

Borssele II: Site evaluation

Recommended subsurface site investigation



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Summary

The Ministry of Economic Affairs and Climate Policy of the Netherlands requested Deltares to conduct a subsurface site evaluation for the intended Borssele II nuclear power plant site in the Zeeland province of the Netherlands.

Within the scope of these studies 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.

This request followed the initial geological and geotechnical subsurface site evaluation reporting for the intended Borssele II NPP (Deltares, 2023). In this follow-up report we provide recommendations for further field investigations to address the current subsurface uncertainties that were highlighted in the subsurface site evaluation report. The proposed field investigations are separated into geotechnical and geohydrological investigations and are specifically aimed at updating the geological model and the understanding of the geotechnical properties and the geohydrological system.

Geological and geotechnical properties should be assessed by means of seven Cone Penetration Test (CPT) transects (total of 92 CPT's). These can be split into two parts. Part A focuses on reducing the uncertainties surrounding the nature and location of the transition between two major types of subsurface build-ups. Part B focuses on characterizing the internal variability of the southeastern part of the subsurface, an area that contains considerable internal variability that currently lacks enough subsurface data for a proper subsurface assessment. In support of the CPT research, complementary geophysical line measurements should elucidate the lateral variability between the CPT transects and give insight into the shallow groundwater conditions (Part C). Other geotechnical parameter tests that should be undertaken include Vertical Seismic Profiling Tests (Part D).

The geohydrological conditions should be assessed by different types of tests to obtain sufficient information on spatially varying permeabilities, the influence of seasons and tides on the groundwater system, hydraulic conductivity between different aquifers and interface between fresh and brackish groundwater.

The permeability of the subsurface will be studied in multiple ways. The eight proposed boreholes will provide samples for permeameter tests, but also for grain-size distributions that can be translated to permeabilities as well. The influence of seasons and tides on groundwater-levels should be assessed for the duration of at least one year at twelve monitoring-well locations on and around the Borssele II site. Slugtests should be performed on all monitoring wells. In addition, two pumping tests should be undertaken, one for each type of subsurface profile. This provides important insight into the anisotropy and vertical variability of the hydraulic conductivity at the project area. Optionally, hydraulic profiling tool (HPT) tests, Mini Pumping Tests (MPT) and electrical conductivity (EC) tests may be performed for further detailing into the heterogeneity of the subsurface geohydrology.

Groundwater sampling should be undertaken to determine the chemical composition of the groundwater at the twelve borehole locations.

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1 Introduction

The Ministry of Economic Affairs and Climate Policy of the Netherlands requested Deltares to propose additional field investigations for the intended Borssele II nuclear power plant (NPP). The current understanding of the build-up and geohydrological properties of the subsurface is limited and contractors for the design of the NPP have therefore too little information for optimising their design and assessment of the risks associated with the subsurface.

This report provides a preliminary workplan and technical recommendations for additional site investigations at the intended site for the Borssele II NPP. The goal of these measurements is to determine static and dynamic subsurface properties to reduce subsurface uncertainties and allow for preliminary design optimization. In Chapter 2 the recommended geotechnical measurements will be proposed. In Chapter 3 the proposed geohydrological measurements are discussed. Both chapters provide a brief overview of the outcomes from the Borssele II subsurface site evaluation and the identified knowledge gaps.

2 Additional Geotechnical Investigations

2.1 Outcomes from the subsurface site evaluation report

From a subsurface perspective, the Borssele II site can be divided into two areas: one in the west with a thick layer of sandy tidal-channel deposits in the upper 20 – 30 m and one in the east with clay and peat layers in the shallow subsurface. The location and nature of the boundary between these two areas is uncertain, which is problematic since the geotechnical and geohydrological properties differ strongly. The uncertainty is mainly due to a lack of subsurface data coverage within a 100 – 200 m wide zone that extends SW to NE across the entire site (indicated in orange in Figure 1). Additional subsurface information is needed to determine whether the boundary between the different subsurface build-up in both areas is sharp or if there is a transitional zone with a more gradual change between two types of subsurface build-up. Determining these dimensional constraints now will facilitate a more efficient planning phase for the Borssele II NPP in a later stadium.

Both areas are covered by an approximately 5-meter-thick anthropogenic cover layer of sand, with its base around 0 m NAP. In the western part a sandy tidal channel fill from the past 1000 years is present. These sediments belong to the Walcheren Member of the Naaldwijk Formation and reach depths of -20 to -25 m NAP. This fill is in direct contact with the sandy marine deposits from the Oosterhout Formation (2.6 – 5.3 million years old).

In the eastern area the subsurface consists of an alternation of sand, clay and peat layers to a depth of -4.5 m NAP. The sand and clay layers are part of the Naaldwijk Formation, the peat layers belong to the Nieuwkoop Formation. This succession represents most of the Holocene period (past 12.000 years) and is absent in the western area due to erosion by the tidal channel. The presence of clay and peat layers make this area more prone to subsidence than the other area. This Holocene sequence rests on the predominantly sandy fluvial Koewacht Formation that also contains clay and silt layers. At around -22 m NAP the marine Oosterhout Formation starts.

2.2 Proposed workplan

To reduce the gap in subsurface data coverage, we propose additional CPT measurements along seven NW-SE transects each separated by approximately 150 m (Figure 1). Boreholes are also necessary, amongst others for ground-truthing the CPT-measurements and for taking samples, but they are described as part of the geohydrological investigations in Section 3.

The location of the CPT transects are strongly influenced by the outline of the solar farm, but if the proposed CPT's will be executed the spread and density of the data will be sufficient nonetheless to determine the nature of the boundary between the two areas.

