and businesses. The area includes reservoirs for storing and regulating water, used for both drinking and industrial purposes.

5.6 Groundwater level monitoring

Publicly available information on measured piezometric levels is available through www.DINOloket.nl and https://www.grondwatertools.nl/gwsinbeeld/. There is only one piezometric data available inside the Terneuzen project area (B48D0354). Surrounding monitoring wells are located at respectively (south)-east (B54E0227, B54B0048, B54B0094 and B54B0064) and 1 km west of the Terneuzen site (B54B0062), see Figure 5-6. Timeseries of these observation wells are included in the figure as well, the ones with a red rectangle are given in more detail in Figure 5-7.

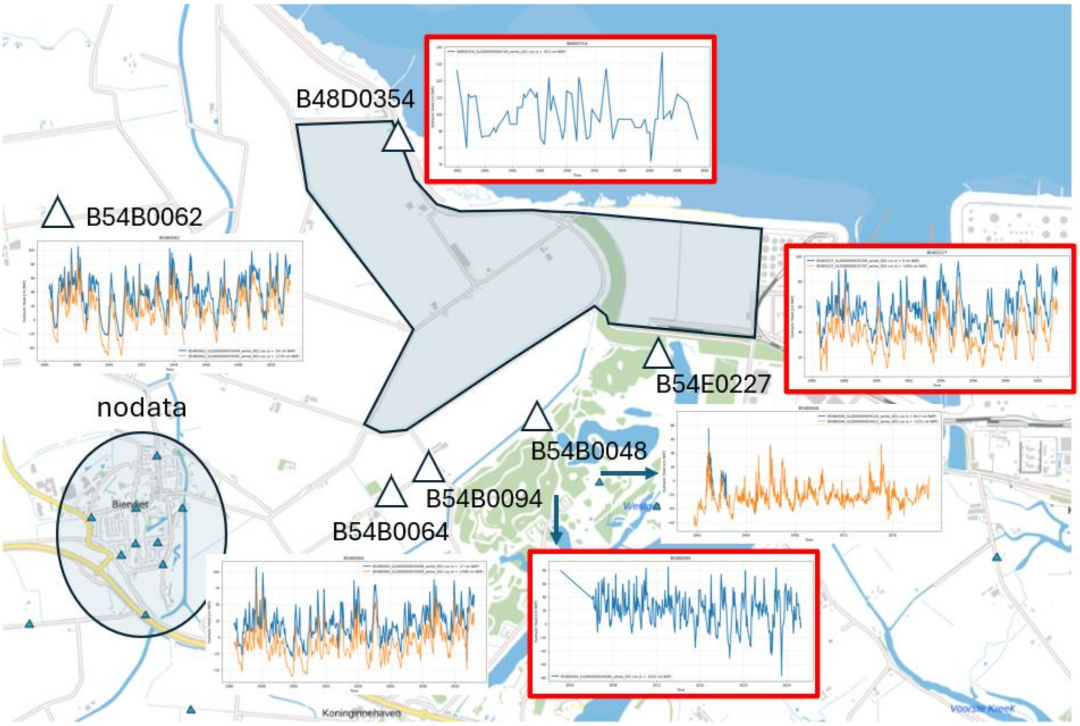


Figure 5-6. Locations of the monitoring wells near Terneuzen site. At Biervliet village (blue circle) many observations wells are present but no records of levels are available.

Most of the measurements, east of the Terneuzen site, were created in 1986 at the development of the nature conservation area “Braakman”; they are all abandoned in 2001. Several monitoring wells are drilled in Biervliet village but there is no data available. Important to note is that all, except for one (B54B0094 at the south side of the Terneuzen site), stopped measuring the groundwater level since decades, unfortunately. See Table 5-4 for all detailed information on the configuration of the monitoring wells.

Table 5-4. Locations of the monitoring wells near Terneuzen site.

Monitoring well	RD-X	RD-Y	Elevation	Number	Top filter	Bottom filter	Data range	
	[m]	[m]	[cm NAP]		[cm NAP]	[cm NAP]	Start measurement	End measurement
B48D0354	38290	375085	148	001	-913	-1013	14-12-1981	28-06-1999
B54B0094	38540	372677	186	001	-1635	-1735	07-03-2003	28-03-2025
B54E0227	40210	373510	208	001	9	-91	14-04-1986	15-03-2001

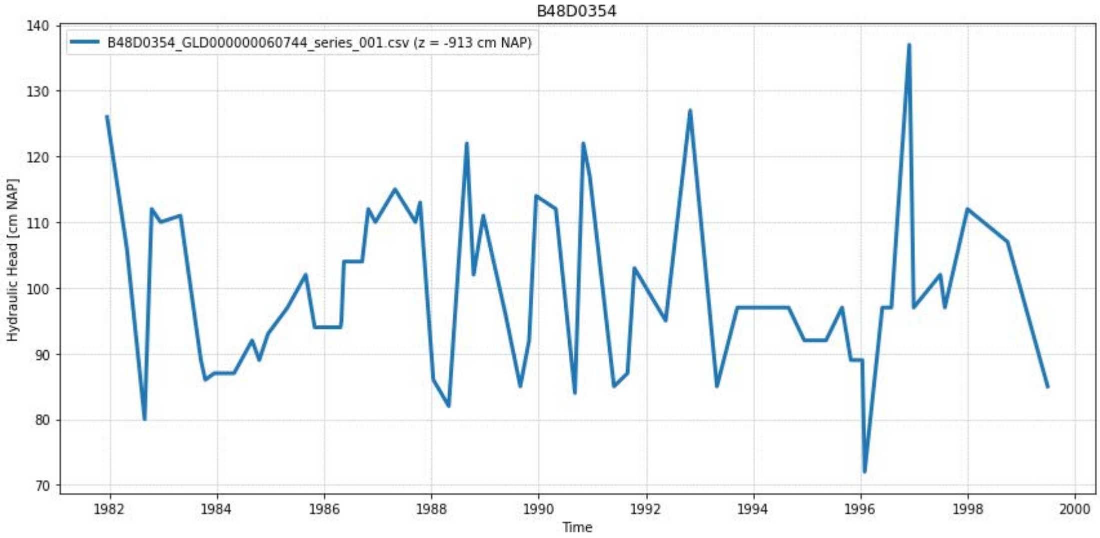
				002	-1450	-1550	14-04-1986	15-03-2001
B54B0048	39340	373070	269	001	69	-31	29-04-1959	28-12-1978*
				002	-1231	-1331	29-04-1959	28-12-1978
B54B0064	38270	372490	180	001	-17	-117	14-04-1986	14-03-2001
				002	-1708	-1808	14-04-1986	14-03-2001
B54B0062	35810	374510	159	001	-54	-154	15-04-1986	15-03-2001
				002	-1736	-1836	15-04-1986	15-03-2001

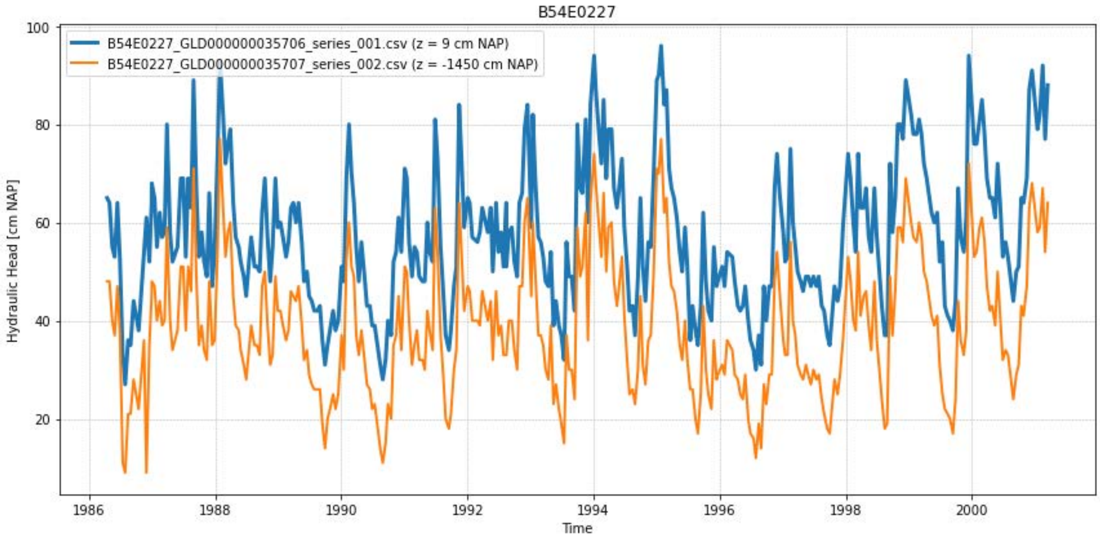
**contains many nodata points after 1968*

Some basic insights may be derived from these historical datasets in more detail (see Figure 5-7). The monitoring well B48D0354 that is at the north side of the Terneuzen site has only a few measurements per year up to 1999. It gives a rough estimation that groundwater levels here tend to vary on average, between 80-130 cm NAP; meaning shallow groundwater levels of 20-70 cm below surface level.

East of the Terneuzen site, along the nature conservation area Braakman several observations are present. Here, agricultural land was transformed into the recreational area under maintenance of Staatsbosbeheer Zeeuws-Vlaanderen. Along the west side of the so-called Braakmankreek, forest was planted and parts of the land were designated as a nature reserve. In recent years, this natural area has undergone a transformation and has been significantly expanded. Many bird species can be seen on the creeks and ponds or in the surrounding meadows. The (geo)hydrology in this area must be preserved in the future.

In between the Terneuzen site and this nature conservation area, several abandoned monitoring wells are present. From their historical records the average groundwater levels vary between 80 and 40 cm (B54E0227) and between 75 and -12.5 cm NAP (B54B0064). For both, the average groundwater level is 130-150 cm below surface level. Highest levels are 75-100 cm below surface level. As said these are all not monitored since 2001. The only active monitoring well is B54B0094 and that shows up to 2016 similar high groundwater levels up to 100 cm below surface levels. From 2016 onwards, the groundwater levels tends to drop below consistently up to -70 cm NAP, for unknown reasons. This might be of interest to investigate in future.


B48D0354
B48D0354_GLD000000060744_series_001.csv (z = -913 cm NAP)
Hydraulic Head [cm NAP]
Time


B54E0227
B54E0227_GLD000000035706_series_001.csv (z = 9 cm NAP)
B54E0227_GLD000000035707_series_002.csv (z = -1450 cm NAP)
Hydraulic Head [cm NAP]
Time

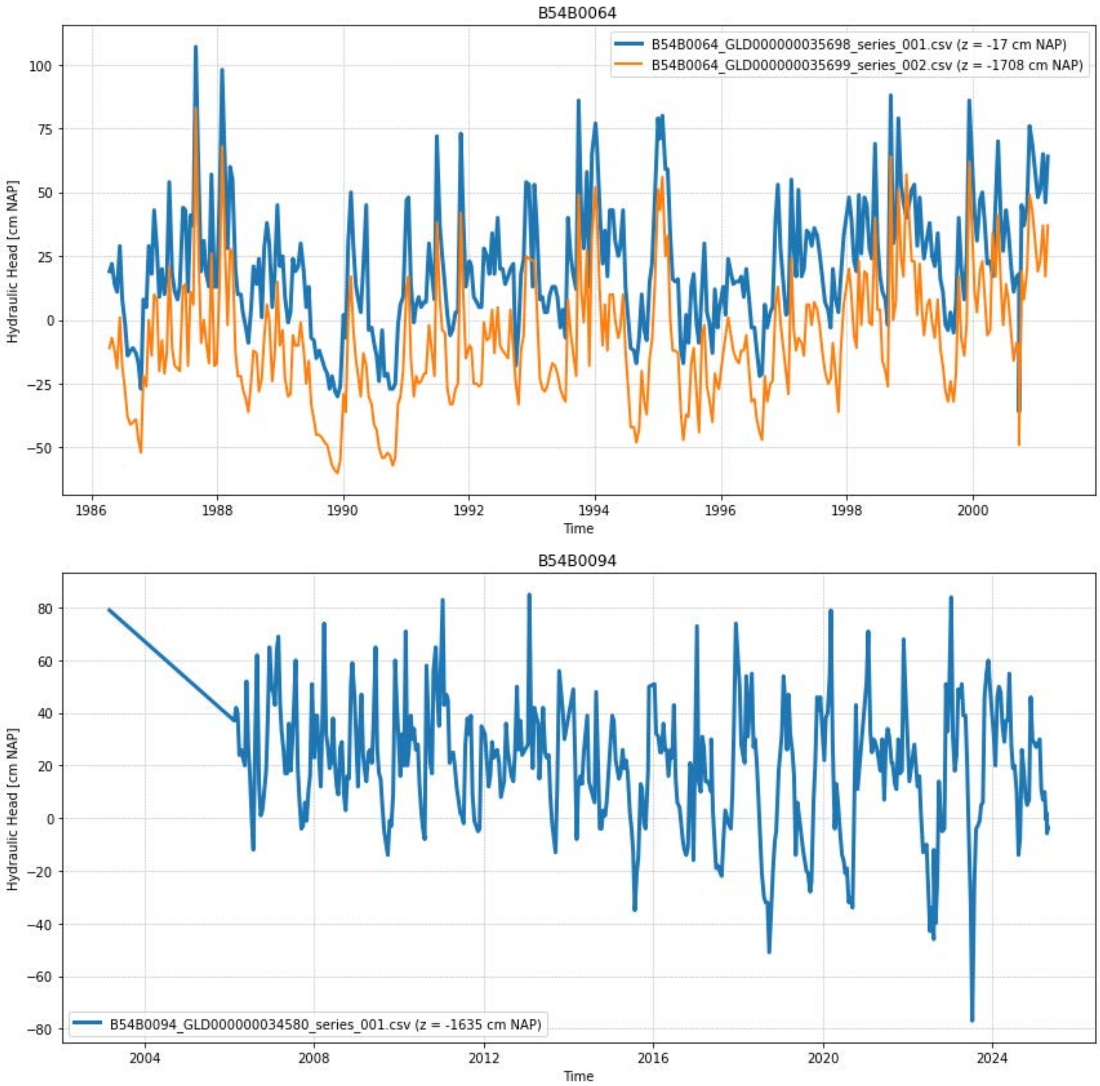


Figure 5-7. Some measured piezometric head around the Terneuzen site: north (B48D0354), east (B54E0227 and south (B54B0064 and B54B0094). The heads are measured from various depths given in the legend of each figure.

For B54B0094, B54B0062 and B54E0227, the average highest (GHG), lowest (GLG) and spring groundwater levels (GVG) are calculated (see https://www.grondwatertools.nl/gwsinbeeld/). These values are listed in

Table 5-5. There is a significant difference of ~30 cm in levels between the filters 001 and 002 for all three monitoring wells. This suggests a strong trend of groundwater seeping downwards. This makes sense as the surface water levels in the streams and canals in the Paulina Polder (part of the Terneuzen site) have a summer river stage of 70 cm NAP and a winter river stage of 40 cm NAP (source: Waterboard Scheldestromen). These are all higher than the average level of the Western Scheldt (0 cm NAP).

Table 5-5. The GHG (average highest groundwater level), GLG (average lowest groundwater level, and GVG (average spring groundwater level) for B54B0094, B54B0062 and B54E0277..

Monitoring well		**Average highest groundwater level**	**Average lowest groundwater level**	**Average spring groundwater level**
		GHG [cm NAP]	GLG [cm NAP]	GVG [cm NAP]
B54B0094	001	55.4	-12.5	25.0
	002	26.2	-40.4	-2.0
B54B0062	001	70.2	0.6	46.5
	002	49.1	-17.6	25.8
B54E0227	001	75.3	35.7	63.3
	002	55.1	17.3	43.4

All observations are not directly in the Terneuzen site and give only a general indication of the groundwater conditions in the nearby neighborhood. In the next subsection an addition is made from the Dutch Hydrological Model (Janssen, 2025).

5.7 Modelled Groundwater situation

5.7.1 Introduction

The groundwater levels at the site are not represented by any existing measurement observation. The nearest measurements are more than 500 meters away. As an addition, predicted groundwater levels can be derived from the Dutch Geohydrological Model (LHM) that simulates groundwater levels from 1970 up to 2022 on a daily basis. The model resolution is 250 x 250 meter and it serves therefore to simulate regional conditions rather than local ones. Nevertheless, the LHM is suitable to give insights in regional geohydrological conditions that might initiate local studies in the future that also can take the presence of aspects like sheet piles and quay walls into account.

The LHM describes the subsurface in eight layers in which the lithology of GeoTOP has been incorporated, see Figure 5-8. The LHM incorporates the effect of the NUNAWAga and NUNAWA2 as low permeability values between two subsequent model layers. The Koewacht and Eem Formation each form separate model layers with artificial intermediate layers. Where these layers are absent, the permeability is lower as they correspond to the NUNAWAga and NUNAWA2 Formation underneath the Braakmanhaven. An aquitard with a low permeability value (k<0.001 m/d) belongs to the NMRUBOk1. Underneath the NMTOz2 and below that the NMTOk1, gain with low permeability values. The LHM represents the geology as characterized by REGIS II, GeoTOP and the detail mapping done in section 4.

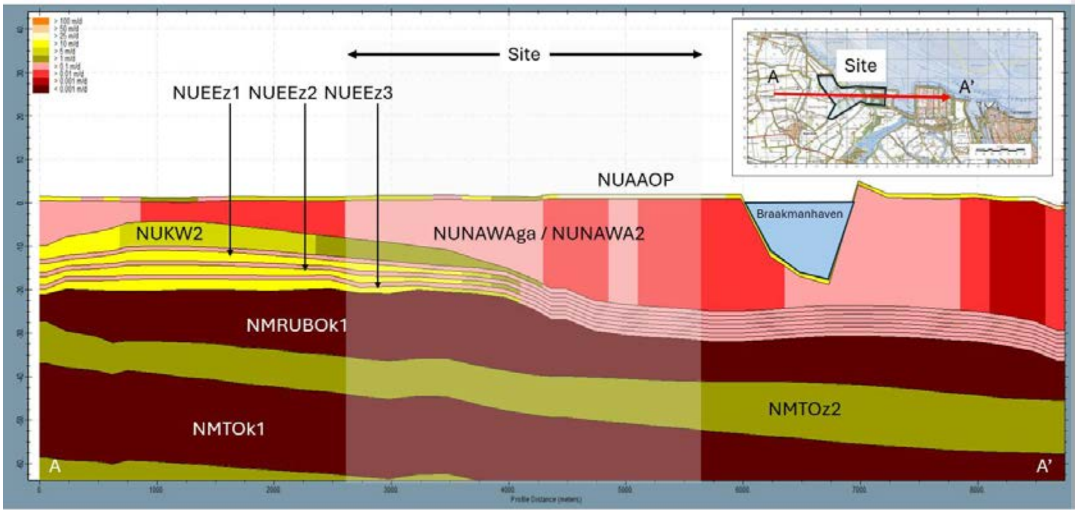
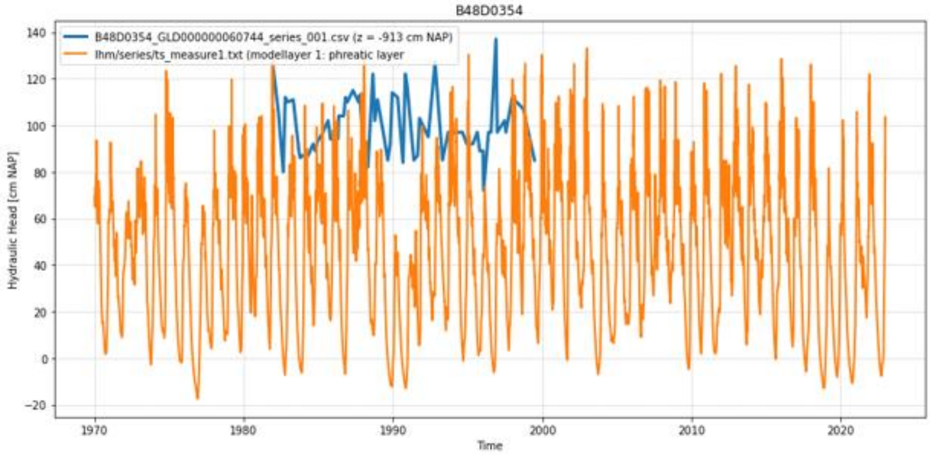


Figure 5-8 Cross section over site Terneuzen through the subsurface of the LHM showing the first seven model layers (aquifers yellow/greenish) and aquitards in between (brown/reddish).

