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Integrated Ground Model Report

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Integrated Ground
Model Report

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List of Abbreviation

BH	Borehole
BHI	Bornholm I
BHII	Bornholm II
BP	Before Present
CPT	Cone Penetration Test
DDC	Dynamic Depth Conversion
DTS	Desk Top Study
Energinet	Energinet Eltransmission A/S
ETRS89	European Terrestrial Reference System 1989
Fs	Side friction
IGM	Integrated Ground Model
IGMU	Integrated Ground Model Unit
m	Meters
MAG	Magnetometer
MBES	Multibeam Echo Sounder
MSL	Mean Sea Level
OWF	Offshore Wind Farm
qc	Cone Tip Resistance
Rf	Friction rate
SBP	Sub-Bottom Profiler
SSS	Side Scan Sonar
STZ	Sorgenfrei-Tornquist Zone
TTZ	Teisseyre-Tornquist Zone
TWT	Two-Way-Time
UTM	Universal Transverse Mercator
u^2	Pore pressure
2D UHRS	2D Ultra High Resolution Seismic

1. Executive Summary

For Energinet Eltransmission A/S on behalf of the Danish Energy Agency, Ramboll has prepared this Integrated Ground Model Report for the Bornholm II (BHII) Offshore Wind Farm (OWF) project to characterise the geological conditions. Denmark has committed to build the first Energy islands following the Climate agreement from June 2020. The offshore wind farm areas will be located in the Baltic Sea, near the island Bornholm. The energy complex will be constructed with an installation capacity of up to 3 GW and will consist of 2 offshore windfarm areas, Bornholm I and Bornholm II. The energy island of Bornholm is expected to be fully operational in 2030.

The BHII OWF site covers approximately 410 km^2 and is situated south of the island Bornholm. Water depth range from 15 m to 57 m. In general, the water depths increase in a north-west to the south-east direction. Seabed topography is relatively calm with no major complex features detected in the seismic or multibeam data. The seafloor sediments are predominately sand in the western and southern areas of BHII, while the eastern part is dominated by clayey areas and the northern part is influenced by larger stones.

This report characterises the geological conditions across the BHII site and illustrates how the geology has been subdivided into seismic and geotechnical soil units. The characterization is based on the geophysical (Energinet, Geophysical Survey Report BHII - Work Package A, 2022) and geotechnical (Gardline, 2023) Preliminary Site Investigations. The geophysical data consisted of approximately 7107 line km of ultra-high resolution seismic (2D-UHRS) collected in a grid with line spacing of 250 m x 1000 m and 2134 line km of sub-bottom profiler (SBP), side-scan sonar (SSS) and magnetometer (MAG) collected in a grid with line spacing of 62.5 m x 1000 m. The geotechnical data at the BHII area consists of 20 geotechnical boreholes (BH) and 53 seabed cone penetration tests (CPT).

Seismic Units and their Geotechnical Units

Analysis of the ground information data extracted from borehole and CPT locations for both the Bornholm I and II Sites has resulted in the characterisation of six Geotechnical Soil Units (Soil Units Ia, Ib, II, III, IVa & IVb) from the Pleistocene to Holocene-aged sediments that overlie the mapped bedrock strata. In addition, six Geotechnical Rock Units of Late Cretaceous to likely Lower Jurassic age have been defined with lithologies ranging from limestone (including chalk) to sandstone and mudstone.

The geotechnical units have been integrated with the geophysical seismic units (seismic unit 1 – seismic unit 4). The first three seismic units (seismic unit 1 - 3) are part of the Quaternary sequence that is resting on the bedrock surface (seismic unit 4). Additional mapping within seismic unit 3 was done based on structural features detected and a distinct sand succession and resulted in the interpretation of an internal horizons H40_i and H45_i. All seismic units have been integrated between geophysical (seismic) and geotechnical data.

Seismic unit 1 (SU 1) is composed mainly of very soft, organic rich clays, gyttja (soil unit Ib) and loose sand (soil unit Ia) of Holocene age in the upper part and comprises both soil units Ia and Ib. Towards the base of the unit, transitional and stiff clays (soil unit II and III) can possibly be encountered. The upper soft sediments are marine and lacustrine, while the transitional and stiffer sediments at the base are glaciolacustrine. The thickness of this unit ranges from 0 – 39 m throughout the site. This unit represents the post-glacial clay and post-glacial marine sediments, deposited during the Yoldia Sea, the Ancylus Lake and Littorina Sea period stages and the Baltic Ice Lake stage.