The geotechnical work can be subdivided in four parts. CPT's in Part A are planned to minimise the uncertainty related to the location of the boundary between the two subsurface types. Part B addresses the subsurface variability on the eastern and southern parts of the site by means of CPT's. Geophysical line measurements proposed to be undertaken in Part C should provide further insight into subsurface variability between CPT's. In part D we propose four Vertical Seismic Profiling Tests for better characterization of the subsurface response to earthquake loading.

2.2.1 Cone Penetration Tests (Part A)

Part A focuses predominantly on filling the gap in subsurface data coverage between the two subsurface types to better constrain the boundary of the incised tidal channel sediments. This first part of the workplan consists of 63 CPT measurements.

Each CPT should reach a depth of 40 m below surface level (i.e., reach a level of circa -35 m NAP).

- Seven NW – SE transects provide between three and five CPT's each with a spacing between CPT's of 50 m. This results in 29 CPT's that provide a basic coverage for the location of the boundary between the two subsurface types. Locations are indicated in Table 1.
- CPT results should be submitted on the day of measurement in field. Based on the results of these measurements a rapid geological assessment should allow to identify the position of the boundary in near-real time.
- The geological assessment should lead to infill between the two CPT's where the change in subsurface buildup can be identified. The infill should have a spacing of one CPT every 10 m to pinpoint the location of the boundary. This results in 28 additional CPT's (four per transect) and should allow for detailed assessment on the position of the edge of the Sloe.
- One of the lines (Transect 5) should be extended with an additional six CPT's spaced 50 m apart to cover the full width of the site. This provides additional detail on the lateral variability within the eastern subsurface buildup.

2.2.2 Cone Penetration Tests (Part B)

Part B consists of an additional 29 CPT's that are located predominantly on the eastern and southern parts of the site (Table 2). These CPT's extend the transects of Part A to the southern limits of the site (Figure 1). The main target with these CPT's is to address the variability of the Koewacht Formation at depths of -5 to -22 m below NAP. Like Part A, each CPT should reach a depth of 40 m below surface level (i.e., reach a level of circa -35 m NAP).

The Koewacht Formation is only located to the south of the boundary that will be investigated in Part A. The site evaluation indicated there may be considerable lateral and vertical variation within this unit. This is expressed as rapid lithological alternations varying from gravel and sand to clay that were deposited in a fluvial environment. Particularly for hydrogeological purposes the internal variability of the Koewacht Formation will be an important aspect to better constrain.

2.2.3 Geophysical line measurements (Part C)

To reduce uncertainties during the building phase (e.g., during the placement of sheet piling) it is recommended to undertake multiple geophysical line measurements along the transects where CPT's are taken. This provides additional insight in the degree of lateral variability between CPT measurements and reduces the risk that additional variability between CPT measurements may remain unnoticed. The proposed locations for these line investigations are given in Table 3.

The preferred geophysical technique depends on the site conditions, specifically the amount, depth and location of electric cables in the subsurface. Given the Borssele II site is currently used as a solar farm, many underground electricity cables are anticipated to be present. These impose restrictions on where measurements may be taken by posing a potential source of interference to geophysical measurement techniques that used electrical resistivity for imaging the subsurface. A detailed underground site layout with the position of all cables in the solar field should be obtained prior to setting up the measurements in the field.

The preferred technique to do the geophysical line measurements is Electrical Resistivity Tomography (ERT). This technique is suited to map the subsurface variability based on the electrical resistivity and conductivity differences present between different types of sediment. This way, ERT aids in obtaining information about the subsurface buildup, groundwater levels and mapping of structures in the subsurface. However, this technique is also sensitive to disturbance from underground electrical cables and may therefore not provide satisfactory results.

The most viable alternative technique to use in case underground electrical cables prevent the use of ERT measurements would be to use shallow seismic reflection techniques.

Specifically, the geophysical line measurements should be focused on:

- Geophysical line 1 should be planned parallel to CPT transect 3 and has an approximate length of 150 m.
- Geophysical line 2 should be located parallel to CPT transect 5 and has an approximate length of 300 m.
- Geophysical lines 3 and 4 should connect between CPT transects 5, 6 and 7 on the eastern end of the site. The direction of these lines allows to image potential channels in the shallow subsurface that were indicated on topographic maps from prior to the construction of the Sloehaven harbor. At the same time, the perpendicular direction compared to lines 1 and 2 may add to the 3D subsurface interpretation.
- Lines 3 and 4 should have an approximate length of 320 m and 360 m, respectively.
- The line measurements are planned near the Electrical Conductivity (EC-) measurements in CPT's and/or boreholes with sediment descriptions. This is important to allow for a coherent and integrated subsurface interpretation.
- The depth to which the measurements should image the subsurface should be at least 40 m below surface level.

2.2.4 Other geotechnical parameter tests (Part D)

For the dynamic analysis of the location and the structure (e.g., for determining the response to earthquake loading) information on the dynamic (in fact small strain) stiffness of the subsurface is needed. This information can be obtained from VSPT's (Vertical Seismic Profiling Tests). In addition to the recommended CPT's four Vertical Seismic Penetration Tests (VSPT's) are recommended.

- Of these VSPT's, two should be located on Transect 3 and two on Transect 5.
- On both transects one VSPT is to be located to the west (in the sandy tidal-channel fill) of the anticipated boundary between the two zones.
- The other VSPT's are to be located to the east of the anticipated boundary between the two zones.
- Depth of the VSP should be equal to the depth of the CPT's at these locations, i.e. to 40 m below surface level.
- Measurement of the shear wave velocity should be done preferably at 0.5 m depth intervals.