5.7.2 Simulated groundwater levels

Using the LHM it is possible to describe the long-term groundwater levels at various locations on the Terneuzen site, where observations are absent. As a validation it has been compared with the phreatic observations in B48D0354, B54B0048, B54B0064, B54B0094, B54E0227 and B54B0062 as described in the previous subsection, see Figure 5-9.


B48D0354
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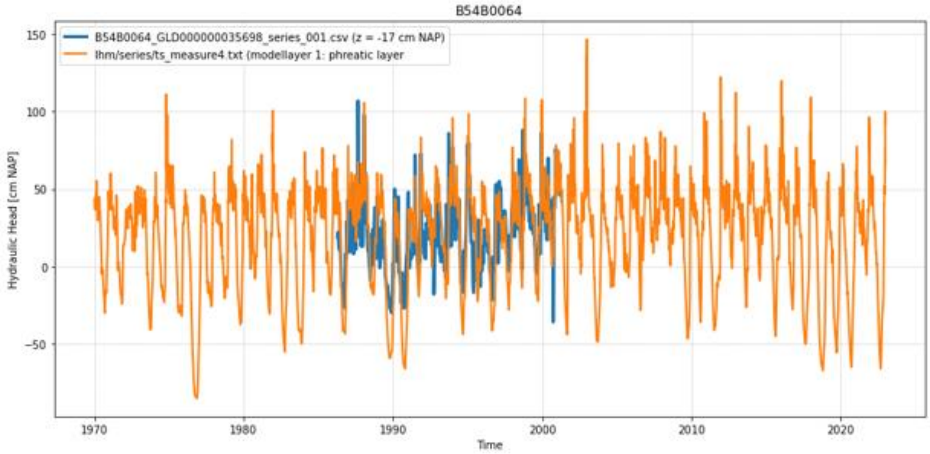
lhm/series/ts_measure1.txt (modellayer 1: phreatic layer
Hydraulic Head [cm NAP]
Time


B54B0064
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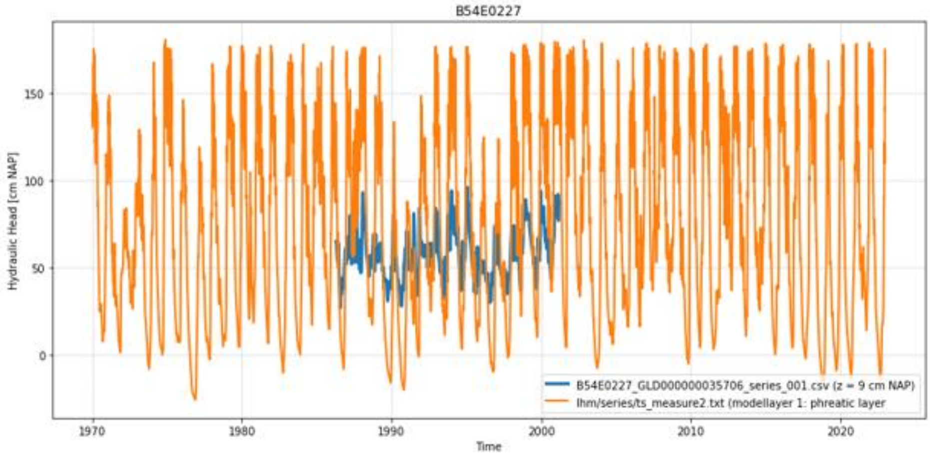
lhm/series/ts_measure4.txt (modellayer 1: phreatic layer
Hydraulic Head [cm NAP]
Time


B54E0227
B54E0227_GLD000000035706_series_001.csv (z = 9 cm NAP)
lhm/series/ts_measure2.txt (modellayer 1: phreatic layer
Hydraulic Head [cm NAP]
Time

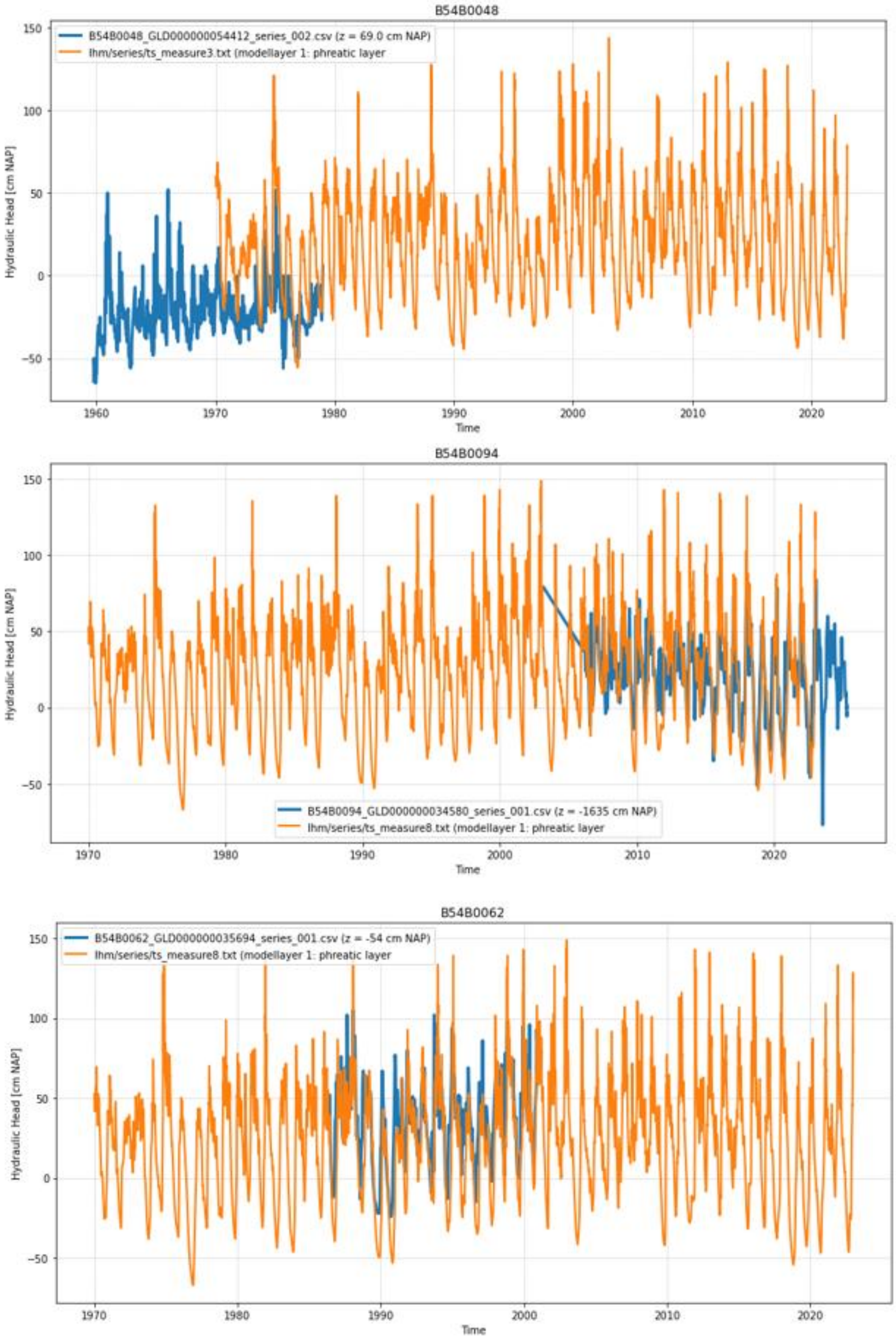


Figure 5-9 Simulated with LHM (in orange) and measured (in blue) groundwater levels for 6 locations with measurements nearby the Terneuzen site.

First of all, important to note that LHM is a regional groundwater flow model, simulating groundwater levels at a resolution of 250 x 250 meter. The calculated groundwater levels are therefore an average value and might differ from an observation just because the local representation of a measurement does not represent an average value for a larger area. That said, it is clear that some of the observations are well represented by the LHM (B54B0064, B54B0094 and B54B0062). These are all observations further land inwards and further away from the nature conservation area Braakman. Observations near that area (B54B0048 and B54E0227) are less well represented probably due to a lack of a proper implementation of that area in LHM. A clear mismatch, caused by the resolution, is observation B48D0354. That measurement is close-by the dike and the average value LHM is not representative for the local condition measured at that location. A regional model is always less accurate for local areas that show abrupt changes. This can be computed for various locations in the Terneuzen site to give an estimate of the groundwater level to be expected, see Figure 5-11.

Both, for the west and south area of the Terneuzen site, the computed groundwater level is varying between 50 and 150 cm NAP. As the surface level is approximately 170 cm NAP (see Figure 5-10), it means that groundwater levels approach the surface level in wet periods up to a few tens of centimeters. In dry periods (summers), the groundwater level might drop to -20 cm NAP, which means a depth to the groundwater table of almost 200 centimeters. This is mainly caused by high evaporation rates in summer and lack of fresh water to replenish the groundwater levels by artificial recharge and/or a dense network of surface water elements.

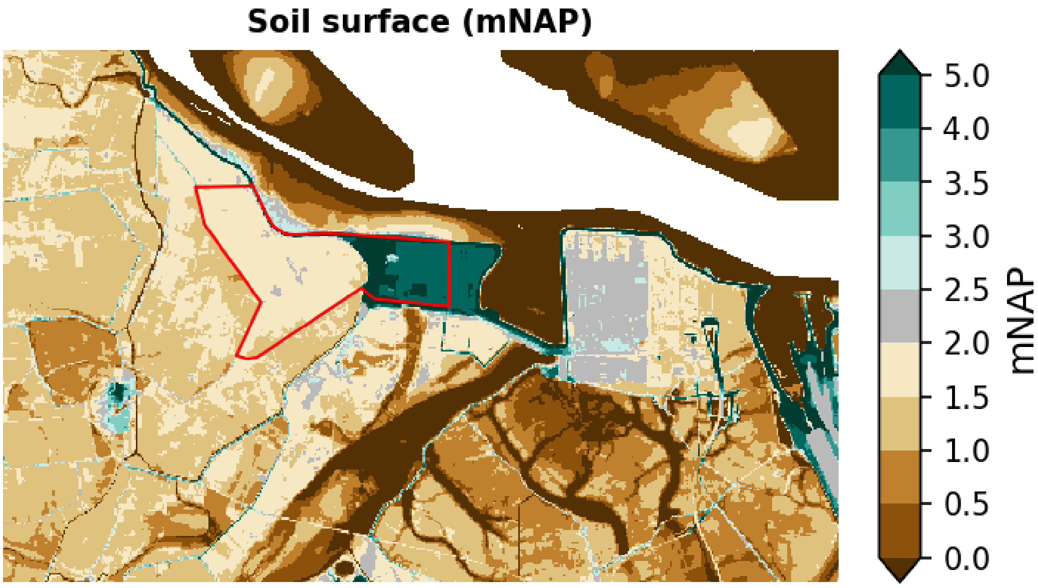


Figure 5-10 Soil surface elevation at and around the project sites (source: AHN2).

The east side of the Terneuzen site is significant higher in elevation than the west part. The surface level is here 450-500 cm NAP. This is an industrial site which is reclaimed in earlier times (in the 1970s). As a consequence, groundwater levels become higher as evaporation acts at a significant higher level. The lack of drainage network through this part of the site increase groundwater levels to fluctuate through time. The maximal groundwater to be expected at the center of this area is 450 cm NAP, slightly a few tens of centimeters below surface level. In dry periods, it drops almost 300 cm to 150 cm NAP. In all cases it discharges to the surrounding polders and Western Scheldt.

The tidal range is ~450 cm at the Braakmanhaven (0 cm NAP to 450 cm NAP, see https://nl.tideschart.com/Netherlands/Zeeland/Westerschelde/) but in general, tidal effects exponentially decrease by distance into the subsurface. Occurrence of sheet piles and/or low permeable material in the subsurface further determine the distance where tidal influence may be noticed. On a small timescale (hourly) it is not expected that tidal influence might be noticed in the groundwater levels at the polder. The surface water along the inside of the dike, probably dampens this tidal effect to migrate further land inwards. Though, this might influence the eastern side of the Terneuzen site as no surface water exists in between the Western Scheldt and the area of interest. This needs to be examined in more detail if this becomes relevant. In all cases, it would be advised to install at least three (or more) monitoring wells, as proposed in Figure 5-11.

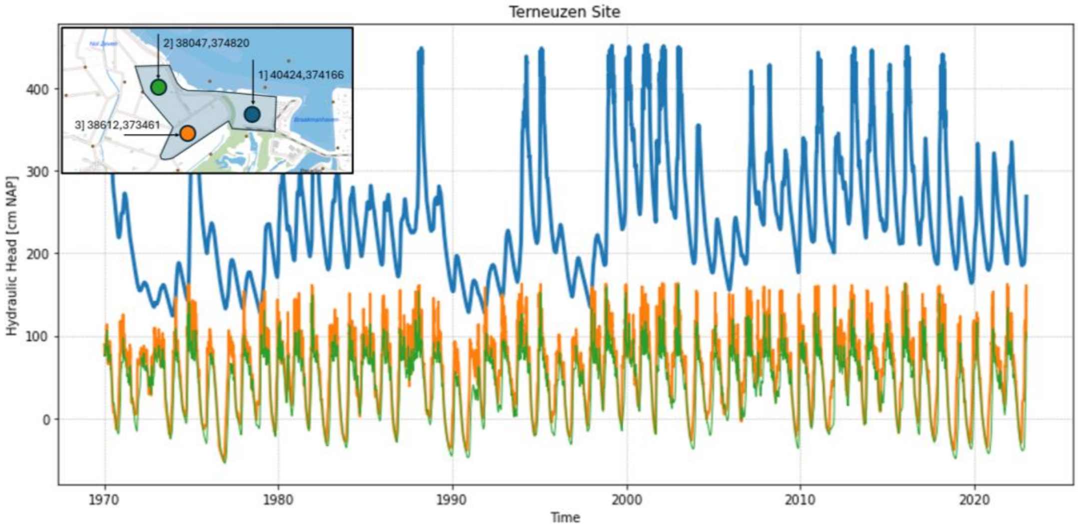


Figure 5-11 Timeseries from the LHM for three locations on the Terneuzen site.

With the LHM also 2D characterizations of the groundwater levels were produced. These are given in Figure 5-12. It shows the calculated mean groundwater level over time (2010-2020) of the area, both in mNAP and meters below soil surface. The left part of the Terneuzen site shows a deeper groundwater to the west and shallower to the east. Here, the maximal groundwater levels tend to emerge above surface level once in a while. Those high groundwater levels tens to occur in the eastern part of the Terneuzen site as well though the surface level is significantly higher than in the western part of the Terneuzen site. This is caused by the fact that the estimated vertical resistance of the Holocene deposits are 100-200 days more than in the Paulina Polder. A visualization of the resistance of the Holocene cover layer in LHM is given in Figure 5-12 lower right subfigure.

Besides the mean groundwater levels, Figure 5-12 (bottom figures) also gives the calculated mean highest (GHG) and mean lowest (GLG) groundwater levels over the period 2010-2020. These are defined as the average of the three highest resp. lowest groundwater levels of every year. Particularly the GHG is relevant, as it relates to inundation risk. In most parts of the Terneuzen site, the GHG is less than 1 m.b.s.l. which makes it vulnerable for groundwater disturbance. The GLG, on the other hand, is significantly lower than the GHG.

The LHM results are uncertain and the presented results should be considered indicative and illustrative. A more localized modelling approach, fed with local data and calibrated and validated on a decent set of on-site piezometric measurements is necessary to be able to obtain more reliable modelling results.

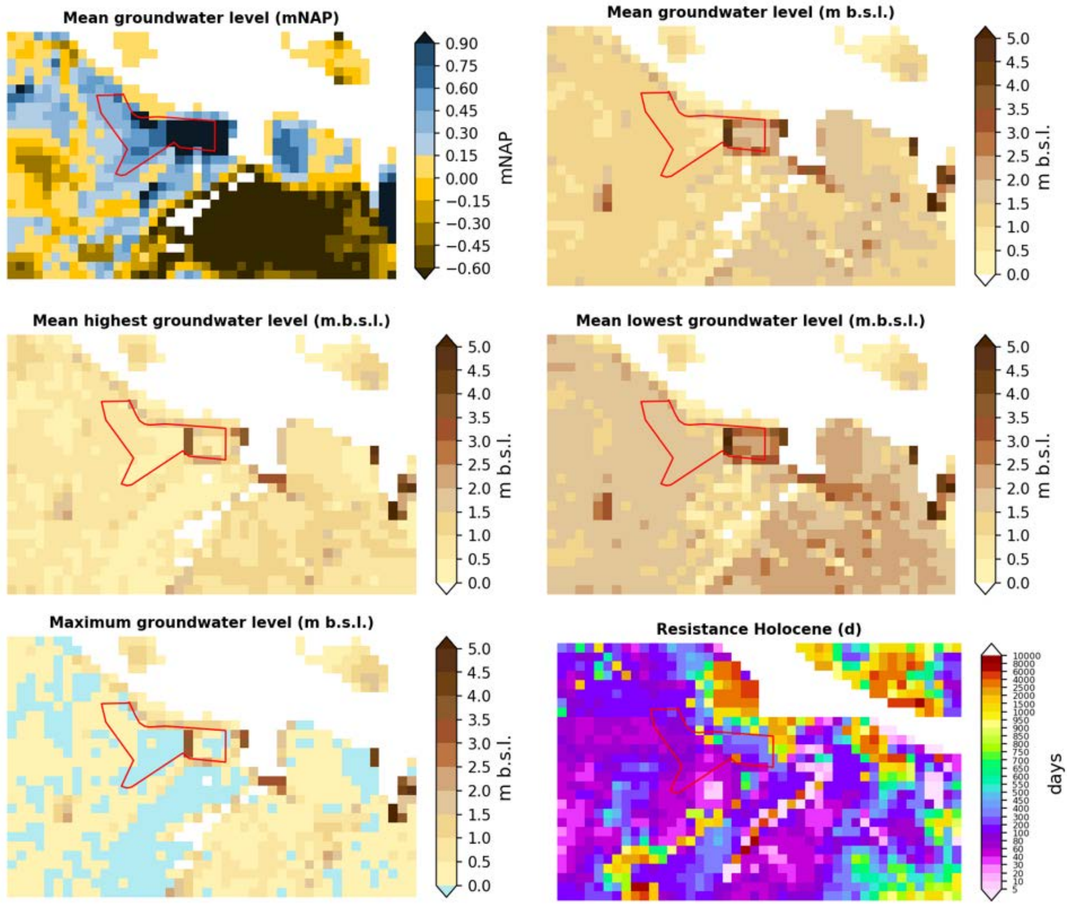


Figure 5-12 Calculated groundwater levels by the LHM over the period 2010-2020. M.b.s.l = meters below soil surface level; vertical resistance of the Holocene is given in the lower-right subfigure.

The fact that no groundwater monitoring wells are present at the potential project sites makes the geohydrological evaluation and model results of the site uncertain. It is advisable to develop and execute a monitoring plan, preferably consisting of multiple monitoring wells for the site with filters at different depths, to capture both horizontal and vertical gradients. . Monitoring should continue for at least one year to capture seasonal effects. High frequency monitoring would be advisable for at least a short period to capture tidal effects.

5.8 Calculated salt concentration

The Terneuzen site is located near salty seawater. Salt water has a higher density than fresh water and therefore affects groundwater flow. In Van Baaren et al. (2017) the local density distribution is described after mapping using airborne electromagnetic measurements.