Seismic unit 2 (SU 2) is comprised of transitional and stiff clays (soil unit II and III) which has not been included within SU 1. The clays have been also deposited in a glaciolacustrine environment at the time of the retreat of the Weichselian glacier. Thickness of SU 2 ranges between 0 – 36 m. The unit represents the first Baltic Ice Lake stage.

Seismic unit 3 (SU 3) is mainly composed of very dense sand (soil unit IVa) in the northern part of the site, and clay till (soil unit IVb) with a sand succession in the upper part in the south-western part of the site. The thickness of this unit ranges from 0 – 103 m throughout. Due to a general shifting deposition between the two sediment types a distinction has not been done, except for the central – northern part of the site where the horizon H45_i representing top of very distinct sand succession within SU 3 was mapped.

Seismic unit 4 (SU 4) represents the bedrock. Based on the variations in geotechnical properties, each bedrock type has been subdivided into two segments, aiming to capture the distinct strength characteristics of each rock type. Consequently, a total of six rock units have been identified. Va1 and Va2 are constituted by limestone/mudstone. Va1 is categorised as soft, encompassing limestone/mudstone with characteristics ranging from very weak to medium weak, while Va2 is characterised as hard, showcasing limestone/mudstone with attributes ranging from weak to extremely strong. As for rock units Vb1 and Vb2, comprised of chalk, Vb1 is designated as soft chalk, whereas Vb2 is classified as hard chalk. Finally, rock units Vc1 and Vc2, both composed of sandstone, portray Vc1 as soft, featuring sandstone with properties ranging from extremely weak to weak, and Vc2 as hard, displaying sandstone with medium-strong to strong characteristics. The bedrock varies in age from Cretaceous to Jurassic. The typically encountered rock type is limestone/mudstone of varying strength. Depth below seabed for top bedrock ranges from 0 – 109 m.

Integrated Ground Model Units

The BHII Integrated Ground Model presented herein is derived from the aforementioned seismic and geotechnical units; it comprises four Integrated Ground Model Units, designated IGMU 1 through to 4. All the IGMUs have been created through integration of the geophysical (seismic) and geotechnical data and the key relationships between the Seismic Horizons, Seismic Units and Geotechnical Units are illustrated in Table 1.1.

Table 1.1 illustrating the relationships between the Integrated Ground Model Units (IGMU) and the defined Seismic and Geotechnical Units. Also provided are the dominant lithologies and estimated age of the IGMUs.

Integrated Ground Model Unit	Top Seismic Horizon	Bottom Seismic Horizon	Geotechnical Soil Unit	Seismic Unit	Lithology	Depositional Environment	Age
IGMU 1	H00	H25	Interbedded Soil Unit Ib Soil Unit Ia	Seismic Unit 1	Interbedded Soft, organic rich clay and gyttja Loose sand	Marine and lacustrine Distal shoreface or delta front/fan	Post glacial – Late Pleistocene/ Holocene
IGMU 2	H25	H30	Soil Unit II	Seismic Unit 2	Transitional clay	Glaciolacustrine deposits	Late glacial – Pleistocene
			Soil Unit III		Stiff clay	Glacial moraine	Late glacial – Pleistocene
IGMU 3	H30	H50	Soil Unit IVa	Seismic Unit 3	Dense sand	Sandy delta or ice front subaqueous plume fan	Glacial – Pleistocene
			Soil Unit IVb		Glacial till	Glacial till and ice front distal subaqueous fan or distal delta front	Glacial – Pleistocene
IGMU 4	H50	---	Soil Unit V	Seismic Unit 4	Variable	Variable	Jurassic and Cretaceous

IGMU 1 is represented by seismic unit 1 and is comprised of soil unit Ia (loose sand of Holocene age) and soil unit Ib (very soft, organic rich clays and gyttja), with possibility of encountering soil unit II (transitional clays) and soil unit III (stiff clays) at the base. The upper sediments within the unit are deposited in marine and lacustrine environment, while the base has been deposited in glaciolacustrine environment.

IGMU 2 is represented by seismic unit 2 and is comprised of soil unit II (transitional clays) and soil unit III (stiff clays). The clays have been deposited in a glaciolacustrine environment at the time of the retreat of the Weichselian glacier.

IGMU 3 is represented by seismic unit 3 and is comprised of soil unit IVa (very dense sand) in the northern part of the site, and soil unit IVb (clay till) with a sand succession in the upper part in the south-western part of the site. These sediments were deposited during the last glacial period.

IGMU 4 is represented by seismic unit 4 and is comprised of soil unit V. The bedrock varies from limestone/mudstone to sandstone and chalk. The age of the deposited sediments is Cretaceous to Jurassic.