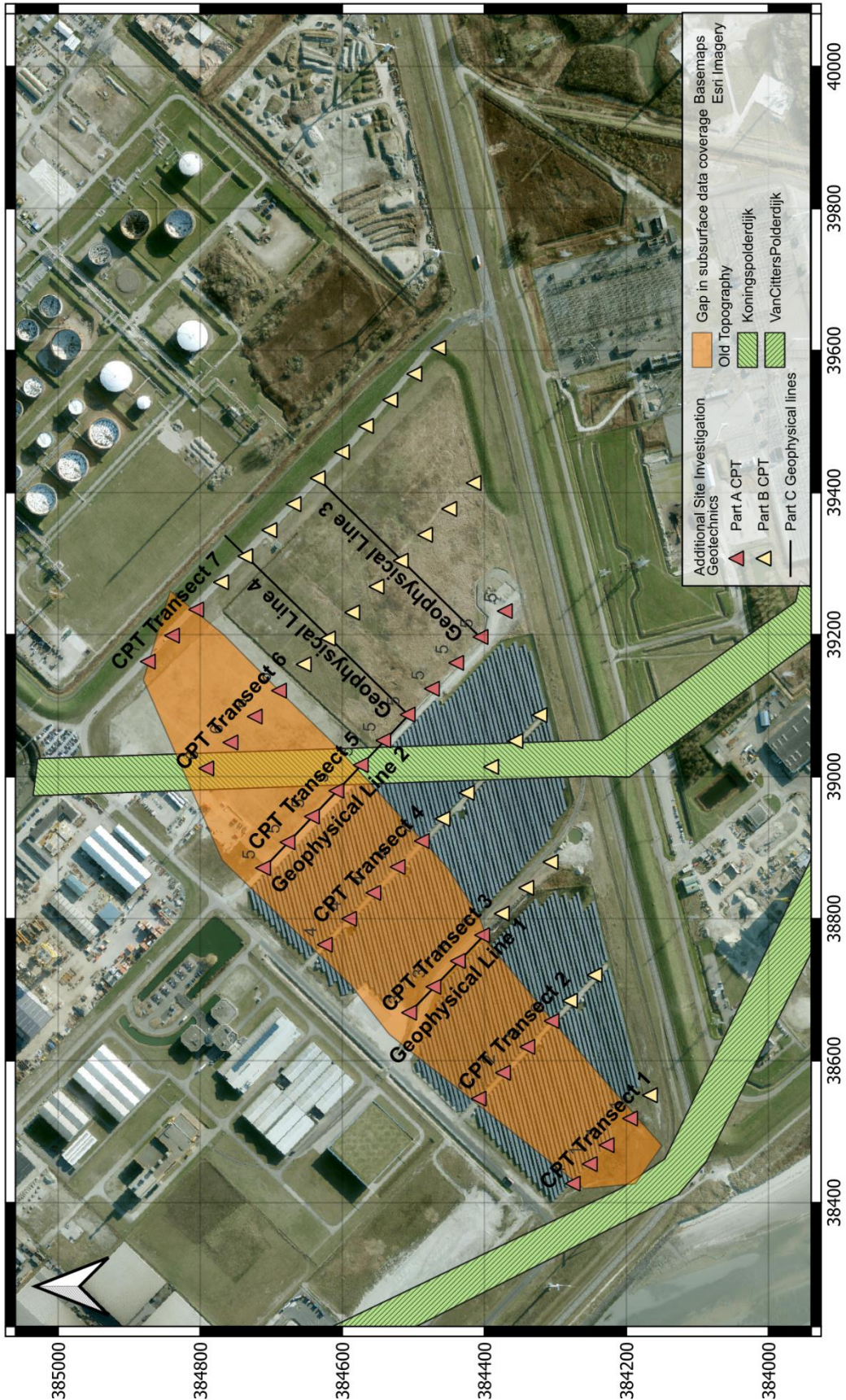


Figure 1 Location map of the Borssele II site. Indicated are proposed new CPT locations (large triangles) for both Part A (red), Part B (yellow) and Part C (geophysical lines in black).

Table 1 Proposed locations for the 35 CPT measurements as part of Part A. X and Y coordinates are given in Dutch RD grid, this is done similarly in all other tables of this report. The subset of locations where standard CPT's should be combined with Electrical Conductivity (EC-) CPT's and Vertical Seismic Profiling Tests (VSPT's) are indicated. These measurements will be discussed in later sections.

Transect	ID	X [m]	Y [m]	EC	VSPT
1	1-1	38454	384252	1	
1	1-2	38427	384276		
1	1-3	38481	384228		
1	1-4	38519	384195		
2	2-1	38547	384408		
2	2-2	38583	384374		
2	2-3	38619	384340		
2	2-4	38656	384305		
3	3-1	38668	384506	1	1
3	3-2	38704	384472		
3	3-3	38740	384437		
3	3-4	38777	384403	1	1
4	4-1	38763	384625		
4	4-2	38800	384591		
4	4-3	38836	384556		
4	4-4	38873	384522		
4	4-5	38909	384488		
5	5-1	39087	384508	1	1
5	5-2	39051	384542		
5	5-3	38871	384712		
5	5-4	38908	384677	1	
5	5-5	38944	384643		
5	5-6	38980	384608		
5	5-7	39016	384574	1	1
5	5-8	39124	384474		
5	5-9	39160	384440		
5	5-10	39197	384405	1	
5	5-11	39233	384371		
6	6-1	39012	384792		
6	6-2	39048	384757		
6	6-3	39085	384723		
6	6-4	39121	384689		
7	7-1	39162	384874	1	
7	7-2	39199	384840		
7	7-3	39235	384806		

Table 2 Proposed locations for the 29 CPT measurements as part of Part B. x and y coordinates are given in Dutch RD grid.