Before the land reclamation of the eastern part of the Terneuzen site (1970s) the subsurface was presumably filled entirely with this high-density saline water. Over time, groundwater recharge from excess precipitation gradually displaced this saline water and formed a freshwater lens. Local drainage systems and/or permeability of the subsurface have influenced this process. The higher the groundwater level raises, the larger this freshwater lens can develop. As freshwater has a density of 1000 kg/m^3 and salt water 1025 kg/m^3, according to the Ghyben-Herzberg-principle the ratio between both specifies the depth of the fresh-salt interface, thus the interface should be at 1000/(1025-1000)=40 m depth. This is a hydrostatic approach and does not accommodate for local distortions of this relationship such as variance in permeabilities, changing boundary conditions or mixing salt and fresh water. In addition, it does not quantify how this freshwater lens evolves in time, a model is needed to do that. Under Dutch-conditions (net recharge 250 mm/year and void ratio of 0.15), it generally takes 10-20 years to freshen the first 5 meters of the subsurface as it takes the above mentioned recharge multiple times to flush voids completely with freshwater (e.g. 3-5 times) to replace the salt. Another 20-30 years to freshen the next 5 meters and an additional 50 years to double the fresh water lens in thickness. For the eastern area of the Terneuzen site, which was reclaimed in 1977 and was initially saline, it took approximately 30-50 years for this freshwater lens (thickness of approximately 10 meter) to form in that area. This polder is fresh up to a depth of maximal 10 in the utmost west part of the polder where brackish water seepages into a dewatering stream that borders the Paulina Polder. At the east-side of the Terneuzen site, brackish water is still near the surface, mainly caused by ancient salt before the land reclamation in 70s. In the centre of the Terneuzen site the fresh water lens is approximately 10 meter thick due to net recharge in winter periods. If the recharge declines due to high built-up areas and/or intense drainage networks, the lens decreases in the future. Extracting groundwater for industrial usage is not sustainable since this introduces high velocities of groundwater flow that extracts salt water (upconing) and increases mixture of salt and fresh water (dispersion).

Underneath this NMRUBOK1 there is significant fresh water available. This is probably fresh due to millions of years of freshening through groundwater flow from recharge areas south (Baaren, 2017). Holocene transgressions resulted in the deposition of sediment in a saline environment, and infiltration of saline water on top of the old (pre-Holocene) clay deposits. After the land reclamations by mankind, freshening of the saline deposits took place. Where freshening has taken place, only just a thin layer of saline groundwater is present between the fresh groundwater above and the old clay deposits below.

The western part of the Terneuzen site has a lower elevation and shows higher values of salt concentration near the dike. Is also shows an up coning of brackish groundwater to streams in between the Pauline Polder and the Breukels Polder.

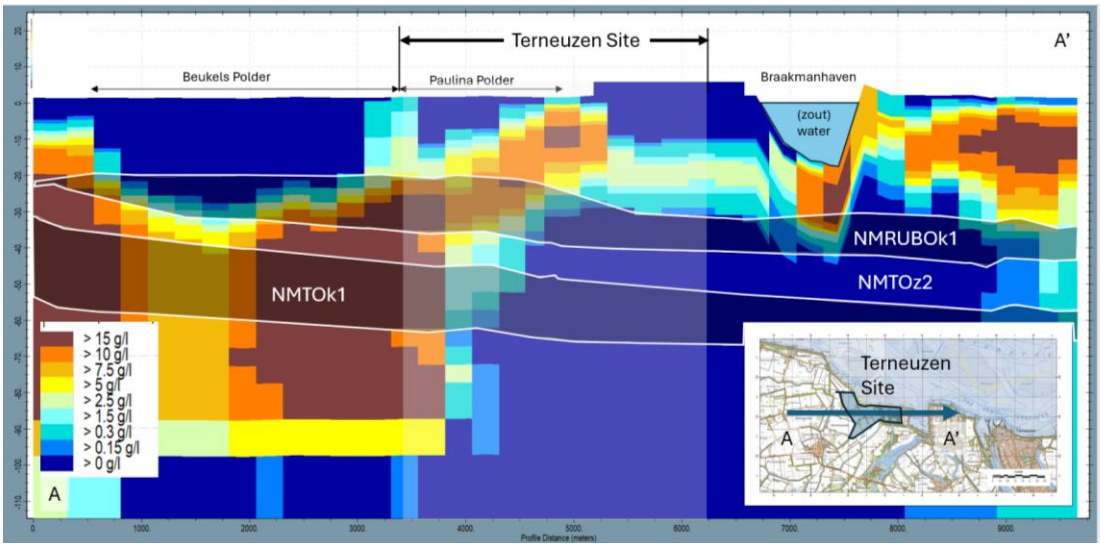


Figure 5-13 Cross section from west to east through the Terneuzen site showing the calculated salt concentration in the subsurface (g/l).

The presence of salt in the subsurface can accelerate corrosion of steel and concrete structures and may alter soil properties, leading to stability issues and reduced durability of foundations.

5.9 Attention Points

There are no public piezometric measurements at the Terneuzen site. Therefore, groundwater levels were simulated using the Dutch Hydrological Model. In the west and south areas, levels range between 50–150 cm NAP, approaching surface level during wet periods and dropping to –20 cm NAP (~2 m depth) in dry summers. The east side is significantly higher in elevation, with groundwater levels reaching up to 450 cm NAP—just below surface—and falling to 150 cm NAP in dry periods. In all areas, groundwater discharges toward the surrounding polders and the Western Scheldt. Which makes it vulnerable for contaminant transport. At the eastern site, a ~10 m thick freshwater lens is present, limited in growth by the low-permeable NMRUBOk1 aquitard. In the Paulina Polder, fresh water extends to 10 m depth in the far west, while brackish water is near the surface in the east. Below the NMRUBOk1 layer, older deep freshwater is present, but industrial extraction is challenging due to induced saltwater intrusion from high groundwater flow velocities.

The LHM results are uncertain and the presented results should be considered indicative and illustrative. A more localized modelling approach, fed with local data and calibrated and validated on a decent set of on-site piezometric measurements is necessary to be able to obtain more reliable modelling results.

6 Geotechnical parameters

6.1 Geotechnical cross sections

6.1.1 Available CPTs

Only a limited number of CPTs are available at the Terneuzen sites. Penetration depth is about NAP -20 m for the two CPTs near the Paulinapolder and about NAP – 25 m for the 12 CPTs near Mosselbanken. The location of the available CPT's is shown in Figure 6-1.

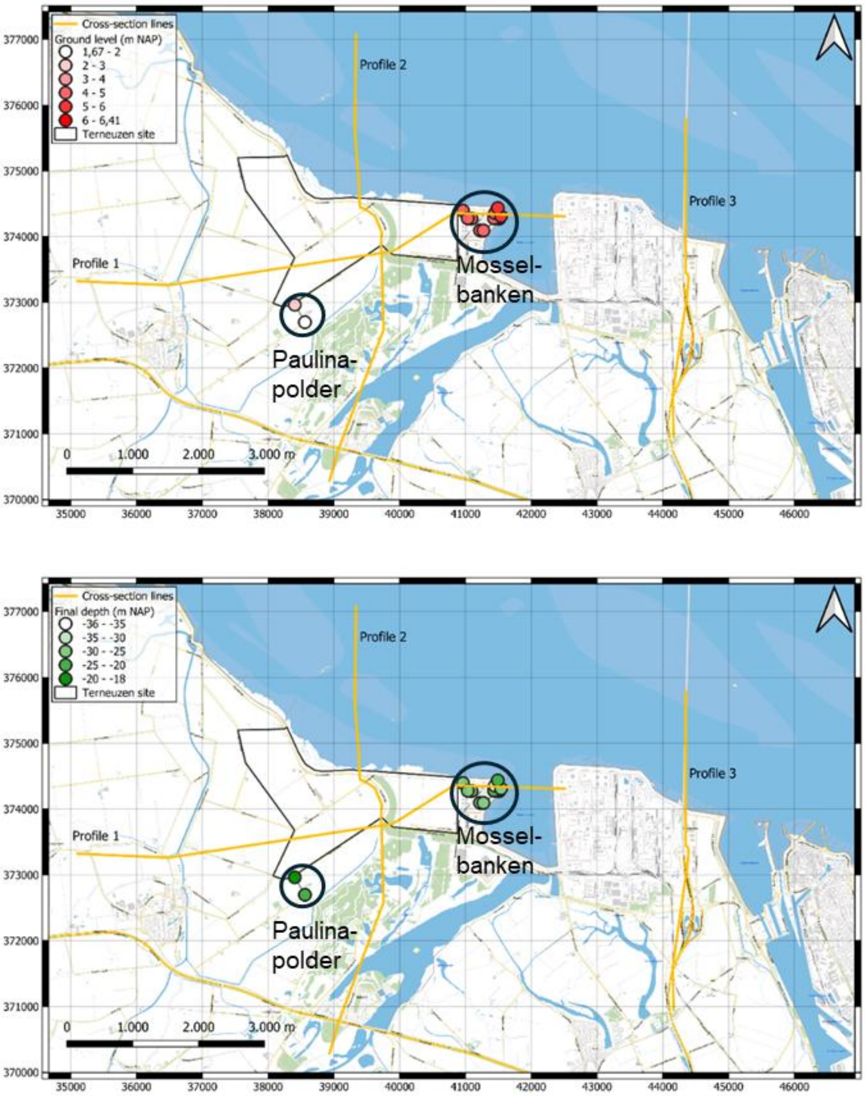


Figure 6-1 The ground level (top) and final penetration depth (bottom) of CPT's for the Paulina Polder and Mosselbanken.

For the geotechnical analysis, soil properties are derived for the Paulina Polder and the Mosselbanken. For the deeper layers available information from the Westerschelde Tunnel, Sluiskil Tunnel and the Nieuwe Sluis Terneuzen is used to provide initial design properties.

Section 6.1.2 and Section 6.1.3 describe the the Paulinapolder and the Mosselbanken, respectively, and section 6.5.1 provides an overview of geotechnical soil profiles. Figure 6-1 highlights the ground level and final penetration depth of the CPTs used for the two locations.

The soil classification in Section 6.1.2 and Section 6.1.3 is based on the classification by Robertson (1990), which has been adjusted by Fugro to the Dutch conditions. The lithologies are determined separately for each CPT in 20 cm depth interval based on (normalized) cone resistance and friction ratio. The automatic procedure then divides the CPTs in intervals with a length of 25 m along the cross section. Within each interval the lithologies over depth are grouped and a distribution of the present lithologies at each depth within each 25 m interval is computed. The profile is coloured according to these percentages. The subareas are described in further detail in the following paragraphs. The used CPTs may be further from the cross section in the perpendicular direction, and the cross section therefore provides an overview of the geotechnical properties of the area.

6.1.2 Paulina Polder

Figure 6-2 present the geotechnical cross section for CS1. Figure 6-3 highlights the cone resistance of the CPTs closest to the cross-sectional line. Figure 6-3 provide an indication of the resistance of the top and sand layer. These plots also provide an insight into the local variation within layers.

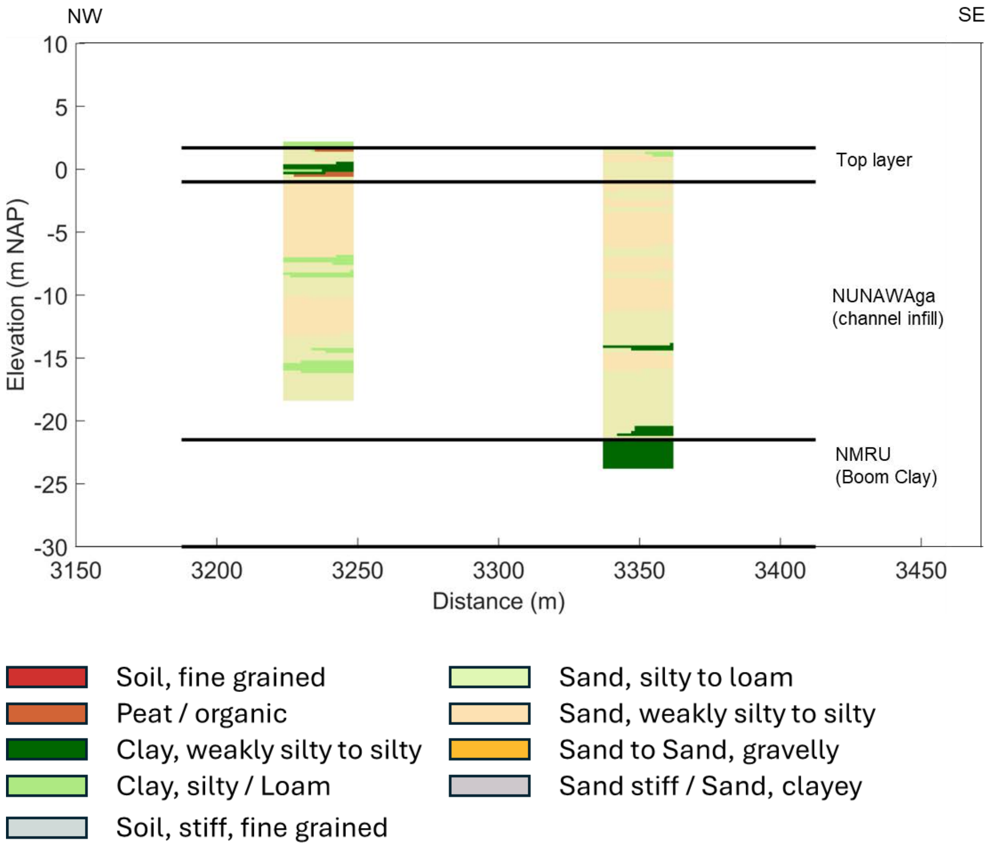


Figure 6-2 The geotechnical lithological classification of the Paulinapolder according to automatic CPT classification performed on the CPTs used for the Paulinapolder (see Figure 6-1). The black lines provide interpreted layer boundaries.

The present ground level in the Paulinepolder is about NAP + 1.7 m. The available CPTs show a top layer with a thickness of about 2-3 m which may contain clay, peat or sand. The top layer is highly variable and it is expected to be removed before construction.

The Holocene layer below consists mainly of sand with locally clayey and silty interbedded layers. In the two CPTs they appear to be non-continuous, even though the CPTs are relatively close to each other when compared to the size of the site. Local variation in the Holocene layer is therefore expected. According to the geological cross sections, multiple formations may be present above NAP -23 m, but these are not clearly distinguishable in the available CPTs. The cone resistance usually ranges from 5-15 MPa within this layer, occasionally dropping to 1-3 MPa in the clayey zones. Figure 6-4 shows the normalized cone resistance. Using NEN9997 Table 2.b it is concluded that the sand is loose to medium dense.

The top of the Rupel formation (NMRU) is penetrated by one of the CPTs showing a cone resistance in the order of 3.5 to 5 MPa. This corresponds to the stiff “Boom” clay. The depth of the Rupel Formation and the sandy Tongeren formation below is approximated based on the geological cross sections. The Tongeren formation is known for its glauconite content.

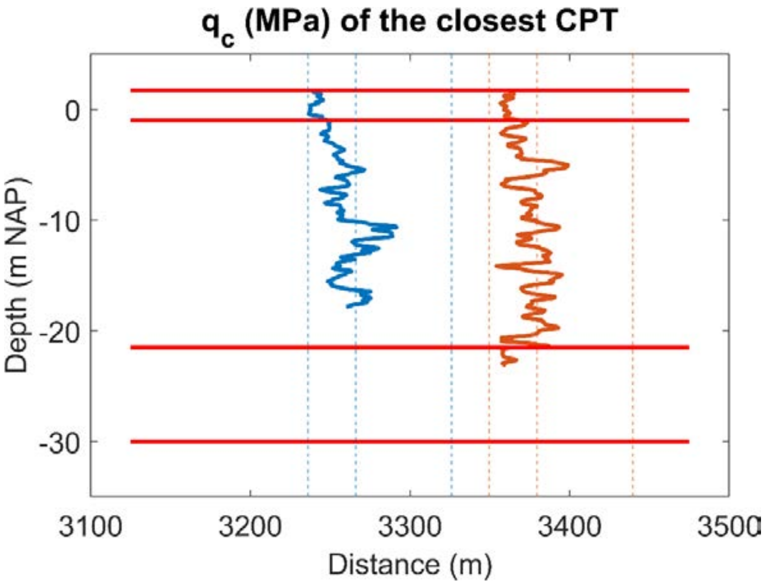


Figure 6-3 The cone resistance of the closest CPT to the cross section line for the Paulinepolder (see Figure 6-1 for the location). For each CPT the dotted lines indicate a cone resistance of 0, 10 and 30 MPa.

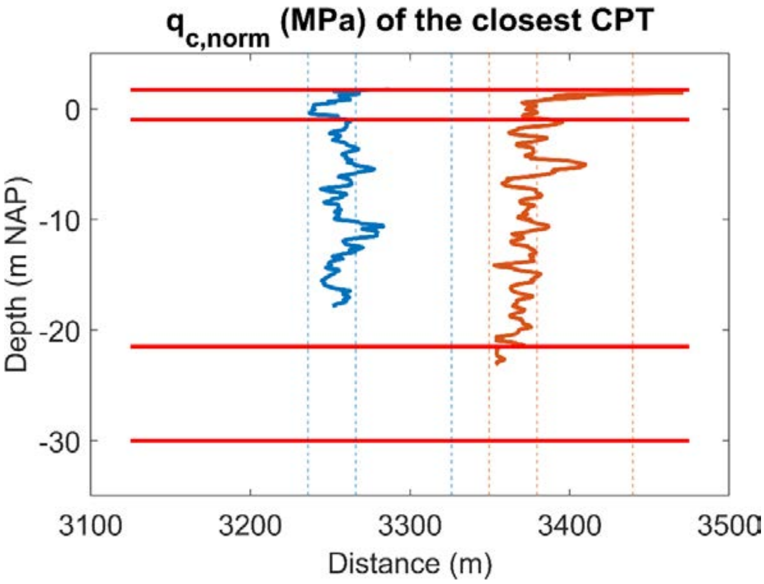


Figure 6-4 The normalized cone resistance of the closest CPT to the cross section line for the Paulinepolder (see Figure 6-1 for the location). For each CPT the dotted lines indicate a normalized cone resistance of 0, 10 and 30 MPa.

6.1.3 Mosselbanken

Figure 6-5 presents the detailed view of the cross sectional layering of the Mosselbanken, and Figure 6-6 and Figure 6-7 highlight the cone resistance of the CPTs closest to cross-section line. The contour plots are created by assigning the values of the closest CPTs at their position along the cross section and interpolating in between the CPTs. The land has been raised with sand, the NUAAOP layer in this figure. The boundary between this layer and the underlying Holocene sand layer is not clearly distinguishable in the CPTs. The cone resistance in both layers varies between 10 and 30 MPa. Some clay/silt zones may be present locally which causes a drop of the cone resistance to roughly 1 to 3 MPa. These clay/silt zones a rare at the Mosselbanken site. Figure 6-8 shows the normalized cone resistance. Using NEN9997 Table 2.b it is concluded that the sand in the NUAAOP layer is medium dense to dense and the Holocene sand layer below this layer is loose to medium dense.

The top of the Rupel formation (NMRU) is penetrated by all the CPTs showing a clear distinction of the layer with a cone resistance in the order of 3.5 to 5 MPa. This corresponds to the stiff “Boom” clay. The depth of the Rupel Formation and the sandy Tongeren Formation below is approximated based on the geological cross sections. The Tongeren Formation is known for its glauconite content.