Geotechnical provinces

Challenging ground conditions are identified in BHII area from an offshore windfarm foundation design perspective considering a combination of top soft soils, clay tills, dense sands, and highly variable strength of bedrock found at a relatively shallow depth.

Considering that the water depth at the site is within the expected range for a fixed foundation, two geological conditions are more relevant and hence have been used to create a Geotechnical Province map. The two elements are:

1. The thickness of the Holocene to Pleistocene sediments above the Bedrock, or to describe it in another way, the depth below seabed to bedrock strata. A criterion for foundation concept selection is the presence of rock. To identify areas of shallow, intermediate, or deep rock, three divisions are made considering bedrock depths of less than 15m (shallow), between 15m to 40m (intermediate) and more than 40m (deep). These provinces combined with an analysis of the top units and rock strength could define the type of foundation.

   The foundation types analysed are monopiles, jacket with either piles or suction buckets and gravity base. For the installation of monopiles and jackets piles is required either deep bedrock or soft rock if they are to be driven by a hydraulic hammer, otherwise they will require drilling or a combination of drive and drilling with an associated time, cost and complexity. Suction bucket jackets could be installed in areas with intermediate to deep bedrock depending on the type of Holocene to Pleistocene sediments. Gravity base foundations are installed in shallow bedrock but also depend on the type and thickness of the top sediments, which leads on to the second geological element described.

2. The thickness of the soft sediments (soil unit Ia & Ib). Here the distinction is made between those areas without these sediments, with a thickness of less than 5m or greater than 5 m. The cut-off is given to analyse areas with sandy soils which could be beneficial for the installation of suction buckets, cluster areas where soft soils could cause deep settlements in gravity-based foundations or problems with cables and areas with deep soft sediments that do not contribute to the overall bearing capacity of the foundation.

Based on these subdivisions 9 Geotechnical Soil Provinces have been defined which can be used, together with the tables with interpreted parameters as a first pass guide to help define feasible foundation design options in different parts of the BHII Site.

In a preliminary analysis of the provinces is observed that gravity-based foundations can be challenged due to excessive settlements on the soft soils. Moreover, suction buckets capacity and installation is compromised due the combination of soft soils and glacial deposits. Monopiles and jacket piles can be used as foundations for the site considering either drilling in the bedrock or a combination of drive and drilling or driving alone. It needs to be noted that drilling large diameter monopiles has an added level of complexity in terms of installation. At Bornholm II the Geotechnical Soil Provinces change across the windfarm, not being easy to define an unique type of foundation or an unique type of installation method.

The conclusions related to foundation are considering the current site investigation. These conclusions are subject to change as more ground information is collected from the BHII Site.

Leg Penetration Analysis
Analysis of potential installation vessel leg penetration has been conducted. Based on the type of soils and the predicted leg penetration, there are risk categories of low, medium and high risk.

For a given soil profile in the southeast of BHII, owing to the presence of locally very thick soft clays, deep penetrations, of up to 16.2 m are predicted based on the standard spudcan size of a jack-up installation vessel.

2. Introduction

This section includes a brief introduction of the project along with a short summary of the scope of works.

2.1 Project Summary

Ramboll has been contracted by Energinet Eltransmission A/S to update a provided Ground Model for the Bornholm Offshore Wind Farms (OWF); Bornholm I (BHI) and Bornholm II (BHII). The purpose of this report is to present the Integrated Ground Model for BHII, which is based on geophysical data and results acquired from the GEOxyz survey completed in 2021/2022 as well as geotechnical data acquired by Gardline in 2022.

Both proposed OWF (BHI and BHII) are located to the south-west of the Danish Island of Bornholm in the Baltic Sea. This report focuses on BHII site, which is located 15 km to the south-west of the island.

The location of the two sites (BH I and BHII) compared to Bornholm is illustrated in Figure 2-1. The combined BHII site is approximately 17.8 km wide in NW-SE direction and 32.2 km long in NE-SW direction and covers approximately 410 km^2 with a water depth ranging between 15.04 to 57.30 m.