Transect	ID	X [m]	Y [m]	EC	VSPT
1	1-5	38551	384167		
2	2-5	38684	384280		
2	2-6	38720	384245		
3	3-5	38807	384375		
3	3-6	38843	384341		
3	3-7	38880	384307		
4	4-6	38941	384459		
4	4-7	38977	384425		
4	4-8	39014	384391		
4	4-9	39050	384356		
4	4-10	39087	384322		
6	6-5	39158	384655		
6	6-6	39195	384620	1	
6	6-7	39231	384586		
6	6-8	39268	384552		
6	6-9	39304	384518	1	
6	6-10	39341	384484		
6	6-11	39377	384449		
6	6-12	39414	384415		
7	7-4	39274	384771		
7	7-5	39310	384737	1	
7	7-6	39347	384703		
7	7-7	39384	384669		
7	7-8	39420	384635	1	
7	7-9	39457	384601		
7	7-10	39494	384567		
7	7-11	39530	384533		
7	7-12	39567	384499		
7	7-13	39604	384465		

Table 3 Proposed location for starting points and endpoints of the geophysical line research. x and y coordinates are given in Dutch RD grid.

Geophysical line	X [m]	Y [m]	Length
Starting point Line 1	38668	384506	150 m
Endpoint Line 1	38777	384403	
Starting point Line 2	38871	384712	300 m
Endpoint Line 2	39087	384508	
Starting point Line 3	39087	384508	360 m
Endpoint Line 3	39337	384762	
Starting point Line 4	39196	384401	320 m
Endpoint Line 4	39420	384958	

3 Additional geohydrological investigations

3.1 Outcomes of the geohydrological site investigation report

To obtain a complete geohydrological characterization of the Borssele II site, it is important to gather more data on layer properties and groundwater flow. The geohydrological characterization at the Borssele II site is complex due to the presence of two geological subregions. Detailed information on both subregions is required to obtain full insight into the geohydrological conditions of the entire area. The available geohydrological data at the Borssele II site is available in the site evaluation report of Deltares (2023).

Previously, pumping and slug tests were conducted at the project location. Permeameter tests on sediment cores were done but the obtained hydraulic conductivities were erroneously small compared to the pumping and slug test data and therefore not deemed representative for the bulk hydrogeological properties. On the northeast side of the project area, two pumping tests were conducted in the Koewacht Formation and the Breda Formation. On the northwest side of the project area, a pumping test was conducted in the Breda Formation. Hence, geohydrological data based on pumping tests from the Walcheren Member in the Sloe channel is lacking.

3.2 Proposed workplan

To gain a solid basis for design and to determine potential risks from the nuclear power plant to environment and surrounding area through the subsurface, a validated set of parameter data and a database of hydraulic head gradients in the aquifers is essential. To improve the knowledge of the geohydrological conditions at the Borssele II site additional tests and monitoring are proposed. These proposed tests and monitoring are based on the data gaps in the site evaluation report of Deltares (2023).

Unfortunately, no recent piezometric head data is available at the Borssele II site. Groundwater levels in the aquifer may be expected to change drastically over time due to tidal and wind effects at both the Westerschelde estuary to the southwest and the Sloehaven harbor in the north. Hence, frequent piezometric head monitoring at and around the project site is proposed.

Furthermore, the (hydro-)geological setting of the project site is complex. On the west side of the project area no continuous confining layers are present in the subsurface down to a depth of -64 m NAP (top of the Rupel Formation). The phreatic aquifer, as well as the two confining aquifers on the east side of the project area are hydraulically connected to the eastern unconfined aquifer. This, together with the complexity of the tidal effects on groundwater levels, should be considered when investigating the potential risks related to geohydrological conditions of the subsurface.

During previous site investigations pumping tests were analyzed. Unfortunately, these tests lack geohydrological data on the sandy tidal channel fill belonging to the Walcheren Member of the Naaldwijk Formation that is present on the western part of the Borssele II site. Hence, we propose new pumping tests while considering the gathered data on tidal effects on groundwater level changes and the complex geohydrological structures in the subsurface. For a proper geohydrological site investigation a pumping test location on the western part of the Borssele II site and a pumping test location in the eastern part of the site are selected.

Moreover, insight into the anisotropy and vertical variability of the hydraulic conductivity at the project area is essential. This is especially the case for the western part of the project area where no confining layers are present and the Walcheren Member directly overlays the Oosterhout Formation. To predict vertical flow paths in the subsurface, insight into local variability of the permeability is essential. Hence, slugtests and permeameter tests on sediment samples are proposed to obtain insight into local permeability at given depths in the aquifers.

The fresh-salt interface at the project area should be mapped to interpret groundwater heads. This is done by groundwater sampling and CPT's with additional Electrical Conductivity (EC)-conus measurements. EC-measurements will provide vertical salinity profile at selected locations. EC-data will also be used as reference to extrapolate data from the Electrical Resistivity Tomography geophysical line measurements (see Section 2.2.3) to provide four profiles with the fresh-salt interface at the project location.

Optionally, tests with the Hydraulic Profiling Tool (HPT) and Mini Pump Test (MPT) are suggested. This will provide more detailed information on spatial variability in the in situ hydraulic conductivity at the project site on a multi m³ scale and will help to estimate potential pathways in the subsurface.

In the following sections the various proposed measurements will be discussed in more detail. Table 4 to Table 11 at the end of the document provide the locations for the various proposed wells and sample depths.

3.2.1 Stage 1-1: Piezometric head monitoring

Monitoring wells should be placed according to the *SIKB 2001 protocol*. The proposed borehole locations and well screen depths are given in Table 4. At each borehole location, two separate boreholes should be drilled to install the four monitoring well screens. One borehole should be drilled down to a depth of -16 m NAP for the installation of the two shallower monitoring wells a) at -1 m NAP and b) at -15 m NAP. A second borehole should be drilled to a depth of -60 m NAP for the installation of the deeper monitoring wells c) at -35 m NAP and d) at -55 m NAP.