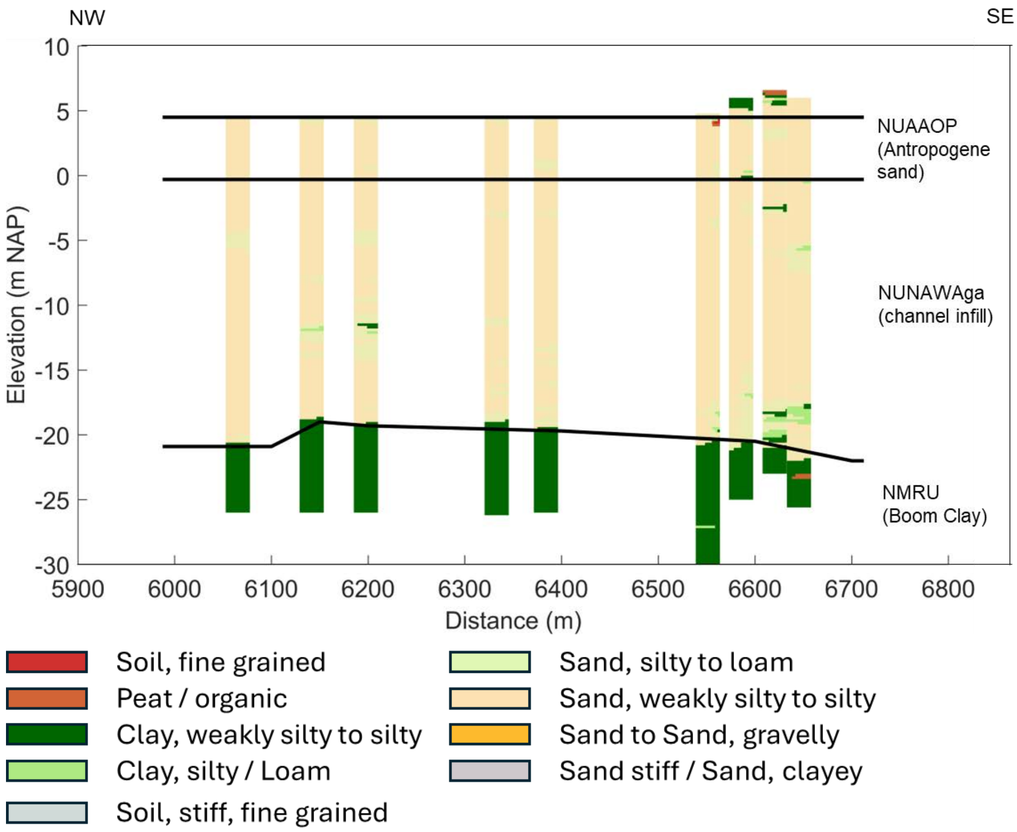


Figure 6-5 The geotechnical soil classification of the Mosselbanken according to automatic CPT classification performed on the CPTs used for the Mosselbanken (see Figure 6-1). The black lines provide interpreted layer boundaries.

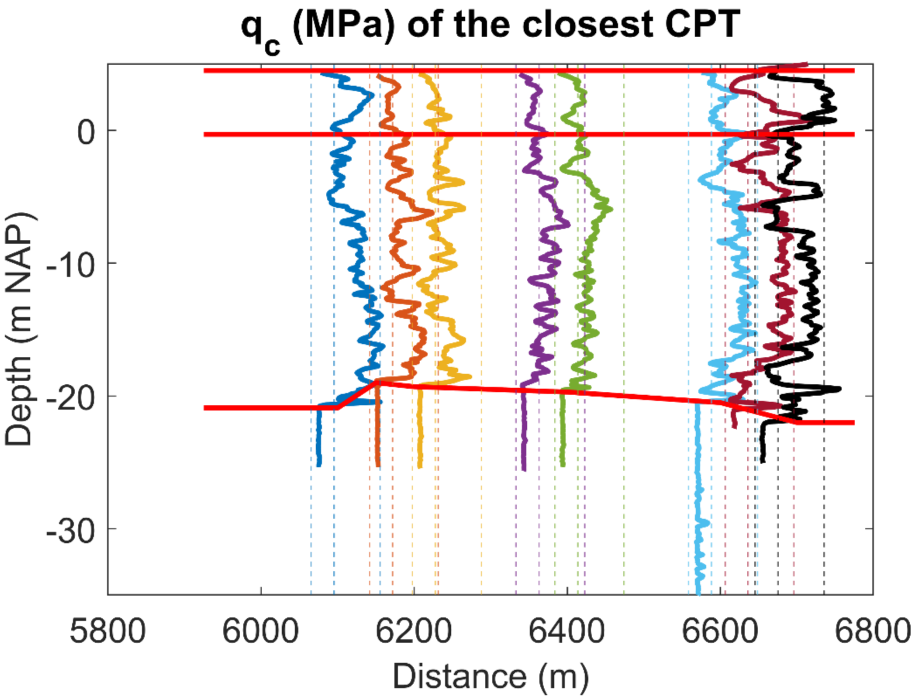


Figure 6-6 The cone resistance of the closest CPT to the cross section line of the Mosselbanken (see Figure 6-1 for the location). For each CPT the dotted lines indicate a cone resistance of 0, 10 and 30 MPa. Red lines indicate surface level, top of tidal deposits and top of the Boom Clay.

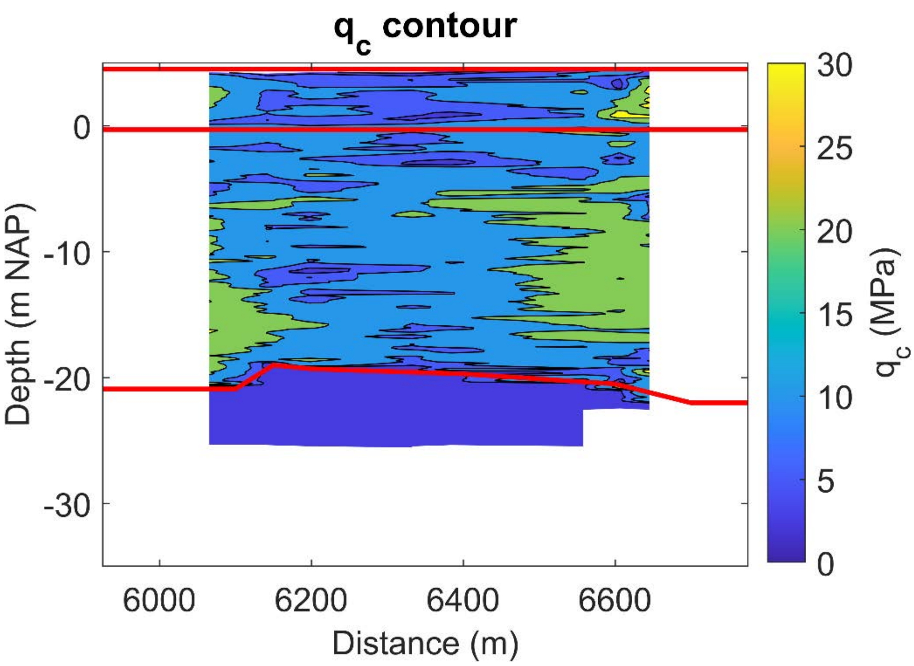


Figure 6-7 A contour plot of the cone resistance of the closest CPT to the cross section of the Mosselbanken (see Figure 6-1 for the location). Red lines indicate surface level, top of tidal deposits and top of the Boom Clay.

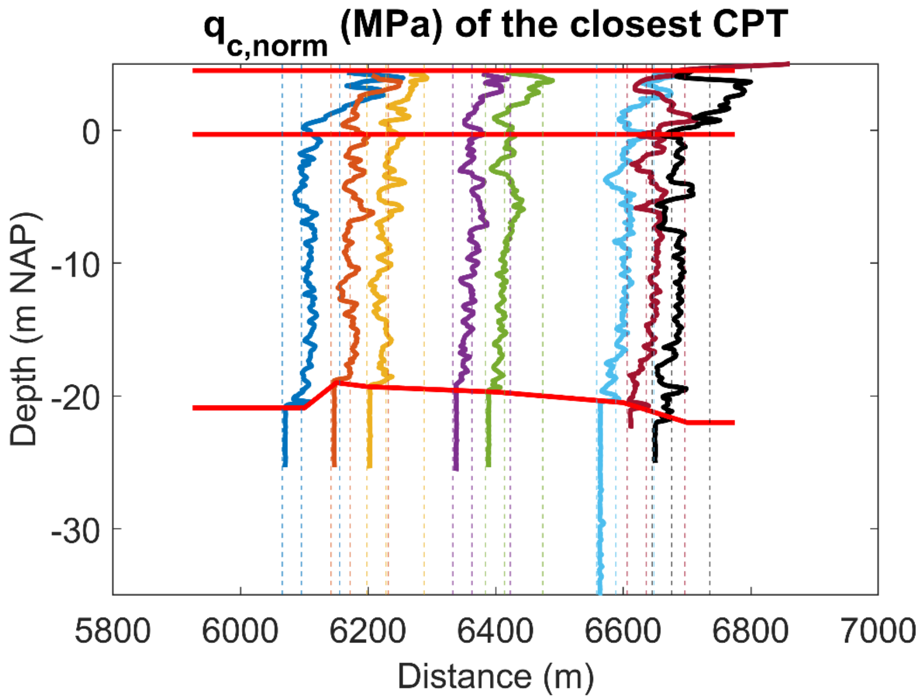


Figure 6-8 The normalized cone resistance of the closest CPT to the cross section line of the Mosselbanken. For each CPT the dotted lines indicate a normalized cone resistance of 0, 10 and 30 MPa. Red lines indicate surface level, top of tidal deposits and top of the Boom Clay.

6.2 Selection of soil parameters NUAAOP and NUNAWAga layers

6.2.1 Used approach

Due to the low number of CPTs within the vicinity of the sites the local variation in parameters for the cross sections is not derived. Instead the properties of the top sand layers are determined from the soil type in NEN9997 Tabel 2.b. The NUAAOP layer consists of medium dense sand. The NUNAWAga layer consists of medium dense sand, loose sand and interbedded clay layers. The resulting properties for these soil types based on NEN9997 Tabel 2.b.

6.3 Selection of soil parameters NMRU and NMTORU layers

Within this section the parameters for the Rupel and Tongeren Formations are discussed based on investigations at the Sluiskil Tunnel (de Boer et al, 2011), Nieuwe Sluis Ternuizen (MOW,2015) and the Westerschelde Tunnel (Grondmechnica Delft, 1995). The sections provide ranges for the parameters of the two formations, using the input from these reports. Note that in these reports the Boom clay and glauconite sand formations are each split into two layers. For this report, the two layers are not split into 4 sublayers due to lack of data on the Paulina Polder and the Mosselbanken. The results of the 4 sublayers are therefore presented as two layers in the geotechnical summary in section 6.5.

6.3.1 Geotechnical description

At the Westerschelde tunnel (Grondmechnica Delft, 1995) the Rupel formation is described as a very stiff Boom Clay, which is divided into 2 portions (BK1 and BK2). The clay is weakly silty at the top (BK1) and more silty at the bottom (BK2). BK2 Boom clay contains thin sand layers and lenses, of less than 2 mm thickness. Locally, thicker sand layers occur within this lower portion of the Boom clay. The cone resistance is typically between 4-5 MPa at this site. The Boom clay may contain shells. It is not clear of the same division is present at the Terneuzen site. If this is the case, due to the erosion of the top of the Boom clay in the Terneuzen site, the BK1 subunit might be thinner or entirely absent (especially towards the south).

The Tongeren Formation is a sand layer containing glauconite with a cone resistance between 10 and 30 MPa (Grondmechnica Delft, 1995). The layer can contain cementation and the glauconite content is between 4% and 8%. Glauconite has a low unit weight, a flexible grain and has a significant difference in mechanical properties when compared to quartz sand.

6.3.2 Unit weight

Ranges of the wet unit weight of the two formations are provided based on the previous investigations (de Boer et al., 2011, MOW, 2015) and Grondmechnica Delft (1995)) in Table 6-1.

Table 6-1 Unit weight for the Boom clay and Tongeren sand

layer	Wet unit weight γ [kN/m^3]		
	Minimum	Maximum	Advised for first design
Rupel Boom clay	18.3	20.4	19.5
Tongeren Sand	19.1	20.9	20.0

6.3.3 Strength parameters

Ranges of the friction angle, effective cohesion and undrained shear strength are provided in the upcoming sections based on previous investigations by de Boer et al (2011), MOW (2015) and Grondmechnica Delft (1995)

6.3.3.1 Friction angle ϕ

Table 6-2 Friction angle for the Boom clay and Tongeren sand

layer	ϕ [degr]		
	Minimum	Maximum	Advised for first design
Rupel Boom clay	18.1	22.4	20
Tongeren Sand	28.8	34.7	32

6.3.3.2 Cohesion c

The Boom clay can have a significant effective cohesion ranging in the tests between c = 20 and c = 50 kPa.

6.3.3.3 Undrained shear strength

Table 6-3 Undrained shear strength for the Boom clay

layer	**Undrained shear strength c_u [kPa]**		
	Minimum	Maximum	Advised for first design
Rupel Boom clay	10.0	359.2	100.0

6.3.4 Stiffness parameters

The Sluiskiltunnel report (de Boer et al., 2011) describes measurements for the determination of the stiffness. The results are converted to E_{oed} results, such that the various tests can be compared. The results are summarized in Table 6-4.

Table 6-4 Summary of stiffness parameters for the Boom clay and Tongeren Sand

layer	**Stiffness E_{oed} [MPa]**		
	Triaxial tests	Compression tests	Cone Pressiometer tests
Rupel Boom clay	33-109	17-25	19-50
Tongeren Sand (part 1)	43-259		143-166
Tongeren Sand (part 2)	165-270		211-253

6.4 Settlement parameters

The report for the Sluiskil Tunnel (de Boer et al., 2011) describes the settlement parameters for the NEN-Koppejan parameters C_p, C_s, C'_p and C'_s. These NEN-Koppejan parameters can be converted to the NEN-Bjerrum parameters, as explained in the manual of D-Settlement. The following formulas are used:

$$\frac{C_c}{1+e_0} = \frac{\ln(10)}{C'_p}$$

$$\frac{C_{sw}}{1+e_0} = \frac{\ln(10)}{C_p}$$

$$C_\alpha = \frac{1}{C_s}\ln\left(\frac{\sigma_p}{\sigma'_0}\right) + \frac{1}{C'_s}\ln\,(\frac{\sigma'_0 + \Delta\sigma}{\sigma_p})$$

Table 6.5 highlight the settlement parameters for the Boom clay, based on the report of the Sluiskiltunnel (de Boer et al, 2011), including the consolidation coefficients.

Table 6-5   Summary of settlement parameters for the Boom clay

layer	Settlement parameters							Cassagrande	Taylor
	C'$_p$	C'$_s$	C_p	C_s	$\frac{C_c}{1+e_0}$	$\frac{C_{sw}}{1+e_0}$	C_α	c_v	c_v
Rupel Boom clay	21	354	61	709	0.11	0.038	0.0028	4.1E-7	9.6E-7
Rupel Boom clay (sandy)	18	343	106	964	0.13	0.022	0.0026	4.1E-7	9.6E-7

6.5 Summary of geotechnical parameters

6.5.1 Selected geotechnical soil profiles

A summary of the material properties for these representations is provided in Table 6-6 and

Table 6-7. Note that these results arrive from the limited dataset available at Terneuzen. The NUNAWAga layer mainly consists of medium dense sand, with thin layers of loose sand or clay. The stiffness of the bottom layer has not been back calculated to a reference stiffness. Design E_{oed} parameters for these layers are provided in Table 6-8. Further investigation for the stress effect on the stiffness of these layers is required due to the over consolidation of the clay and the glauconite content of the sand.

Table 6-6 Summary of the material properties for the Paulinapolder.

layer	Top of layer	Relative density	Unit weight	Strength parameters		Stifness	Settlement parameters		
	m + NAP		γ kN/m^3	c kPa	ϕ degr	E_{ref} MPa	$C_c/(1+e_0)$	$C_{sw}/(1+e_0)$	C_a
Toplayer	1.7								
NUNAWAga, medium dense sand	-1.0	Medium dense	20	0	32.5	45	0.0038	0.0013	0
NUNAWAga, loose sand		Loose	19	0	30	15	0.0115	0.0038	0
NUNAWAga, interbedded clay layers			18	1	27.5	2	0.0920	0.0307	0.0037
NMRU, Boom clay	-21.5		19.5	25	20		0.12	0.030	0.0027
NMTORU, Sand, glauconite	-30.0	Medium dense	20	0	32		0.0038	0.0013	0

Table 6-7 Summary of the material properties for the Mosselbanken.

layer	Top of layer	Relative density	Unit weight	Strength parameters		Stifness	Settlement parameters		
	m + NAP		γ kN/m^3	c kPa	ϕ degr	E_{ref} MPa	$C_c/(1+e_0)$	$C_{sw}/(1+e_0)$	C_a
NUAAOP, Antropogene sand	4.5	Medium dense	20	0	32.5	45	0.0038	0.0013	0
NUNAWAga, medium dense sand	-0.3	Medium dense	20	0	32.5	45	0.0038	0.0013	0
NUNAWAga, loose sand		Loose	19	0	30	15	0.0115	0.0038	0
NUNAWAga, interbedded clay layers			18	1	27.5	2	0.0920	0.0307	0.0037
NMRU, Boom clay	-20.5		19.5	25	20		0.12	0.030	0.0027
NMTORU, Sand, glauconite	-40.0	Medium dense	20	0	32		0.0038	0.0013	0

Table 6-8 Design stiffness parameters.

layer	Stiffness E_{oed} [MPa]
Rupel Boom clay	30
Tongeren Sand	150

6.5.2 Attention points

The properties described here are based on a limited dataset. It is advised to increase the density of CPT measurements, especially in the Paulinapolder. CPTs should be performed such that at least the Tongeren layer is penetrated, i.e. up to a depth of approximately 50 meters. Lab testing on the NUNAWAga and NUAAOP sand layers is required to classify their material properties.

Lab testing on the NMRU (Boom clay) and NMTORU (sand, glauconite) should be performed and compared to the thorough investigations at the Westerscheldetunnel, Sluiskiltunnel and Nieuwe Sluis Terneuzen. Non-typical behaviour can be expected in these layers, but substantial knowledge of the behaviour is available due to the previous investigations. The Boom clay is known to contain concretions and thin sand layers. To determine the depths of the deeper layers below the Boom clay additional site investigation is required (initial estimates are made based on the geological descriptions and the limited CPT dataset).

From a geotechnical hazard inventarisation at the Sluiskiltunnel (Verweij et al., 2009) the following hazards must be investigated:

- The Boom clay and glauconite sand layer can be significantly over consolidated. Especially in the Boom clay this can result in high horizontal soil pressures, which may be temporarily reduced during construction.
- The strength and stiffness of the Boom clay layer can make the installation of piles or sheet pile walls complex. Additionally, concretions can be present within this layer. The cementation of the Tongeren sand layer also increases the risks of pile or sheet pile wall installation. The glauconite content of the sand layer may reduce the bearing capacity of the foundation.

- The swelling behaviour of the Boom clay may be different when compared to other clay types. The layer may also be more permeable than expected.
- In the past static liquefaction has occurred in the NUNAWAga within the Westerschelde and the Terneuzen Canal (at groundlevel). This is mainly an issues for the flood protection in the area.

7 Subsidence, settlements and bearing capacity

7.1 Subsidence of the shallow subsurface

This section gives an overview of the potential subsidence which may occur at the surface of the Terneuzen site area. Subsidence in this area is mostly related to the dehydration of weaker layers such as peat- or clay-rich deposits (see Figure 7-1). Dehydration of these weak layers can lead to soil consolidation, soil creep and decomposition of organic matter. This is particularly prevalent in areas where land has been reclaimed from the sea.
In Terneuzen, weaker layers and/or lenses (peat, clay) can be present in the Naaldwijk Formation, although only locally as the general composition is sandy at the site. Peat layers belonging to the Nieuwkoop Formation are likely absent in the site, but are observed in the vicinity.