Monitoring wells for piezometric head monitoring are to be placed in multiple stages. To start, 15 borehole locations for piezometric head monitoring are selected for Stage 1.1. This results in installation of 60 monitoring well screens (four monitoring well screens for each borehole location) in all three aquifers, as well as in the Walcheren Member on the westside of the project area. Four monitoring locations are to be placed outside the Borssele II site to obtain insight into the hydraulic head gradient in the aquifers from the inland towards the harbor area and Westerschelde. This will provide a rough estimate of the current groundwater flow at the Borssele II site (see Figure 2).

The following steps need to be considered during installation and monitoring of piezometric head:

- The monitoring wells should be installed as soon as possible to enable continuous monitoring of the groundwater levels.
- Continuous monitoring should be done for at least one year to obtain insight into the seasonal variation in the groundwater levels. It should be able to adjust the frequency of the monitoring on demand for the entire monitoring system.
- Installation by Cable Tool Drilling (CTD) in combination with Ackerman sediment sampling (see also Table 8 and Table 9).
- Well screen of monitoring wells to be constructed with screen length of 1 m.

- Backfilling around well screens with coarse sand, grain size adapted to screen slot size and grain size distribution of original sand in the aquifer.
- Cross connection between well screens to be prevented by clay sealing with Micolit between well screens.
- It is preferred to plan the pumping and slugtests in the monitoring wells after the monitoring in Stage 1 to prevent any influence on the measurements.

3.2.2 Stage 1.2: Monitoring tidal effects on groundwater

The southwest end of the Borssele II site borders the Westerschelde estuary. Tidal effects in the Westerschelde could have major impact on the groundwater levels in the vicinity of the Westerschelde. In the northernmost part of the project area tidal effects coming from the Sloehaven harbor need to be considered. Hence, continuous piezometric head monitoring is recommended to obtain insight into daily groundwater fluctuations in the aquifers.

Additional monitoring wells are required for determining the tidal effects on groundwater levels. Two rows of each 6 monitoring wells are to be placed perpendicular to the coastline. In the east, the hydraulic head is monitored in the phreatic aquifer and the two confined aquifers (Koewacht Formation and Oosterhout/Breda formations). In the west, the tidal effects on groundwater levels in the Walcheren Member should be monitored.

The groundwater head monitoring to investigate tidal effects will be used for two purposes. Firstly, the monitoring can be used to investigate the lateral impact of groundwater fluctuations in the different aquifers. This will provide insight to what extent (amplitude) groundwater levels are fluctuating at given distances from the Westerschelde. Secondly, the groundwater level monitoring can be used to analyze damping (decrease in amplitude of the fluctuating water level), and retardation of the tidal wave to investigate the hydraulic conductivities and resistance of the waterbed of the Westerschelde.

Measuring the tidal effects from the Westerschelde and harbor should be performed in three rows with each three monitoring locations (Figure 3). These should be placed perpendicular to the coast. Locations PB-1 to PB-3, may be reused from Stage 1.1. In addition, the drilling of six additional borehole locations for the installation of 24 additional monitoring well screens is required. These well screens are divided across all three aquifers on the eastern part of the site, as well as in the Walcheren Member on the western part of the Borssele II site. Proposed well screen depths are given in Table 5.

The following needs to be considered during installation and the monitoring of piezometric head:

- Monitoring well installation requirements are the same as mentioned for Stage 1.1.
- Measuring hydraulic head at short measuring intervals (measurements every 1 – 5 minutes over a full week) for 13-hours measurement analyses.
- Data should be obtained at different tides and sea levels in the Westerschelde and the harbor. This will require six monitoring cycles:
 - Two measurements at average seawater levels.
 - Two measurements at spring (King) tide in storm season (max seawater levels).
 - One measurement at low sea levels.
 - One measurement at neap tide.

3.2.3 Stage 2: Pumping tests

Stage 2 is to be performed after the monitoring in Stage 1 is finished. In total 10 additional borehole locations are required for the installation of 40 monitoring well screens for the pumping tests (Figure 4). Locations PB-4 to PB-8 will be reused after Stage 1.1 for

monitoring during the pumping tests. Proposed well screen depths and locations are given in Table 7. A more detailed monitoring plan will be made when the pumping tests are planned in greater detail based on the CPT and sediment sample data.

Pumping tests must be conducted according to the *NEN-EN-ISO 22284-4* standard. To obtain reliable data on the hydraulic conductivity of each aquifer, multiple pumping tests are recommended.

- Two borehole locations are planned for the placement of the pumping wells (Table 6).
- Drilling of the pumping wells can be done with reversed-circulation rotary drilling. Completion and drilling should be performed according to *SIKB protocol 2101*.
- A packer or blinding of the filter screen is required to perform pumping tests at desired aquifer depths (see well screen specifications in Table 6).
- Perform variable rate test and constant rate test to obtain the geohydrological parameter values of Aquifer 2, Aquifer 3 and the Walcheren Member.
- Monitoring on two rows of monitoring wells with each three monitoring locations at radial distances of 2, 5, 10, 50 m (as shown in Table 6).
- The filters of the pumping wells are screened over the entire aquifer depth. Hence, lateral groundwater flow during pumping tests is enabled and the partial penetration effects on groundwater flow for all pumping wells are small using the selected screen depths in Table 7.
- The pumping tests should be planned in detail after the CPT's are done. Based on the CPT-data the exact aquifer and confining layer depths will be re-evaluated and used to plan the exact screening depths of the pumping well and monitoring wells.

3.2.4 Slugtests

Slugtests must be conducted according to the *NEN-EN-ISO 22284-2* standard. The slugtests should be performed on all the installed monitoring wells for seasonal piezometric head monitoring and the pumping tests. In Table 4 the monitoring wells (PB-1 to PB-12) are listed.

The following procedure is recommended for the slugtests:

- Perform both constant flow rate tests and variable head tests on all monitoring wells.