The European Ground Motion Service (EGMS, www.copernicus.eu) and the Bodemdalingskaart 2.0 (Bodemdalingskaart 2.0, www.skygeo.com) both show ground motion data on a local, national and continental scale with millimeter accuracy. They are derived from Sentinel-1 radar images at full resolution, on which a multi-temporal interferometric analysis (InSAR) is done. These data includes both natural and anthropogenic ground motion.

Figure 7-2 shows the ground motion for the province of Zeeland and the Terneuzen site area in the time interval of October 2017 to October 2022. The area is stable in terms of ground motion on a regional scale compared to e.g. the region of Hoek van Holland and Rotterdam. The Terneuzen site area also shows a relatively high degree of stability. In the most eastern part slightly higher rates are observed. This might be related to the former presence of tidal channels and the landfill used to elevate the land between 1975 and 1977. The average ground motion is about -1 mm/year at the Terneuzen site area. Minimum and maximum amounts of ground motion at the Terneuzen site area are +6 mm/year to approximately -10 mm/year, but these numbers are outliers. Note that at some locations ground motion measurements are related to human activities such as construction and moving objects on the location. Positive values of ground motion (uplift) and larger negative values consisting large steps in the data are usually related to these types of human activities.

The *Climate Impact Atlas* (2023) shows the potential subsidence scenarios for different IPCC scenarios. Subsidence scenario ‘low’ is associated with IPCC scenario GL which projects a limited climatic warming of 1 ºC in 2050 and 1.5 ºC in 2085, and a fixation of the groundwater table which limits the subsidence. This results in a relatively limited subsidence since dehydration of the weak layers remains limited for this scenario. Scenario ‘high’ is related to the IPCC WH scenario which projects a temperature rise of 2 ºC in 2050 and 3.5 ºC in 2085, and indexation of the groundwater table (i.e. lowering along with the amount of subsidence). The conditions in this scenario will lead to more substantial subsidence.

The subsidence scenarios indicate a clear relationship between the expected amount of subsidence and the subsurface build-up. The expected amount of subsidence for climate scenario ‘high’ in the period 2020-2100 is shown in Figure 7-3 on top of the geological map of the Netherlands. The two main subsurface build-ups in the region consist either of clayey tidal deposits with peat layers or sandy channel fills (NUNAWAga). They are indicated in the map with white and grey respectively. The amount of predicted subsidence is indicated in the yellow (low subsidence) to purple (high subsidence) colours. Channel fill consistently shows up as an area of low predicted subsidence, while areas with clay and peats deposits are related to significantly higher levels of predicted subsidence. Highest rates of subsidence are linked to thick peat layers.

At the Terneuzen site the same distinction can be made. In the east part of Terneuzen, the predicted amount of subsidence is negligible (<3 cm), in correspondence with the anticipated location of the sandy tidal channel fill of the Braakman. In the rest of the site no subsidence is predicted. This is a relatively low amount of subsidence compared to other parts of Zeeland where the expected subsidence may be as high as 60 cm. This difference is caused by the fact that the Holocene sequence at Terneuzen is relatively thin and largely composed of sandy sediments compared to the more northern parts of Zeeland.

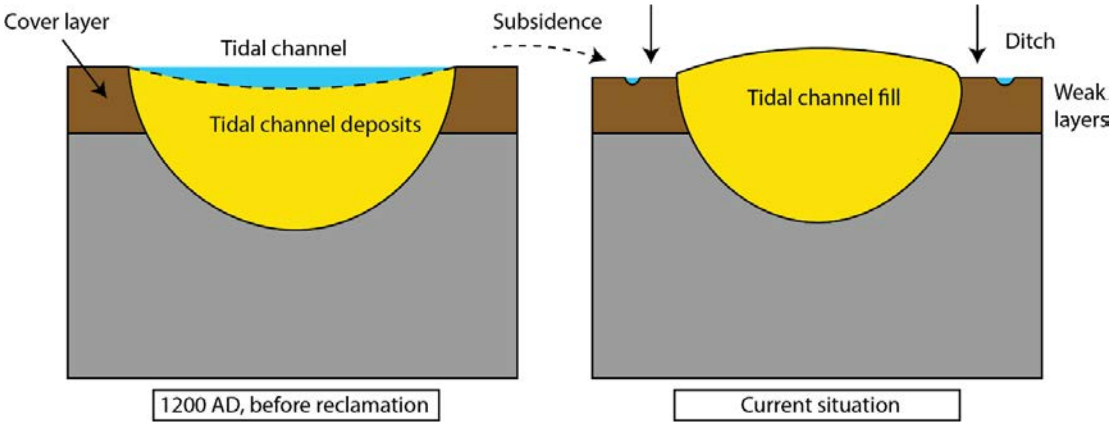


Figure 7-1 Schematic cross-sections through creek ridges highlighting their formation and typical subsequent post-depositional history. a) the situation before human reclamation in 1200 AD and b) the current situation with associated subsidence in the weaker layers adjacent to the creek ridges. Adapted from Pauw et al., (2015).

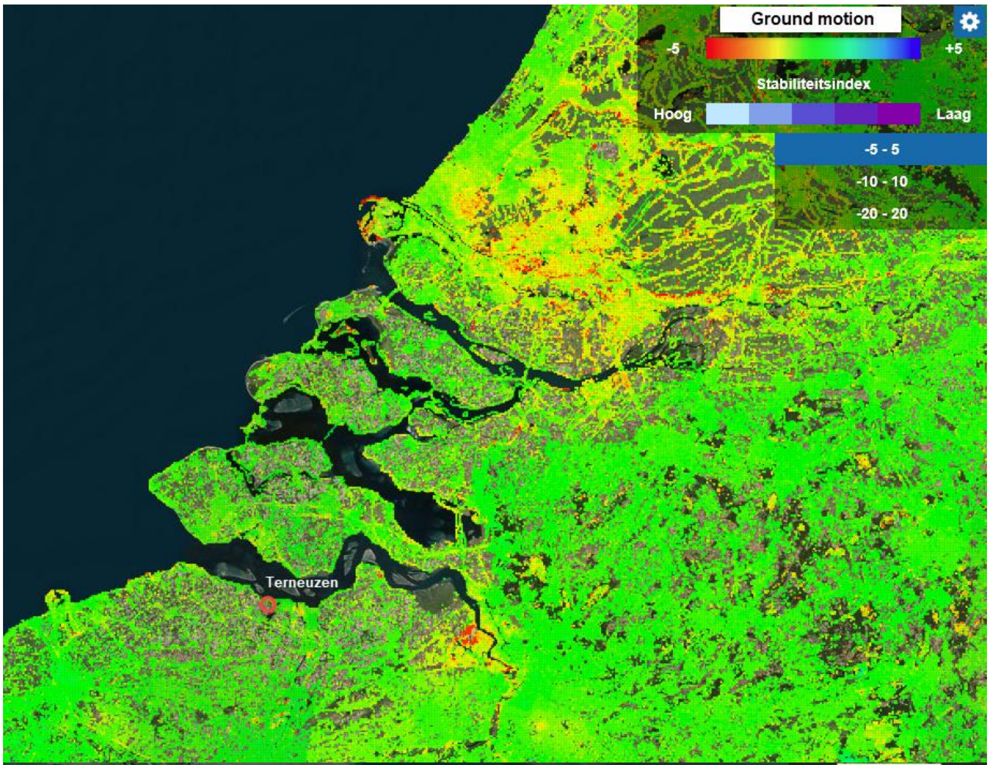


Figure 7-2 The amounts of ground motion for the period October 2017 to October 2022 shown on the regional scale in the upper image and the local scale of the site area in the lower image (Bodemdalingskaart 2.0). The area is stable (green colours) in terms of ground motion on a regional scale compared to e.g. the region of Hoek van Holland and Rotterdam. The site area also shows a relatively high degree of stability. Some parts of the site show slightly more subsidence (eastern part, red and orange dots). Some of these locations with higher subsidence may be related to human activities on the site, such as construction of moving of objects on the site. These locations can be recognized by steps in the ground motion data. The ground motion data can be viewed in the 'Bodemdalingskaart 2.0'.

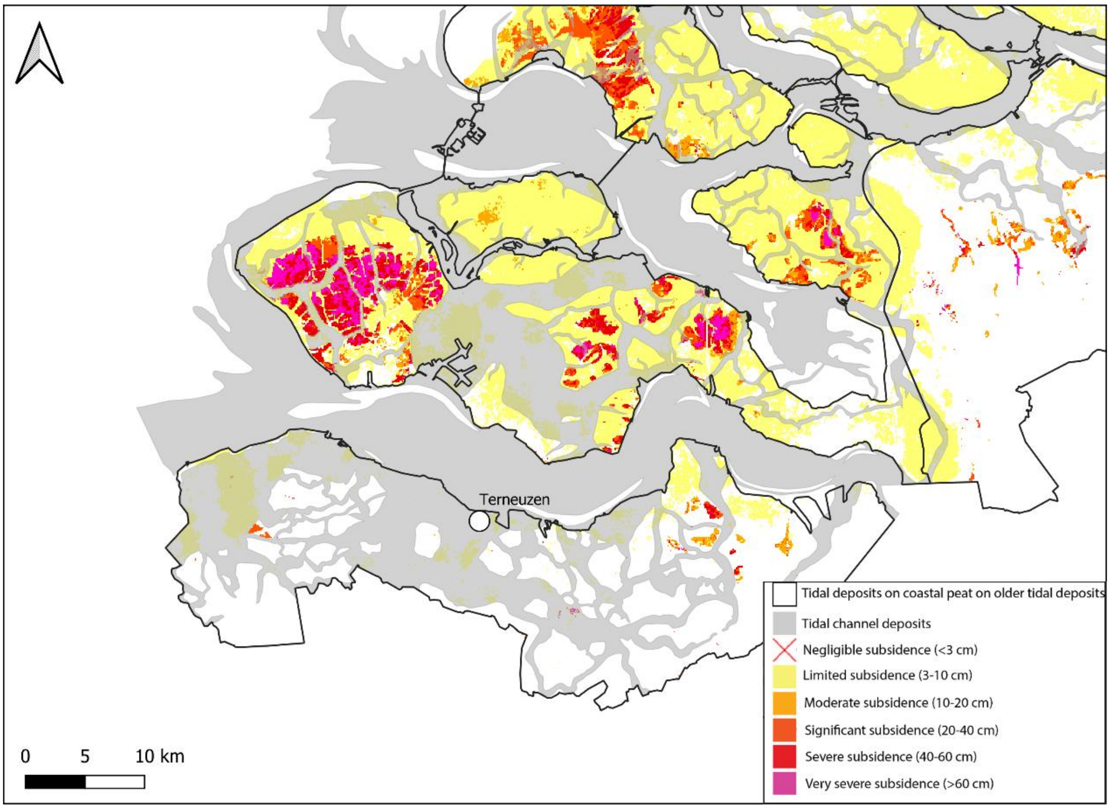


Figure 7-3 Map of the predicted amount of subsidence in the Zeeland Region until 2100 under IPCC future climate scenario WH (after Climate Impact Atlas, 2021). A clear relation is visible between the amount of subsidence and the type of deposits. In Terneuzen, negligible amounts of subsidence occur in areas with tidal channel deposits (NUNAWAga) covered by tidal deposits, indicated in grey on the map. In other areas of Zeeland farther away from Terneuzen moderate to very severe subsidence may occur.

7.2 Settlements

This section provides a first assessment of the potential settlement of the building at the two sites (Paulinapolder and Mosselbanken) in Terneuzen. The objective of the settlement calculations is to get a first estimate (order of magnitude) of the settlements to be expected when building a power plant at the envisaged locations.

7.2.1 Building dimensions

The final building dimensions will be determined by the vendors. For the first estimate of the settlement and bearing capacity the following building dimensions are used:

- Length: 100 m
- Width: 60 m
- Basement depth: 15 m below ground level

The load at foundation level was provided by the client as 690 kPa. This is equivalent to roughly 27.5 m of solid reinforced concrete.

Additionally, it is assumed that the local ground level will be raised from the current ground level to a platform height of NAP + 8 m before building construction starts. Raising will be done with well compacted sand.

According to the information provided, the building will be founded on a shallow foundation, i.e. no piled foundation is used. Installation of piles is considered by one or more vendors. However, these piles will not be used as a direct foundation, but with the objective to enhance strength and stiffness of the subsurface. The top of these piles will be below the foundation level of the reactor building. The building will not rest directly on these piles. For the present analyses the presence of these piles will be ignored.

7.2.2 Locations

At the Terneuzen location two sites (Paulinapolder and Mosselbanken) are considered. The main differences in subsoil conditions between these two locations is the interpreted thickness of the Boom clay layer and the different original ground level.

7.2.3 Building timeline

For the analyses the following timeline will be used:

- Year 0: start preparation site, increase surface level to desired platform height of NAP +8 m by applying a well compacted sand layer
- Year 1-3: consolidation time, to limit the residual settlements due to backfilling area to required platform height
- Year 3: start construction of the civil works. (among others: building the concrete structures)
- Year 8: start installation turbine etc.

7.2.4 Calculation methodology

The settlement calculations are performed with the program D-Settlement of Deltares.
The new reactor building is modelled as a vertical load at foundation level (15 m below ground level). This is below ground water level, so the structure experiences an upward force due to the groundwater pressure at foundation level. The applied net load at foundation level is therefore reduced to consider this upward force. The load is applied such that the total vertical stress at foundation level (GL – 15 m) equals the surcharge load.

Figure 7-4 provides the cross-sectional setup of the model, while Figure 7-5 provides the top view of the load. The settlements are computed at the centre of the building, i.e. point 2 in Figure 7-5.

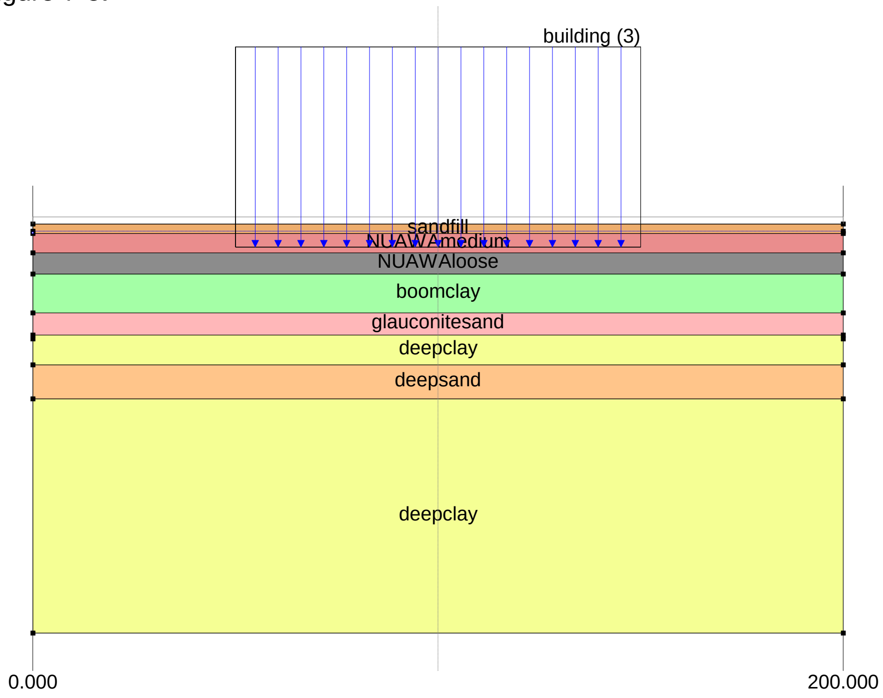


Figure 7-4 Cross section of applied load, modelled depth is 200 m, sediment layering varies for the three locations considered.

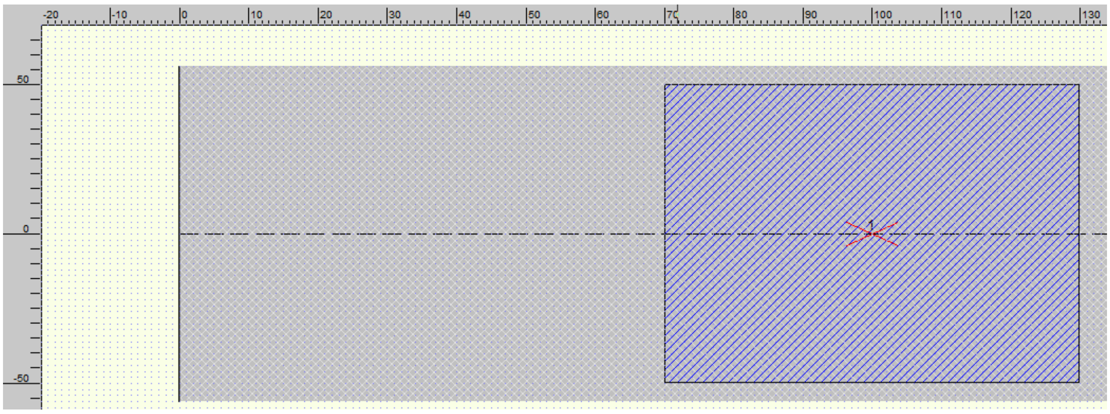


Figure 7-5 Top view of applied load, the red asterisk indicates the point for which the settlements are calculated.

7.2.5 Settlement parameters

The settlement parameters are taken from the geotechnical parameter selection (see Section 6.4). However, the contribution of the deeper clay layers (below NAP – 30 m) cannot be ignored for the calculation of the total settlement. No sufficient information on the properties of these layers is available. Therefore, some assumptions are made.

The depth and thickness of these layers are selected using the geological description. The settlement parameters are selected based on the given soil description and, in absence of a qualitative description, values from NEN-9997-1 for clay are used. The Dutch code NEN-9997-1 combines the Eurocode NEN-EN 1997-1 and the Dutch national annex.

Settlement behaviour of these layers greatly depends on the overconsolidation ratio (OCR). As these layers are of older age, overconsolidation due to aging will be present.

For the settlement calculations the following approach is used:

- Soil layering (selection of clay layers) is made based on the geological subsoil description
- Lower bound of the model is at NAP – 200 m
- A low value for the creep (C_α) is used
- The clay layers are assumed to be overconsolidated, OCR = 2 is used
- For CR (= Cc/(1 + e0)) the values for stiff clay are used
- For RR a value of CR/RR = 5 is selected, this differs from the ration used in the Dutch code NEN-9997-1, but is believed to better represent the settlement for stresses below the pre-consolidation stress

7.2.6 Calculated settlement

For the settlement calculations, the deep subsurface, to a depth of NAP – 200 m, is modelled, as shown in Figure 7-4. The construction time of the reactor building is taken into account by applying the load in four steps with a 1-year interval. The settlement as function of time at foundation level is shown in Figure 7-6 and Figure 7-7 for the two sites. Figure 7-8 and Figure 7-9 provide the settlement as a function of depth, indicating the contribution of the various soil layers.

Figure 7-6 Settlement-as function of time at foundation level (z = NAP – 7 m), location Paulinapolder. t = 0 years represents the start of the preparation of the site.

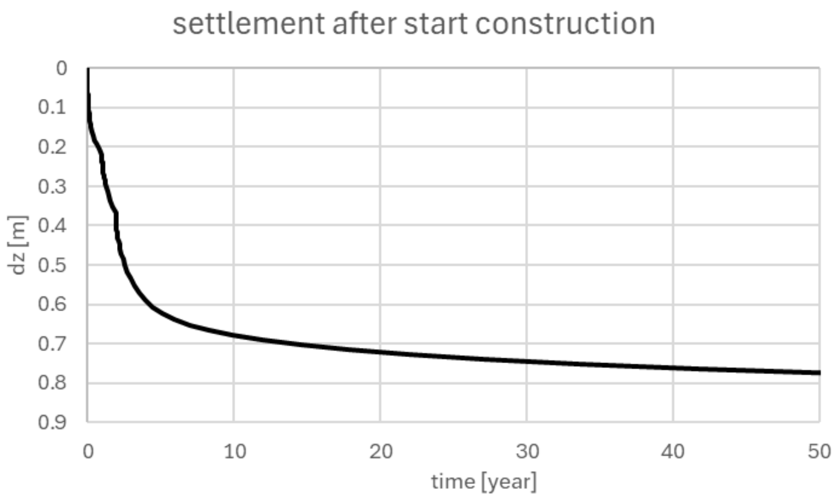


Figure 7-7 Settlement-as function of time at foundation level (z = NAP – 7 m), location Mosselbanken. t = 0 years represents the start of the preparation of the site.