3.2.5 Small scale variability in geohydrological conditions (sediment sampling, geophysical well logging and CPT-HPT tests)

The pumping tests provide data on the large-scale aquifer hydraulic conductivities. However, to obtain insight into vertical variability in hydraulic conductivity for a given aquifer different methods are required. Vertical variability in hydraulic conductivity will provide insight in the local anisotropy of the aquifer.

To obtain data on the spatial variability in hydraulic conductivity the following tests are recommended:

- Borehole logs at all drilling locations based on sediment description.
- Four boreholes should be selected for continuous Ackermann sampling. This is recommended because based on those samples a geological sediment description can be performed under laboratory conditions. These boreholes need to be drilled into the Rupel Formation (confining clay layer) down to a depth of -70 m NAP.
- Tests on sediment samples. To obtain proper sediment samples for testing (*NEN-EN-ISO 22475-1* norm), cable tool drilling with the Ackermann sampling method is required. In the boreholes drilled with the cable tool drilling method monitoring wells will be installed. The sediment samples will be tested on its classification, permeability (according to *NEN-EN-ISO 17892-11* norm), grainsize distribution (according to *NEN-EN-ISO 17892-4* norm). At the listed depths in Table 8 and Table 9, sediment samples with the Ackermann sampling method are planned.

- These sediment descriptions should be combined with geophysical well logging (e.g. spectral gamma-ray and resistivity measurements). This allows for physics-based independent corroboration of the sediment descriptions, particularly related to layer thicknesses and depths of sediment transitions.

For further detailed investigation, two optional measurements are proposed.

- Optionally, 8 CPT's with the hydraulic profiling tool (HPT) can be planned at the locations of PB-1 to PB-8 (see Table 1 and Table 2). Approximate penetration depths with HPT-CPT are generally in the range of 25 – 30 meters below ground level. This tool provides the relative permeability (based on the ratio between specific injection rate of the HPT and the local pressure increase) over the entire penetration depth during the CPT. Permeabilities based on permeameter testing of the sediment samples can be used as reference to provide vertical variability in the permeability.
- Optionally, at given subsurface depths Mini Pumping Tests (MPT's) are planned. MPT's can be used in combination with the HPT. With this technique the in-situ hydraulic conductivity at a specific depth is obtained. For four HPT-CPT's six additional MPT's are required to obtain data over the entire penetration depth of the CPT (Table 10). MPT depths for HPT-CPT for the eastern side of the project area (Table 10 and Table 11).

3.2.6 Fresh-salt interface of groundwater

Data for the depth in the subsurface of the fresh-to-salt groundwater interface are not available at the Borssele II site. Unfortunately, recent regional surveys of this interface only provide data for the surrounding areas (see <https://kaarten.zeeland.nl/map/freshem>). Hence, to obtain insight in the fresh-salt interface at the project area the following tests are recommended:

- Twelve CPT's combined with an electric conductivity (EC) conus to obtain a salinity profile over the entire penetration depth of the CPT. These CPT's are planned in both subregions.
- The EC-CPT data will provide insight into the depth of the fresh-to-salt groundwater interface. This data can be used as reference to interpolate data from the four Electrical Resistivity Tomography geophysical line measurements. This will provide four lines with the fresh-salt interface data.
- Groundwater sampling and testing on the chemical composition of the groundwater at the monitoring wells installed for Stage 1.1 and Stage 2 (*NEN-EN-ISO 22475-1* standard). The sampling must be done under steady-state conditions. Hence, prior to starting the groundwater sampling, a waiting period after the installation of the monitoring wells is required. Moreover, sampling must be done before performing the pumping- and slugtests.



Figure 2 Locations of geohydrological monitoring wells for Stage 1.1.