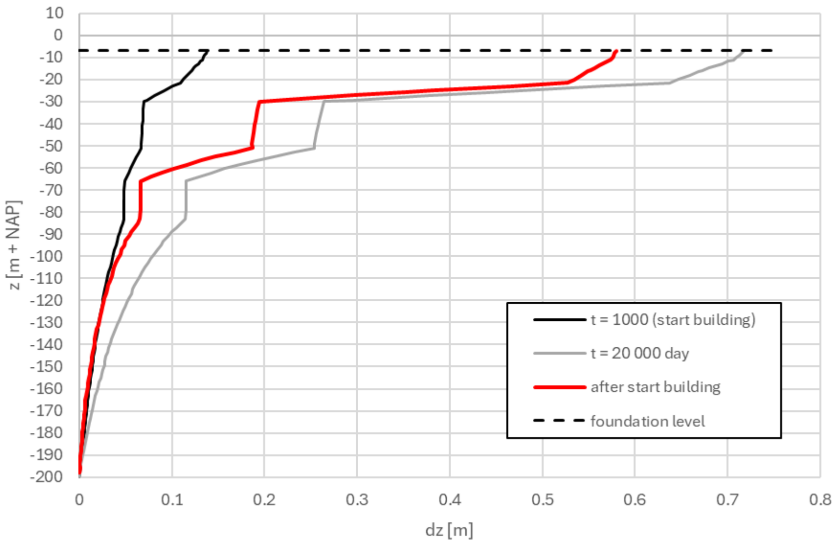


Figure 7-8 Settlement as function of depth, Location Paulinapolder. The red line indicates the additional settlement since the construction of the building, i.e. the difference between the gray and black lines. The dashed line is the foundation level (NAP – 7 m)

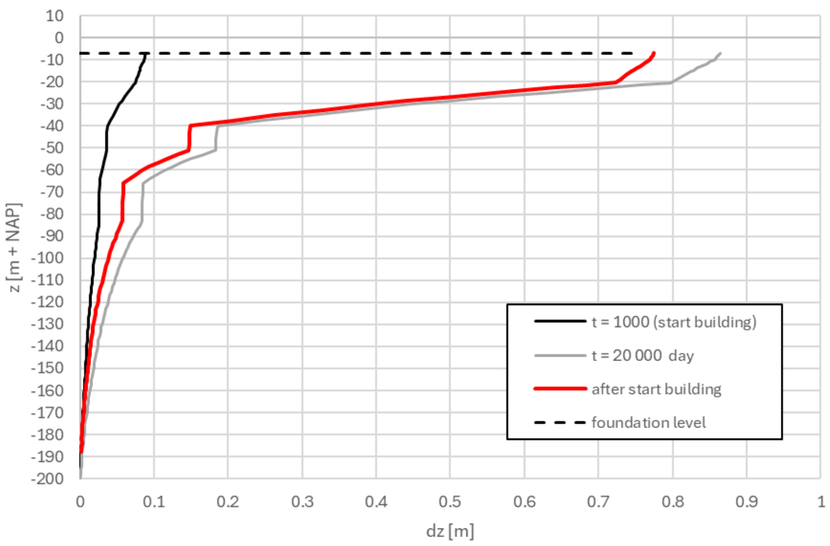


Figure 7-9 Settlement as function of depth, location Mosselbanken. The red line indicates the additional settlement since the construction of the building, i.e. the difference between the gray and black lines. The dashed line is the foundation level (NAP – 7 m)

The resulting settlements of the reactor building 30 years after start of building are:
- Paulinapolder: 0.55 m
- Mosselbanken: 0.74 m

The main contribution to the settlement comes from the Boom clay layer. The settlement at the location Mosselbanken is larger as at the location Paulinapolder. This is due to the larger interpreted thickness of the Boom clay layer at location Mosselbanken. The contribution of the deeper soil layers tot the total settlement cannot be ignored.

Given the large contribution of the Boom clay layer to the total settlement a site specific determination of the thickness of the Boom clay layer and site specific determination of the settlement behaviour is highly recommended.

7.3 Bearing capacity

The objective of these bearing capacity calculations is to estimate the bearing capacity of the subsurface, and the result may be used to decide whether a non-piled foundation may be used or if a piled foundation is needed.

The assumed building dimensions and building timeline are provided in sections 7.2.1 and 7.2.3.

7.3.1 Calculation methodology

For the bearing capacity calculations, the foundation of the structure will be considered as a shallow foundation. Bearing capacity will be assessed using the Brinch-Hansen approach, as described in the governing Dutch geotechnical code (NEN-9997-1). In the present calculations any horizontal load, e.g. due to wind, is not taken into account.

According to the Dutch code NEN-9997-1 the settlement of the building should be within certain limits. For this report the check on settlement is omitted when checking the bearing capacity, as these settlements are already calculated in Section 7.2.

The calculations are performed with the program D-Foundation of Deltares.

7.3.2 Soil parameters

The used soil parameters are taken from the geotechnical parameter selection, see Section 6.5. For the deeper soil layers an estimate is made, using the given soil description.

In the calculations the applicable partial factors, as prescribed in NEN-9997-1, are used. These are:

- Angle of internal friction: 1.15
- Effective cohesion: 1.6
- Undrained shear strength: 1.35

No partial factor on the load is applied as these calculations are for comparative purposes.

7.3.3 Bearing capacity calculation

For the bearing capacity calculations two vertical profiles are used for the considered locations.

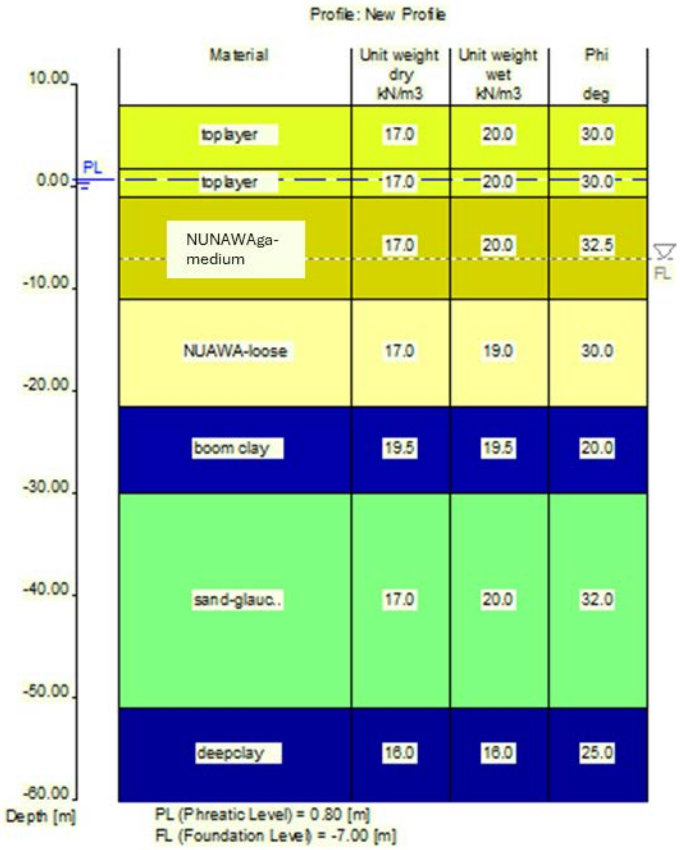


Figure 7-10 Sedimentary layering used in bearing capacity calculation, location Paulinapolder.

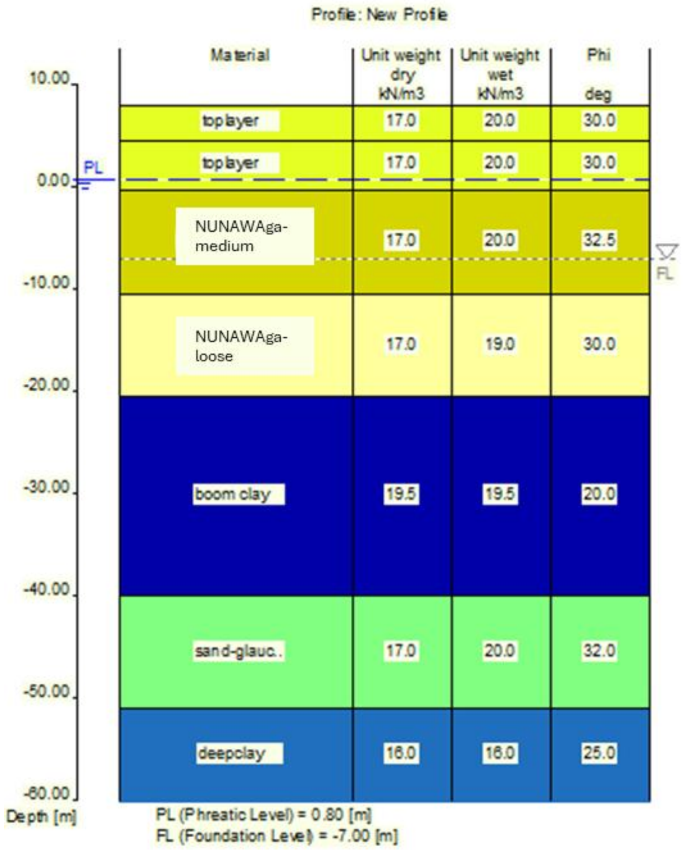


Figure 7-11 Sedimentary layering used in bearing capacity calculation, location Mosselbanken,

The following values for the total bearing capacity (maximum allowable vertical total stress at foundation level) are calculated:

- Site Paulinapolder: q = 783 kPa
- Site Mosselbanken: q = 778 kPa

The bearing capacity is thus well above the required value of 690 kPa. From the calculations it follows that the bearing capacity is governed by the punch-trough mechanism of the Boom clay layer. In the calculations an undrained shear strength of Su = 100 kPa for this layer was used.

8 Seismic hazards

8.1 Faults in the vicinity of Terneuzen

The Terneuzen site is part of the Scheldt Delta region in the southwest of the Netherlands and lies at the northern edge of the stable basement of the London-Brabant Massif (Rijkers et al., 1993). It is not known as a tectonically active region. This is evidenced by the instrumental (since 1911) and historical (since 1142) records that indicate no recent earthquake activity in the region (see Kruiver & Spetzler, 2023). However, the instrumental and historical data alone does not prove the absence of any capable fault in the Terneuzen site vicinity during the previous millions of years. Multiple other sources provide additional circumstantial evidence that indicates minimal tectonic activity in the region.

In the Scheldt Delta region, the European Fault-Source Model 2020 (EFSM; Basili et al., 2022) does not indicate any active faults. Outside of the Scheldt Delta Region, it indicates that the nearest known active faults are the bounding faults of the Roer Valley Graben (RVG) in the southeast of the Netherlands (Figure 8-1). The nearest point of the Gilze-Rijen Fault on the western side of the RVG is located approximately 85 km to the northeast of Terneuzen. On the eastern side of this actively subsiding region, the Peel Boundary Fault is located 125 km away. The most recent major earthquake along this fault line was in 1992 when near Roermond (160 km from Terneuzen) a 5.8 magnitude earthquake occurred at depths of 15 km. Towards the southwest from Terneuzen, the Sangatte Fault in northern France is located approximately 130 km away as the next nearest active fault.

In the scale of the site vicinity (within 25 km), there are two 2D heritage seismic lines available at NLOG. These seismic lines are 761003 and 761005, approximately 15 km north of Terneuzen, and date back to 1976. The quality of these seismic lines is not sufficient to make interpretations on the presence of faults in the shallow subsurface.

At a local scale, the subsurface site evaluation based on all currently available CPTs and borehole descriptions did not suggest any faults in the geological record at the Terneuzen site. This is supported by the regional geological mapping at the surface and in the subsurface as compiled in Dutch regional subsurface models GeoTOP and REGIS/DGM. These models do not require the presence of faults to explain any of the geological data for the last millions of years in the Scheldt Delta region. Across the border in Belgium the only faults within the Neogene and Quaternary (past 23 Myrs) part of subsurface models are related to the Roer Valley Graben and are located at more than 80 km distance (Matthijs et al., 2013).

Separately from subsurface modelling, additional insight can be gained from sedimentary structures preserved in sediments. Sediments may provide a trace of syndepositional tectonic activity as long as they are still poorly consolidated, known as seismites. For instance, soft sediment deformation from ground motion may produce sedimentary structures such as hybrid brittle–ductile structures or sedimentary dikes (e.g. Törő & Pratt, 2016).
These seismites have not been described in the Zeeland Region.

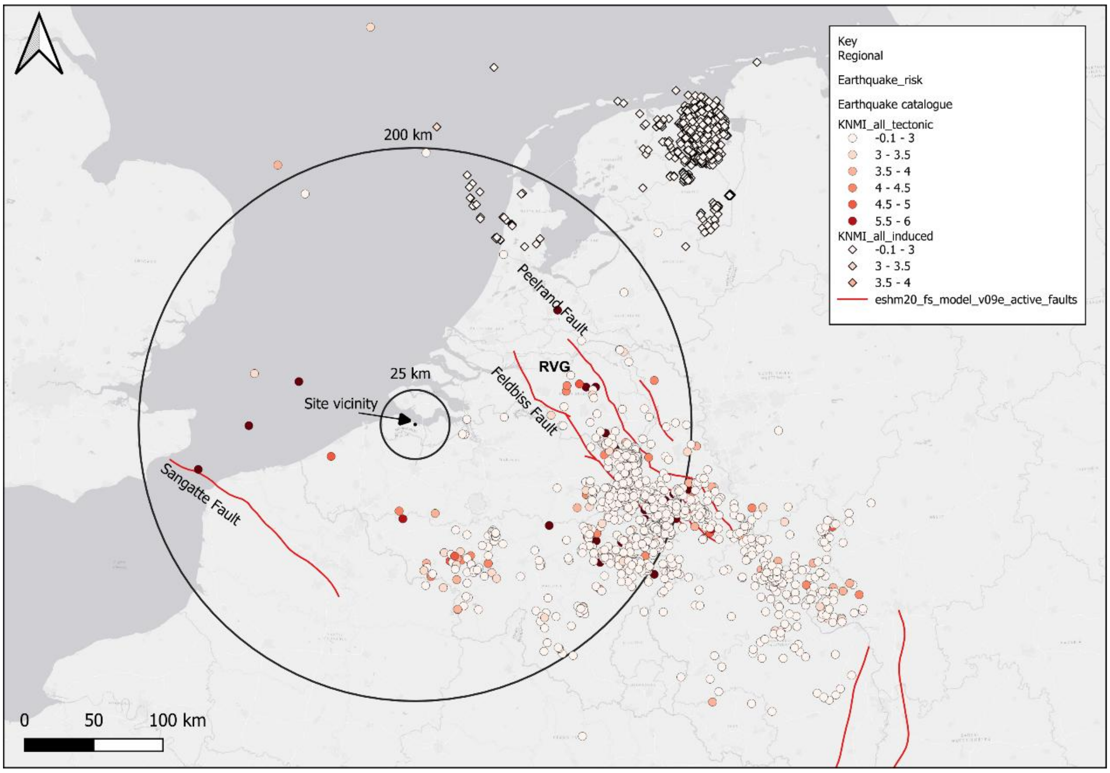


Figure 8-1 Regional map of earthquake activity (colored circles and diamonds) and active faults (red lines). All earthquake intensities (induced and tectonic) are given as Richter scale values. Indicated are 25 km and 200 km equidistance lines surrounding the Terneuzen location. RVG: Roer Valley Graben.

8.2 Initial assessment of liquefaction potential

As no results of a recent site-specific seismic hazard analysis are available, indicative values for the seismic loading are used. Note that a full Probabilistic Seismic Hazard Analysis according to the latest scientific standards and SSHAC recommendations is recommended. The properties used are derived from the hazard curve shown in Figure 8-2. The vertical lines indicate a Peak Ground Acceleration (PGA) of 0.14, 0.38 and 0.8 g, which correspond to yearly probability of exceedance of 10^{-4},10^{-5} and 10^{-6} respectively. A PGA of 0.06 g at ground level was used in the past for the stress test for the Borssele Nuclear Power Plant.

The PGA determined in Figure 8-2 represents the acceleration at the Terneuzen at bedrock level. According to Eurocode 8-1 (2004), in combination with the local soil conditions, an amplification factor of 1.15 is used, such that the PGA at ground level becomes PGA = 0.16g for a yearly probability of exceedance of 10^{-4}. The moment magnitude (Mw) is used as an indication of the duration of the vibrations. Theoretically, the moment magnitude that correlates with the most impactful PGAs at the site should be used. However, further investigation is required to derive these earthquake statistics. Here, a conservative estimate of Mw = 6 is used based on the earthquake in Roermond in 1992, the largest measured earthquake in NW Europe, with measured Mw = 5.3 (Braunmiller et al., 1994).

To summarize, the following seismic parameters are used for the preliminary assessment:

1. PGA = 0.16 g (significantly higher than the value used for the stress test for Borssele NPP)
2. Mw = 6 (which is conservative when compared to the earthquake in Roermond in 1992, but again, a full PSHA will be needed to detail this).

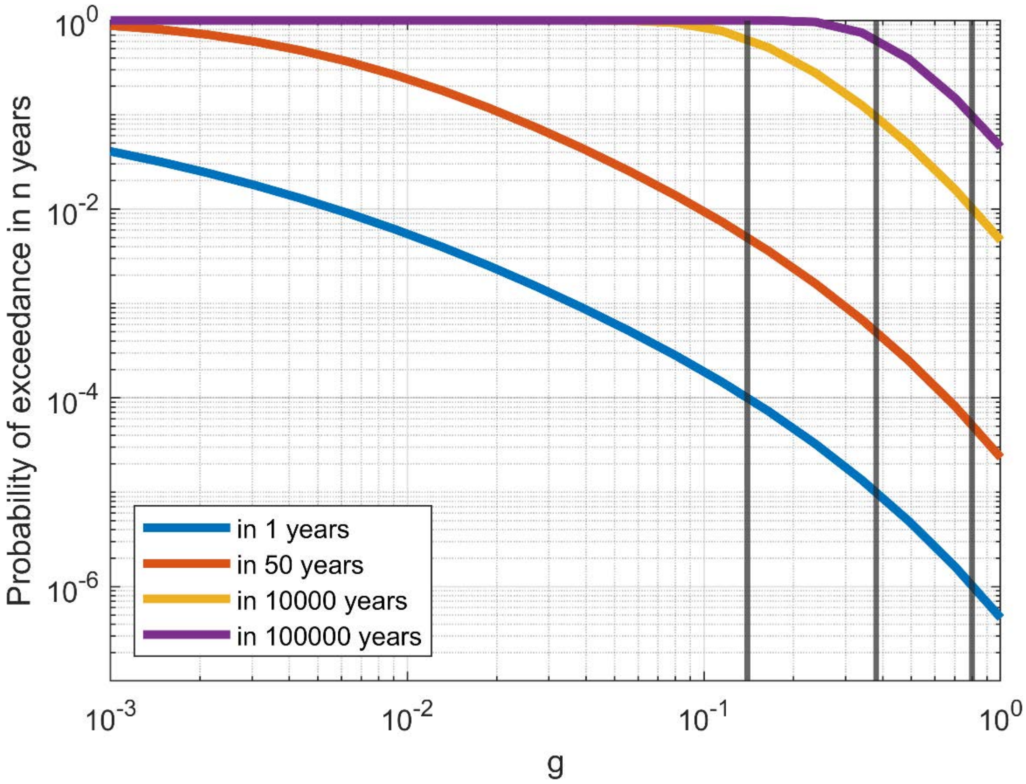


Figure 8-2 PGA Hazard Curves for the Terneuzen. Derived from the publicly available European Seismic hazard model ESHM20 (Danciu et al., 2021). The curves have been derived with the following settings: Longitude 3.782, Latitude 51.300, ESHM20, PGA, rock_vs_30_800ms-1 and the arithmetic mean.