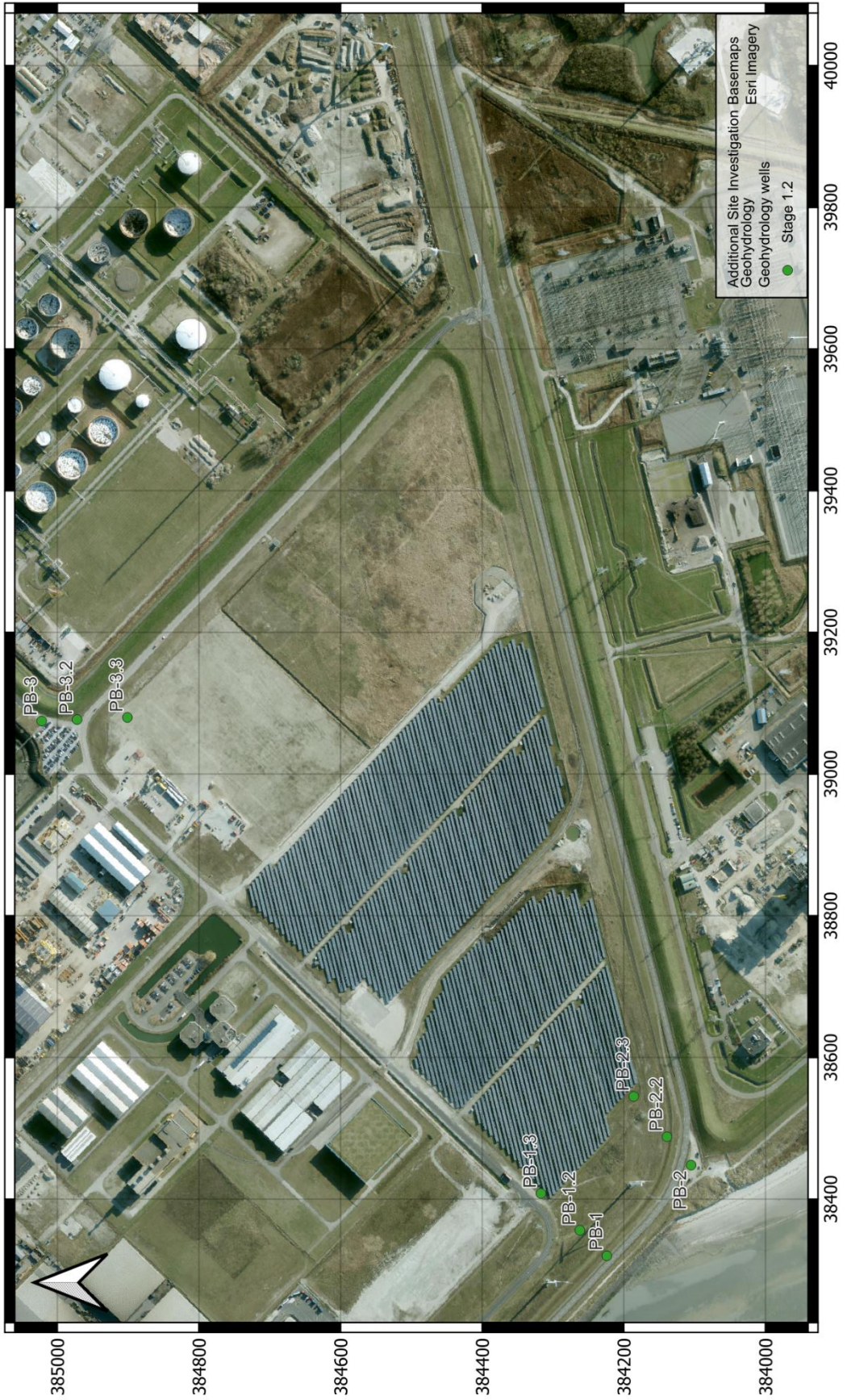


Figure 3 Geohydrological monitoring wells for monitoring the impact of tidal variations on groundwater levels during Stage 1.2.

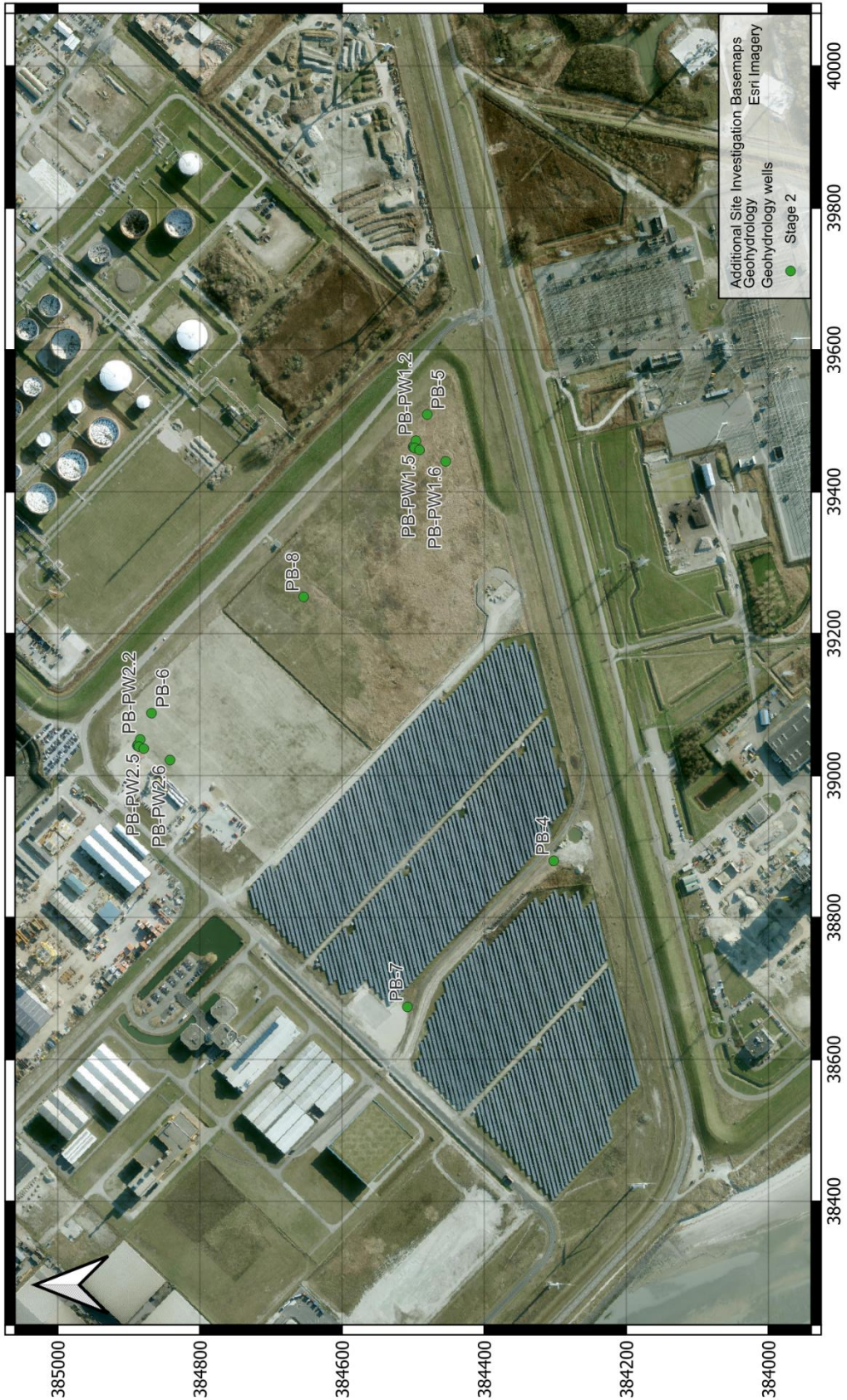


Figure 4 Locations for pumping and monitoring wells for the proposed pumping test in Stage 2 of the geohydrological site investigation.

Table 4 Proposed locations for the twelve geohydrological monitoring wells in Stage 1.1. Locations may need changing in case field conditions do not allow for drilling at the specified location. Note: these monitoring wells require well screens at depths of a) -1 m, b) -15 m, c) -35 m and d) -55 m NAP.

Monitoring well ID	X [m]	Y [m]	Type of well	Sediment sampling
PB-1	38320	384224	Monitoring well	Table 9
PB-2	38448	384105	Monitoring well	Table 8
PB-3	39075	385022	Monitoring well	Table 9
PB-4	38880	384302	Monitoring well	Table 8
PB-5	39509	384480	Monitoring well	Table 8
PB-6	39088	384868	Monitoring well	Table 9
PB-7	38674	384508	Monitoring well	Table 9
PB-8	39252	384654	Monitoring well	Table 8
PB-9	40312	384034	Monitoring well	
PB-10	40541	384573	Monitoring well	
PB-11	39360	385336	Monitoring well	
PB-12	40853	385623	Monitoring well	

Table 5 Proposed locations for the nine geohydrological monitoring wells to monitor tidal effects on groundwater levels (Stage 1.2). Locations may need changing in case field conditions do not allow for drilling at the specified location. Note: these monitoring wells require well screens at depths of a) -1 m, b) -15 m, c) -35 m and d) -55 m NAP.

Monitoring well ID	X [m]	Y [m]	Type of well	Comment
PB-1	38320	384224	Monitoring well	Reused from Stage 1.1.
PB-1.2	38356	384262	Monitoring well	
PB-1.3	38408	384317	Monitoring well	
PB-2	38448	384105	Monitoring well	Reused from Stage 1.1.
PB-2.2	38488	384139	Monitoring well	
PB-2.3	38545	384186	Monitoring well	
PB-3	39075	385022	Monitoring well	Reused from Stage 1.1.
PB-3.2	39077	384972	Monitoring well	
PB-3.3	39080	384901	Monitoring well	

Table 6 Location and depths of well screens for the proposed pumping wells for the geohydrological pumping test of Stage 2. Locations may need changing in case field conditions do not allow for drilling at the specified location.

Pumping wells East	RD-coordinates		Well screen 1		Well screen 2	
	X [m]	Y [m]	Top [m NAP]	Bottom [m NAP]	Top [m NAP]	Bottom [m NAP]
PW1_KOE	39463	384500	-7	-20	-28	-60
PW2	39042	384901	-5	-20	-28	-60

Table 7 Locations for the proposed monitoring wells for the geohydrological pumping test of Stage 2. Locations may need changing in case field conditions do not allow for drilling at the specified location. Note: these monitoring wells require well screens at depths of a) -1 m, b) -15 m, c) -35 m and d) -55 m NAP.

Monitoring well ID	X [m]	Y [m]	Type of well	Comment
PB-PW1.1	39465	384499	Monitoring well	Radial Distance 2.5 m
PB-PW1.2	39472	384496	Monitoring well	Radial Distance 10 m
PB-5	39509	384480	Monitoring well	Radial Distance 50 m
PB-PW1.4	39462	384498	Monitoring well	Radial Distance 2.5 m
PB-PW1.5	39459	384491	Monitoring well	Radial Distance 10 m
PB-PW1.6	39443	384454	Monitoring well	Radial Distance 50 m
PB-PW2.1	39044	384887	Monitoring well	Radial Distance 2.5 m
PB-PW2.2	39051	384884	Monitoring well	Radial Distance 10 m
PB-6	39088	384868	Monitoring well	Radial Distance 50 m
PB-PW2.4	39041	384886	Monitoring well	Radial Distance 2.5 m
PB-PW2.5	39038	384879	Monitoring well	Radial Distance 10 m
PB-PW2.6	39022	384842	Monitoring well	Radial Distance 50 m
PB-4	38880	384302	Monitoring well	
PB-7	38674	384508	Monitoring well	
PB-8	39252	384654	Monitoring well	

Table 8 Sediment sampling depths in the east side of the Borssele II site at the drilling locations of Stage 1.1.

Sediment sample at each drilling location	Geohydrological unit	Sampling depth [m NAP]
1	Phreatic aquifer 1	-2
2	Confining layer 1	-3,5
3	Aquifer 2	-10
4	Aquifer 2	-17,5
5	Confining layer 2	-23
6	Aquifer 3	-27,5
7	Aquifer 3	-40
8	Aquifer 3	-60
9	Confining layer 3	-70

Table 9 Sediment sampling depths in the west side of the Borssele II site at the drilling locations of Stage 1.1.

Sediment sample at each drilling location	Geohydrological unit	Sampling depth [m NAP]
1	Walcheren Member	-2
2	Walcheren Member	-10
3	Walcheren Member	-17,5
4	Aquifer 3	-27,5
5	Aquifer 3	-40
6	Aquifer 3	-60

Table 10 Optional MPT depths for HPT-CPT in the east side of the Borssele II site.

MPT measurements at each HPT	Geohydrological unit	MPT depths during HPT-CPT [m NAP]
1	Phreatic aquifer 1	-2
2	Aquifer 2	-10
3	Aquifer 2	-17,5
4	Aquifer 3	-27,5
5	Aquifer 3	-40
6	Aquifer 3	-60

Table 11 Optional MPT depths for HPT-CPT in the west side of the Borssele II site.

MPT measurements at each HPT	Geohydrological unit	MPT depths during HPT-CPT [m NAP]
1	Walcheren Member	-2
2	Walcheren Member	-10
3	Walcheren Member	-17,5
4	Aquifer 3	-27,5
5	Aquifer 3	-40
6	Aquifer 3	-60

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