The approach outlined by Boulanger & Idriss (2014) is used as liquefaction model. In the analyses no thin layer correction or any other correction for the measured cone resistance at layer boundaries is applied. This may underestimate the cone resistance, and thus overestimate the risk of liquefaction, in strongly layered soils. Considering the similarities between the soil conditions below NAP +0 m for the Mosselbanken en the Paulinapolder, results are presented only for the Mosselbanken. The ground level of the Mosselbanken is closer to the final ground level after construction, and therefore more representative.

A groundwater level of NAP + 0.8 m is used. No liquefaction will occur in the soil layers above the groundwater level. Additionally, the current ground level of approximately NAP +4.5 m is used in the approach. Raising the ground level will increase the effective soil stress, thereby reducing the liquefaction potential. Figure 8-3 provides the Factor of Safety (FS) against liquefaction. If FS is higher than one, liquefaction will most likely not occur given the seismic conditions.

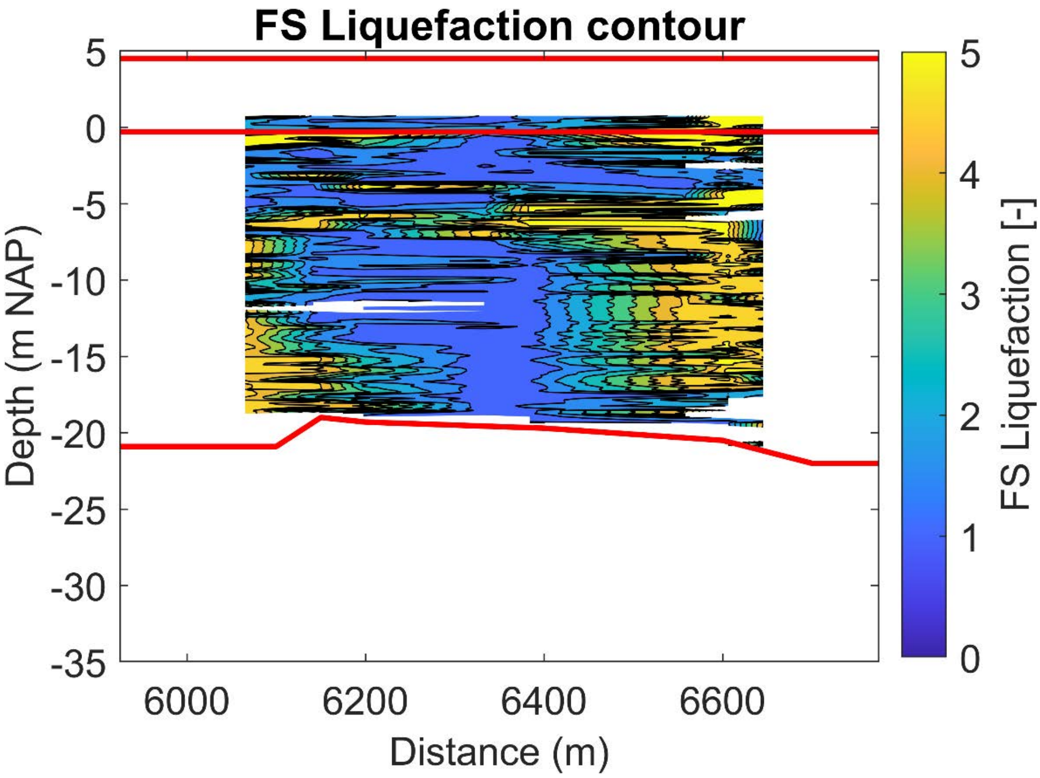


Figure 8-3 Liquefaction assessment based on the closest CPTs. The liquefaction potential is only assessed for sand and silt layers, and positions where CPT data are available. Clayey parts or missing data thus remain white.

The NUAAOP layer is mostly above the expected ground water level. Given that the layer will be densified it is unlikely to liquefy even at higher groundwater levels. The NUNAWAga layers contain loose and medium dense sands. At a PGA of 0.16 the loose zones have a low factor of safety. A few points are just below the limit of 1.0. Since this is only a minor fraction of the layer, the risk of liquefaction is low. The risk of liquefaction will be further reduced by the raised ground level, and can be improved by soil improvement techniques targeting the looser zones. The layers below the Boom clay are unlikely to trigger liquefaction due to their depth and are not further assessed.

Additionally, the liquefaction assessment is performed with the higher bedrock PGA values of 0.38 g (Figure 8-4) and 0.8 g (Figure 8-5). These studies indicate the liquefaction potential for rare earthquakes. It is noted that for these high PGA values the simplified soil amplification factor of EC8 is no longer valid, as the non-linear soil response will largely reduce the amplification. A more realistic estimate of the PGA at ground level can be obtained by performing soil response calculations. For the present study a first estimate is made by extrapolating on the graph given in (Idriss 1990). This results in the following estimates for the PGA at ground level:

- $PGA_{bedrock}$ = 0.38g => PGA_{GL} = 0.38 g
- $PGA_{bedrock}$ = 0.8g => PGA_{GL} = 0.45g

Especially, the NUAWA2, NUNI, NUKW and NUNAWAga layers may be prone to liquefaction at these higher earthquake loads. However, given the low likelihood of these events, further investigation is required to better estimate the earthquake loads and effects. For example, an improved estimate of the PGA at ground level must be determined. Finally, the results can be compared against the stress test for the existing Borssele Nuclear Power Plant using Figure 8-6, which indicates that for this low earthquake load, liquefaction is highly unlikely.

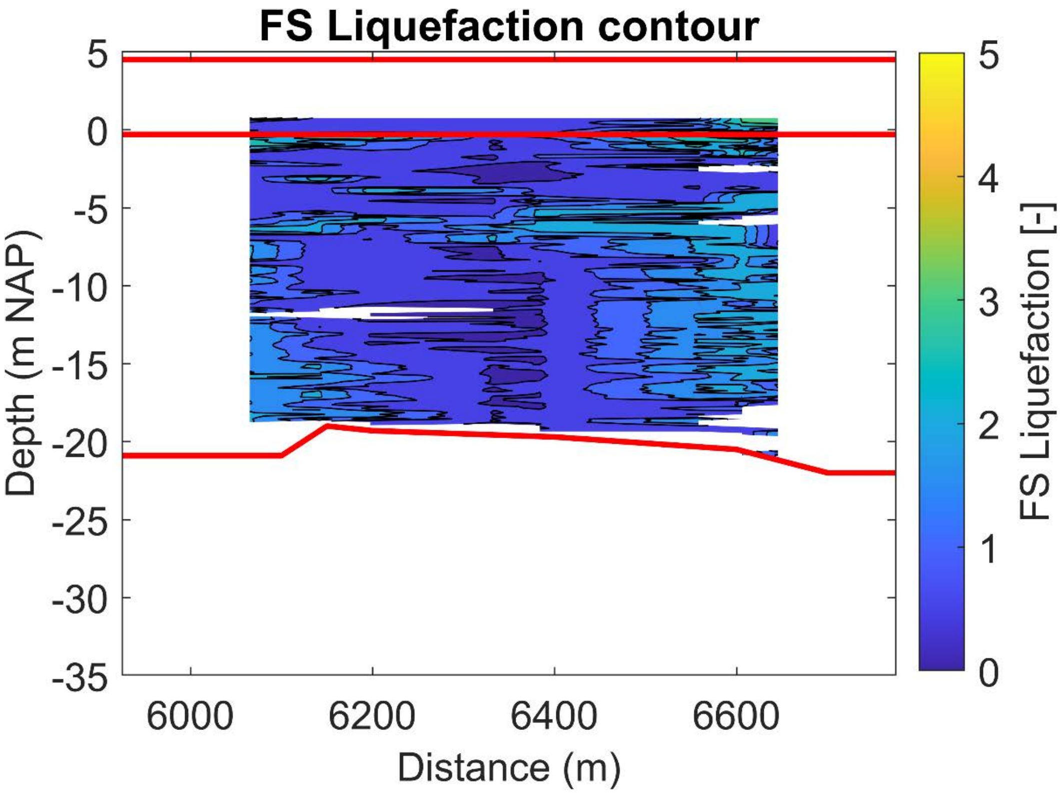


Figure 8-4 Liquefaction assessment with PGA = 0.38 g at ground level, a yearly probability of exceedance of 10-5, based on the closest CPTs. The liquefaction potential is only assessed for sand and silt layers, and positions where CPT data are available. Clayey parts or missing data thus remain white.

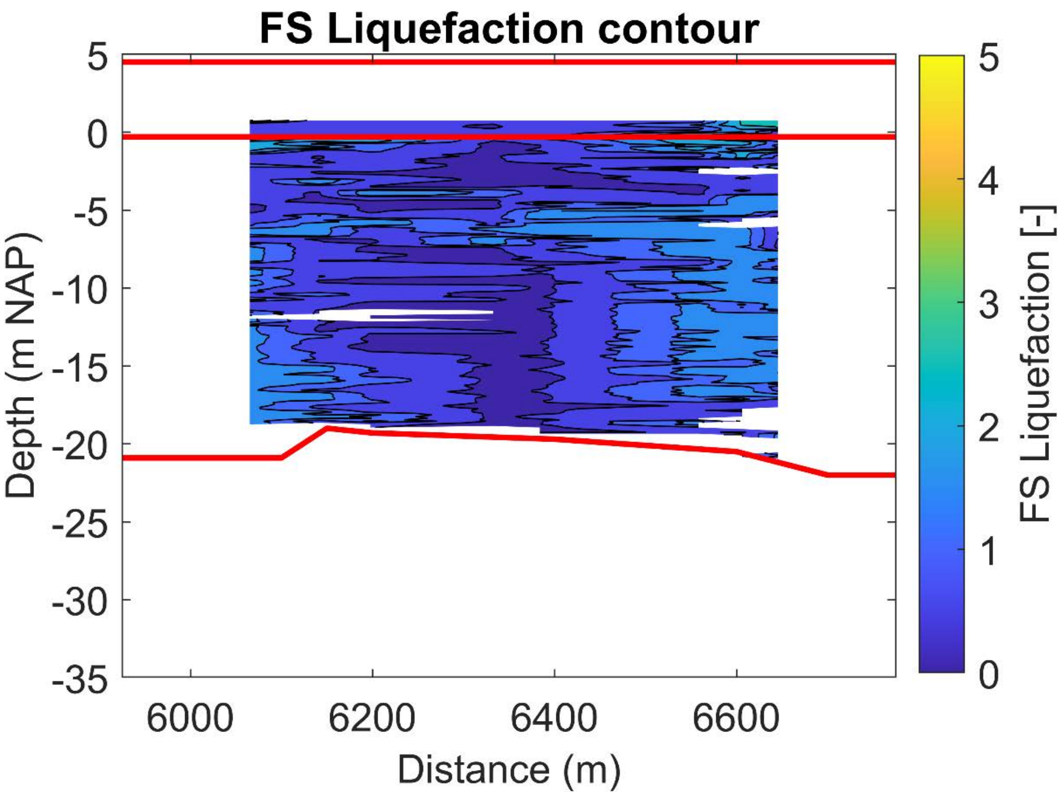


Figure 8-5 Liquefaction assessment with PGA = 0.45 g at ground level, a yearly probability of exceedance of 10^{-6}, based on the closest CPTs. The liquefaction potential is only assessed for sand and silt layers, and positions where CPT data are available. Clayey parts or missing data thus remain white.

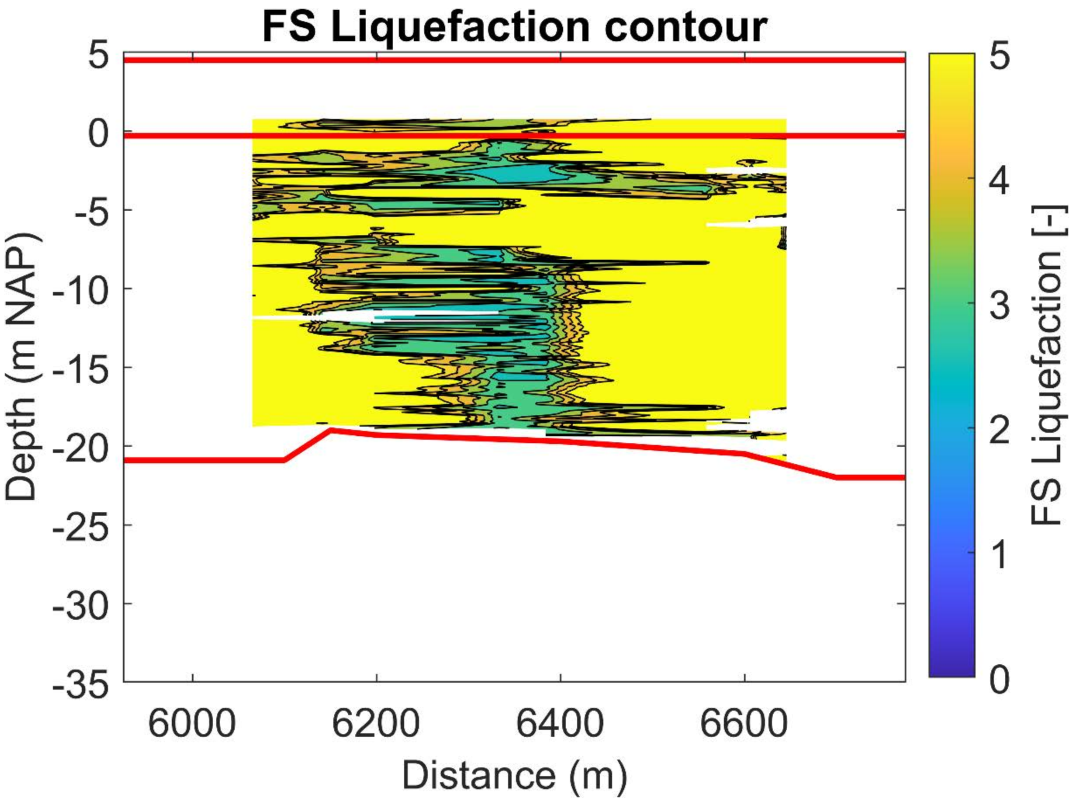


Figure 8-6 Liquefaction assessment with PGA = 0.06 g at ground level, the value used for the stress test Borssele, based on the closest CPTs. The liquefaction potential is only assessed for sand and silt layers, and positions where CPT data are available. Clayey parts or missing data thus remain white.

9 Volcanic hazards

No volcanic activity is known to have taken place in the Netherlands during the last 10 Ma. In this section we will discuss the nearest regions that were volcanically active during the Holocene and Pleistocene. This is far from a complete study on all volcanic activity in northwestern Europe, but within the scope of the current report it provides first insights towards a potential volcanic hazard risk assessment for the Terneuzen site.

9.1 Western and Eastern Eifel Volcanic Fields

The nearest volcanoes are the West and East Eifel Volcanic Fields in Germany. These fields are located respectively 255 km and 275 km to the southeast of Terneuzen. The West Eifel Volcanic Field is located southwest of Bonn and the East Eifel Volcanic Field is situated approximately 40 km to the northeast (Van den Bogaard & Schmincke, 1985).

Volcanic activity in the West and East Eifel Volcanic Fields took place during the early parts of the Neogene, approximately until the late Miocene. After a quiet period, volcanic activity restarted in the Quaternary at 850 ka. The last eruption of the East Eifel Volcanic Field was due to the Laacher See volcano at approximately 12.9 ka. The last eruption of the West Eifel Volcanic Field was approximately 11 ka due to the Ulmener Maar (Förster & Sirocko, 2016; Hensch et al., 2019). Given this relatively recent age, these volcanic fields are considered active on geological time scales according to the IAEA guidelines (International Atomic Energy Agency, 2012) and should therefore be considered at Terneuzen.

The West Eifel Volcanic Field contains scoria cones, maars (tuff rings) and small stratovolcanoes. The East Volcanic Field contains scoria cones, maars, lava flows and the three larger caldera complexes of Wehr, Rieden and Laacher See volcano (Förster & Sirocko, 2016). Therefore, volcanic phenomena which occurred could be amongst others tephra fall out, lava flows, slumps triggered by volcanic earthquakes or base surges. Tephra fall out is one of the volcanic phenomena which can have relatively large travel distances. During the large eruption of the Laacher See volcano about 20 km^3 of tephra was produced (Global Volcanism Program, 2023). Figure 9-1 shows the different lobes of the tephra deposits of the Laacher See volcano, which can be found close to the border of the province of Limburg in the southeasternmost part of the Netherlands. Maps of the areal distribution of ash layers in Van den Bogaard and Schminke (1985) show similar patterns as in Figure 9-1.

All other volcanically active regions in Europe are schematically indicated in Figure 9-2. These are all located farther from Terneuzen and include the volcanoes at the Massif Central in France (~600 km) and the Icelandic volcanoes (~1800 km). Since the historical effects of these volcanoes did not reach the Netherlands to a significant degree, we will only briefly mention them.

9.2 Chaîne des Puys

Holocene volcanic activity has taken place in the Chaîne des Puys, situated in the Massif Central, France. This chain consists of 80 cinder cones, maars and lava domes.
Latest volcanic activity occurred at approximately 8.6 ka during the eruption of the La Vache and Lassolas cone complex. This was also one of the most powerful eruptions of the Chaîne des Puys. Tephra and lava flow deposits of this eruption were found in the surrounding dozens of kilometers within the Chaîne des Puys (Jordan et al., 2016).

9.3 Icelandic volcanoes

Effects of eruptions of Icelandic volcanoes such as the eruption of the Eyjafjallajökull volcano in Iceland in 2010 were relatively limited in the Netherlands. This eruption led to disruption of the air traffic in Europe due to the large volcanic ash cloud (>8 km height) (Petersen et al., 2012). The size of the ash particles that reached northwestern Europe were only submillimeter to tens of nanometers in size (Gislason et al., 2011).

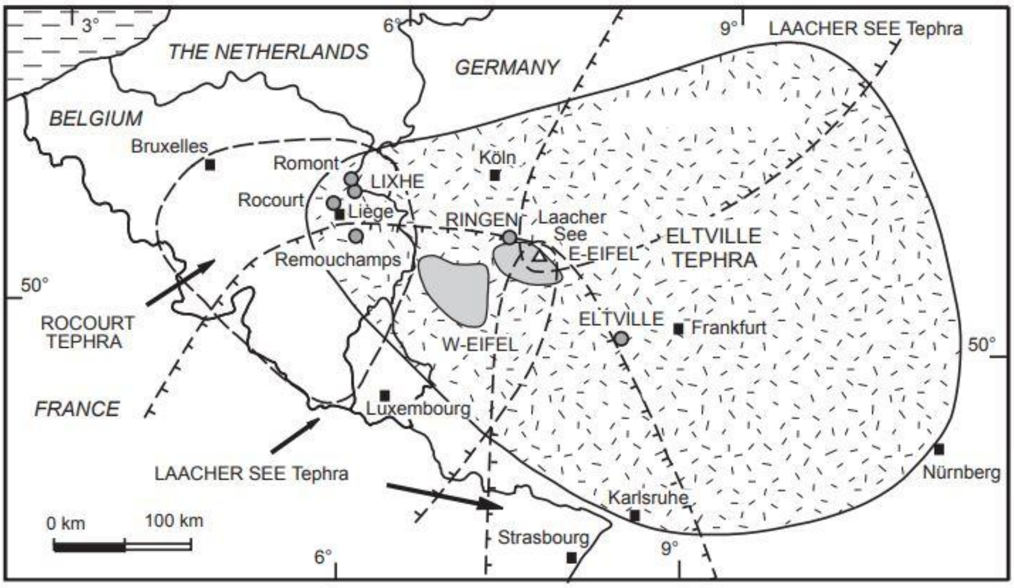


Figure 9-1 Lobes of the Lacher See tephra deposits (Pouclet & Juvinge, 2009).

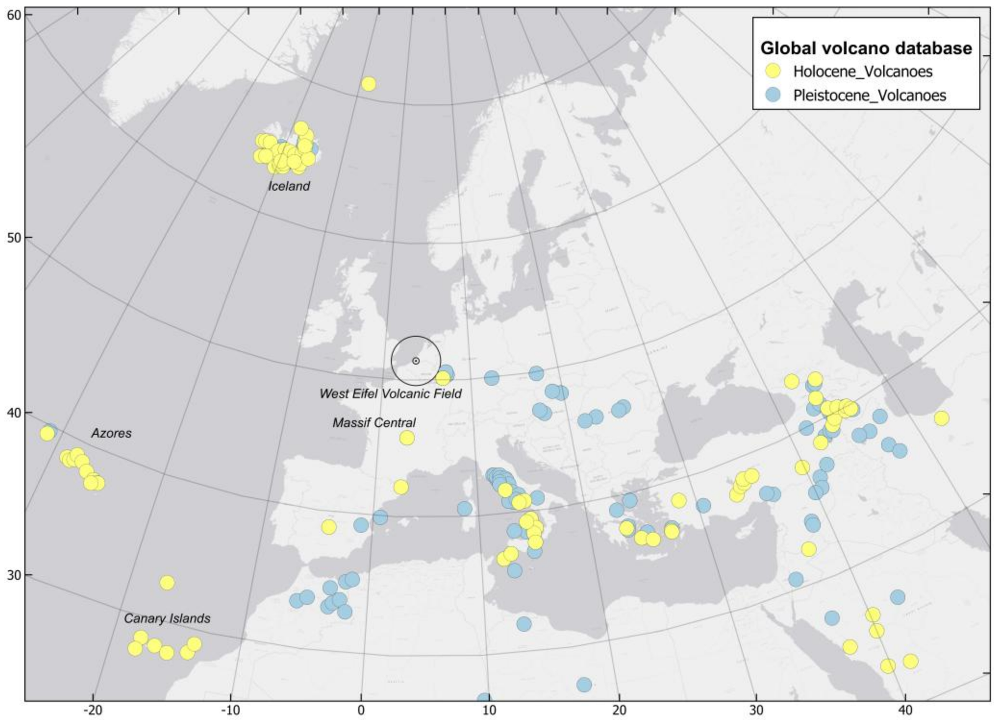


Figure 9-2 Holocene and Pleistocene volcanoes in and around Europe, based on the Smithsonian Institution's Global Volcanism Program database.

10 Conclusions and recommendations

10.1 Site evaluation

The site evaluation focused on the build-up and properties of the subsurface, but has also addressed potential hazards associated with subsidence, settlements, bearing capacity, seismicity and volcanic activity. With respect to subsidence, seismicity and volcanic activity, no major upfront constraints for the development of Terneuzen were identified. Subsidence rates are generally low, and slightly increased in the eastern part of the site were the top 3-4 m consist of landfill material.

The bearing capacity of the subsurface is sufficient to resist the given surcharge load of the reactor building, based on the preliminary investigation. Due to the given load of the reactor building large settlements, in the order of 0.5 m to 0.8 m, during and after construction are expected. The expected settlements and the bearing capacity are uncertain due to a lack of site specific lab testing. Additionally, soil improvement has not been accounted for in this preliminary study. Lab testing should be performed and compared to existing tests on the Boom clay and glauconite sand layers to determine their potentially non-typical behaviour. The data on the top layers of the Paulinapolder and Mosselbanken is scarce.

The general build-up of the subsurface is a layer of sandy, Holocene, tidal deposits (Naaldwijk Formation) till approximately -20 m NAP, on top of almost 23 Myrs older fat and stiff clays of Oligocene age (Rupel Formation Boom Member). Below these clays an alternation of more clayey and more sandy units of Oligocene and Eocene age (Tongeren Formation and Dongen Formation).

In the western part of the site some Pleistocene marine (Eem Formation) and fluviatile (Koewacht Formation) deposits can be present between the Naaldwijk and Rupel Formations. In the eastern part of the site a landfill of 3 to 4 m is located on top of the Naaldwijk Formation, possibly leading to slightly increased subsidence rates.

There are no public piezometric measurements at the Terneuzen site. Therefore, groundwater levels were simulated using the Dutch Hydrological Model. In the west and south areas, levels range between 50–150 cm NAP, approaching surface level during wet periods and dropping to –20 cm NAP (~2 m depth) in dry summers. The east side is significantly higher in elevation, with groundwater levels reaching up to 450 cm NAP (just below surface) and falling to 150 cm NAP in dry periods. In all areas, groundwater discharges towards the surrounding polders and the Western Scheldt. Which makes it vulnerable for contaminant transport. At the eastern site, a ~10 m thick freshwater lens is present, limited in growth by the low-permeable NMRUBOk1 aquitard. In the Paulina Polder, fresh water extends to 10 m depth in the far west, while brackish water is near the surface in the east. Below the NMRUBOk1 layer, older deep freshwater is present, but industrial extraction is challenging due to induced saltwater intrusion from high groundwater flow velocities.

10.2 Recommendations

Based on the current assessment of the subsurface at the Terneuzen site, the available information gives a good general overview of the site. Due to the lack of geological and geotechnical data within the site or near vicinity it is recommended to acquire additional data till the depth of interest, to have site specific information.

For a proper characterization of the geohydrological setting, however, more data is urgently needed. It is advised to install piezometric monitoring wells with filters at different depths as soon as possible. Monitoring should continue for at least one year to capture seasonal effects as well as salt concentrations.

For the potential risks associated with seismic hazards, a full Probabilistic Seismic Hazard Analysis is recommended. Based on preliminary assumptions it is concluded that the risk of full liquefaction is low for earthquake events with a recurrence interval 10.000 years, but that during larger earthquakes liquefaction may be expected in the loose to medium dense NUNAWAga sands.

In our view, a full PSHA would be essential information when ranking the four proposed locations in terms of suitability. The other attention points can be addressed in a later phase.

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A Lithological description of the geological units

In this section, characteristics of each of the geological units will be described in detail. This includes the depositional age, lithology and related depositional environments, defining characteristics of the lower and upper boundaries of each unit, the thickness and typical depths at Terneuzen. In addition, defining characteristics of these units in cone penetration test (CPT) results are discussed – if data are available in the vicinity of the site – in combination with specific points of attention related to geotechnical investigations. The geological formations will be discussed from young to old. Interfingering Holocene members of the Naaldwijk and Nieuwkoop formations are described as part of the formation and are therefore not strictly discussed in chronological order.

For the current report we limit ourselves to the formations that make up the top 200 m of subsurface at Terneuzen, because that is the depth range that is covered by boreholes. The nearest location where a record of older units has been described is the 1900 m deep Kortgene-1 borehole, 24 km to the north of Terneuzen.

For each unit the official abbreviations are given, here the first two letters indicate the group: NU: Upper North Sea Group, NM: Middle North Sea Group, NL: Lower North Sea Group. The next letters indicate the formation and member.

A.1 Naaldwijk Formation (NUNA)

A.1.1 Walcheren Member (NUNAWA) and channel belt generation A (NUNAWAga)

- Link to Dutch stratigraphic nomenclature

https://www.dinoloket.nl/en/stratigraphic-nomenclature/walcheren-member
Channel belt generation A is not separated in the Dutch stratigraphic nomenclature but is mapped separately on the geological map of the Netherlands. It is regionally important in the Scheldt Delta as channel fill from estuarine branches of the Scheldt estuary that were active in the last 500 years.

- Age

Middle to late Holocene (Subatlantic).

- Lithological description

Mainly consisting of clayey or silty fine grey sand, local thin peat layers can occur. Also, shells and shell fragments can occur as admixture. The top part can contain clay layers of decimetres up to two meters thick.

- Depositional environments

Estuarine or back-barrier setting, formed after breaching of the closed barrier coast. Mostly composed of tidal channels and tidal flats, mud flats and tidal marches (e.g. Slupik et al., 2007). At Terneuzen the majority of the NUNAWA deposits are related to the tidal system *Braakman* which belong to the channel belt generation A.

- Lower boundary

Stratigraphically above the peat of the Hollandveen Member of the Nieuwkoop Formation. At the Terneuzen site, the Walcheren Member is incised into the clays of the Rupel Formation, and in the eastern part into the Koewacht Formation.

- Upper boundary

Covered by anthropogenically reworked sediment or exposed at the surface.

- Thickness indication and typical depth interval

At Terneuzen, the Walcheren Member of the Naaldwijk Formation is about 10 m thick at the west side, increasing to 20 m to the west side where the tidal system *Braakman* was located. The top lies around 0 m NAP, its base increasing from -10 m NAP in the west to -20 m in the east of the site.

- CPT characteristics

Some CPTs 100-200 m east of the site show constant low friction ratio (rf) values around 1 and high cone resistance (qc) between ~10 and ~30 MPa (average 20 MPa). In these CPTs no clay layer is captured, which is observed in boreholes within the site.

- Points of attention

A clay layer of decimetres up to two meter can occur at depths around -1 m above NAP.

A.2 Nieuwkoop Formation (NUNI)

A.2.1 Hollandveen Member (NUNIHO) or undifferentiated (NUNI)

- Link to Dutch stratigraphic nomenclature

https://www.dinoloket.nl/en/stratigraphic-nomenclature/hollandveen-member

- Age

Holocene, Subboreal – early Subatlantic.

- Lithological description

Brown to black peat, with occasionally traces of sand in the upper part. The peat can be spongy to very loose.

- Depositional environments

Eutrophic to mesotrophic coastal marsh.

- Lower boundary

Lying directly on top of Pleistocene sands of the Boxtel Formation, with a gradual transition towards slightly humic, silty fine sands.

- Upper boundary

The Hollandveen Member has a sharp erosive contact with the tidal sand of the Walcheren Member of the Naaldwijk Formation.

- Thickness indication and typical depth interval

At Terneuzen, the Hollandveen Member is probably absent, about 3 km west of the site a layer of about 50 cm is present, at depths between 0 m and -1 m NAP.

- CPT characteristics

No CPTs penetrated this unit.

- Points of attention

The peat can be spongy to very loose.

A.3 Boxtel Formation (NUBX)

- Link to Dutch stratigraphic nomenclature

https://www.dinoloket.nl/en/stratigraphic-nomenclature/boxtel-formation
https://www.dinoloket.nl/en/stratigraphic-nomenclature/wierden-member

- Age

Late Pleistocene (Late Weichselian)

- Lithological description

The upper ~1 m consists of slightly humic, non-calcareous, light brown to yellow brown very fine sand and silt (cover sand). This sand is well-sorted and rounded. These cover sands belong to the Wierden Member of the Boxtel Formation. Below these cover sands, alternations of fine to medium sand with sandy loam and clay can be found (Boxtel Formation, undifferentiated).

- Depositional environments

Periglacial aeolian (cover sand) and small-scale fluvial environments: brooks, including channels, overbanks, and floodplains (sand, silt and clay).

- Lower boundary

Very gradual and diffuse transition to the coarser fluvial sand of the Koewacht Formation. The boundary between the Boxtel Formation and the Koewacht Formation is difficult to determine accurately, because of the lithological and genetical resemblance of the deposits of the Boxtel Formation (undifferentiated) and the top of the Koewacht Formation. For further detail see Kiden (2010).

- Upper boundary

Gradual contact with the peat of the Hollandveen Member or with the tidal sand of the Walcheren Member of the Naaldwijk Formation.

- Thickness indication and typical depth interval

At Terneuzen, the Boxtel Formation is probably absent, about 3 km west of the site a layer of about 6 m is present, at depths between -1 m and -7 m NAP.

- CPT characteristics

No local data in the Boxtel Formation.

- Points of attention

The lower boundary of the Boxtel Formation is difficult to determine accurately.

A.4 Koewacht Formation (NUKW)

- Link to Dutch stratigraphic nomenclature

https://www.dinoloket.nl/en/stratigraphic-nomenclature/koewacht-formation

- Age

Late Middle Pleistocene – Late Pleistocene (Saalian – Weichselian).

- Lithological description

The Koewacht Formation has a fining upward trend on formation-scale and consists of grey to brown, poorly graded, fine to very coarse sand, with more silty layers going upward. These fine to coarse transitions are vertically and laterally extremely variable. Basal lags of fine gravel and shell fragments can be found. Reworked shells and sediments from the older marine Eem Formation, Oosterhout Formation or Eocene can be present. Occasionally thin layers of clay or peat may occur.

- Depositional environments

The Koewacht Formation represents fluvial deposition by the Paleo-Scheldt River. This includes braided to meandering fluvial environments, consisting of channels (sand, gravel), overbanks and abandoned channels (clay, loam).

- Lower boundary

Sharp boundary, a lag, with the marine sediment from the Eem Formation or directly on top of the Oligocene clays of the Rupel Formation (Boom Member).

- Upper boundary

Very gradual and diffuse transition to the Boxtel Formation, or sharp boundary with the incised Walcheren Member of the Naaldwijk Formation. The boundary between the Koewacht Formation and Boxtel formation is difficult to determine accurately, because of lithological and genetical resemblance of the top of the Koewacht formation and the small-scale fluvial deposits of the Boxtel Formation (Kiden, 2010).

- Thickness indication and typical depth interval

At Terneuzen, the Koewacht Formation is probably only present in the eastern part of the site, it is approximately 4 m thick at the eastern boundary of the site and decreases in thickness towards the west. It occurs at depths between -8 m and -16 m NAP.

- CPT characteristics

Variable qc and rf, are expected to be related to alternations in fine to very coarse sand with more silty intervals. However, few local data give information, showing a qc roughly between 5 and 20 MPa and rf of ~1 – 2.

- Points of attention

The upper boundary of the Koewacht Formation is difficult to determine accurately. Occasionally layers of peat can occur in the Koewacht Formation.

A.5 Eem Formation (NUEE)

- Link to Dutch stratigraphic nomenclature

https://www.dinoloket.nl/en/stratigraphic-nomenclature/eem-formation

- Age

Late Pleistocene (Eemian).

- Lithological description

The main lithology is grey fine to medium calcareous sand with marine shells. The shells can be concentrated in ~2 meter thick layers with over 30% shell content.

- Depositional environment

Open marine conditions.

- Lower boundary

Sharp contact to the clay of the Rupel Formation or the sand of the Tongeren Formation.

- Upper boundary

Sharp unconformable boundary to the fluvial deposits of the Koewacht Formation.

- Thickness indication and typical depth interval

At Terneuzen, the Eem Formation is possibly present in the eastern part of the site, where it is expected to have a limited thickness of approximately 2 m at the eastern boundary of the site and decreases in thickness towards the west. East of the site it is reaches a thickness of about 4 m. It occurs at depths between -15 m and -20 m NAP.

- CPT characteristics

No local data in the Eem Formation.

- Points of attention

Possible shell layers (>30% shells) of ~2 m can be present.

A.6 Rupel Formation (NMRU)

A.6.1 Boom Member (NMRUBO)

- Link to Dutch stratigraphic nomenclature

https://www.dinoloket.nl/en/stratigraphic-nomenclature/boom-member

- Age

Early Oligocene (Rupelian and possibly early Chattian).

- Lithological description

The main lithology is dark greenish grey poorly calcareous to calcareous fat and stiff clay. Clayey sands with little mica and some glauconite of up to 1.5 m thick occur.

- Depositional environment

Open marine conditions.

- Lower boundary

Sharp contact to the sand of the Tongeren Formation.

- Upper boundary

Sharp unconformable boundary to the tidal sands of the Eem and Naaldwijk Formations or the fluvial sands of the Koewacht Formation as a result of early Miocene and later erosion.

- Thickness indication and typical depth interval

Due to the northward dip of the base of the Rupel Formation, the thickness at the Terneuzen site increases from 10 m in the south to 20 m in the north. The base lies around -30 m NAP in the south and -40 m NAP in the north, the top is around -20 m NAP.

- CPT characteristics

The closest CPTs to the Terneuzen site (100-200 m east of the site) cover the top 5 m of the Rupel Formation and show qc values of 3.5 to 5 MPa with rf values between 3 and 6. Deeper CPTs some km east of the site cover the full depth range and show similar values with an average qc between 3.5 and 4 with smaller intervals up to 7.5 MPa. There is a general increasing trend towards the base. The rf is 2.5 on average, up to maximum of 5.5.

- Points of attention

None.

A.7 Tongeren Formation (NMTO)

A.7.1 Ruisbroek Member (NMTORU), Watervliet Member (NMTOWA) and Bassevelde Member (NMTOBA)

- Link to Dutch stratigraphic nomenclature

https://www.dinoloket.nl/en/stratigraphic-nomenclature/tongeren-formation

- Age

Late Eocene – early Oligocene (Priabonian - early Rupelian).

- Lithological description

Multiple 2 to 20 m thick, poorly graded fine to medium weakly calcareous sandstone beds containing phosphorite pebbles, little mica and up to 20% glauconite. These sandstones are separated by weakly calcareous dark greenish grey fat clays and/or strongly calcareous clayey and silty sandstone with little mica and 10% to 30% fine glauconite sand grains. These finer grained intervals are particularly found in the middle part of the unit (Watervliet Member). The upper part of the Tongeren Formation (Ruisbroek Member) is predominantly sandy and contains progressively less glauconite.

- Depositional environment

Shallow marine conditions, with the presence glauconite in part of the formation indicating low energy conditions below storm wave base.

- Lower boundary

Sharp contact with the clay of the Asse Member of the Dongen Formation. This contact is a regionally extensive disconformable surface.

- Upper boundary

Sharp contact to the clay of the Boom Member of the Rupel Formation. South of the site directly below younger deposits of the Eem Formation.

- Thickness indication and typical depth interval

At Terneuzen, the Tongeren Formation is about 40 m thick with its top lying around -40 m NAP in the north and -30 m NAP in the south of the site. These are indicative numbers, as the geological model is based on limited data in this area.

- CPT characteristics

No CPTs penetrated this unit at the Terneuzen site. CPT 233287, about 3.5 km east of the site, reached into the top part of the sandy Ruisbroek Member and shows an average qc of 22 MPa, maximum 54 MPa, with rf average 1.3 and maximum 3.8.

- Points of attention

Glauconite is present in the sandy sections of the Tongeren Formation.

A.8 Dongen Formation (NLDO)

A.8.1 Asse Member (NLDOAS), Brussels Sands Member (NLDOBR), Ieper Member (NLDOIE)

- Link to Dutch stratigraphic nomenclature

https://www.dinoloket.nl/en/stratigraphic-nomenclature/dongen-formation

- Age

Early to late Eocene (Ypresian - Priabonian).

- Lithological description

The Asse Member is composed predominantly of fat, grey greenish non-calcareous clay. Below, the Brussels sands is composed of an alternation of glauconitic fine sand (with some gravel admixture) with hard, calcareous sandstone layers of decimetres thickness in the top part. In the lower part also loam layers are observed. The Ieper Member consists of clays, described as “generally soft, tough and sticky to hardened and friable”.

- Depositional environment

Open marine environment, with large water depths in the order of 200 m during deposition of the clay rich members (Asse and Ieper). The Brussels sands are deposited in shallower environments, inner-neritic to near-shore.

- Lower boundary

The lower boundary of the Dongen Formation is not identified at Terneuzen.

- Upper boundary

Sharp contact to fine sand of the Bassevelde Member of the Tongeren Formation. This contact is a regionally extensive disconformable surface.

- Thickness indication and typical depth interval

Nearby borehole B54E0285 reaches into the top of the Ieper Member, showing 37 m thick Asse Member clays on top of 66 m thick Brussels Sands. At Terneuzen the geological models indicate a similar thickness. The top of the Dongen Formation at Terneuzen lies around -80 m NAP, based on the models, the total thickness of the formation is around 250 m.

- CPT characteristics

No CPTs penetrated this unit.

- Points of attention

The Brussels Sands contain calcareous sandstone layers of some decimetres thickness that lead to high-resistivity peaks.

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