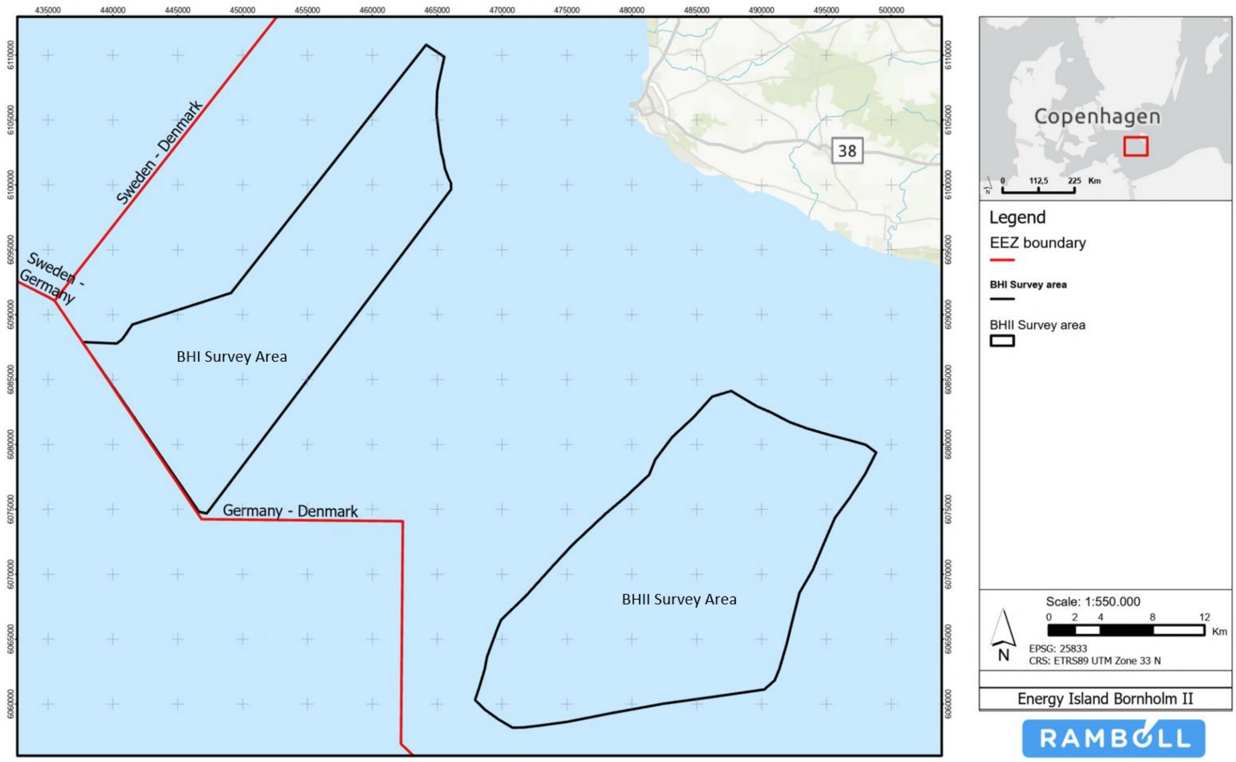


Figure 2-1 Location of the BHI and BHII sites in the Baltic Sea. The polygons show the full extent of the sites, the original areas plus the added extensions (Energinet, Geophysical Survey Report BHII - Work Package A, 2022).

2.2 Scope of work

The results presented in this report include a Conceptual Geological Model (see the last part of section 5.3.4); Spatial Integrated Geological Model (see section 10); Geotechnical characterization of soil units (see section 8) and Soil zonation (see section 12).

The Conceptual Geological Model illustrates the stratigraphic relationship between the soil units and the seismic and is discussed in Section 5.3.4. The Conceptual Models are schematically illustrated in Figure 5-11 and Figure 5-12.

Geotechnical soil units are defined in section 8 based on the ground information collected across the site. Six soil units and six rock units have been defined with the geotechnical properties described and characterized.

An Integrated Ground Model that captures the spatial distribution of the identified soil units correlated with seismic units is discussed in Section 10. Maps illustrating the distribution and thickness of these soil units are presented within the section.

The site has been subdivided into a set of geotechnical soil provinces based on the depth to the bedrock and thickness of the shallow soft soil units.

3. Bornholm II – site location and data gathering campaigns

3.1 Introduction

The BHII survey site is located 15 km to the south-west of the Danish Island of Bornholm in the Baltic Sea (Figure 3-1) and covers an area of 410 km^2. The site was extended to include an additional area to the north and east of the original BHII site to increase the proposed total windfarm capacity to 3 GW. The ground model described in this report covers both the original and the extended parts of the site.

The geophysical campaigns and one geotechnical campaign were undertaken on the BHII site starting in 2021 and concluding in late 2022 (Table 3.1). Data from these campaigns, integrated with regional geological knowledge, have been utilised to create the Ground Model described in this report.

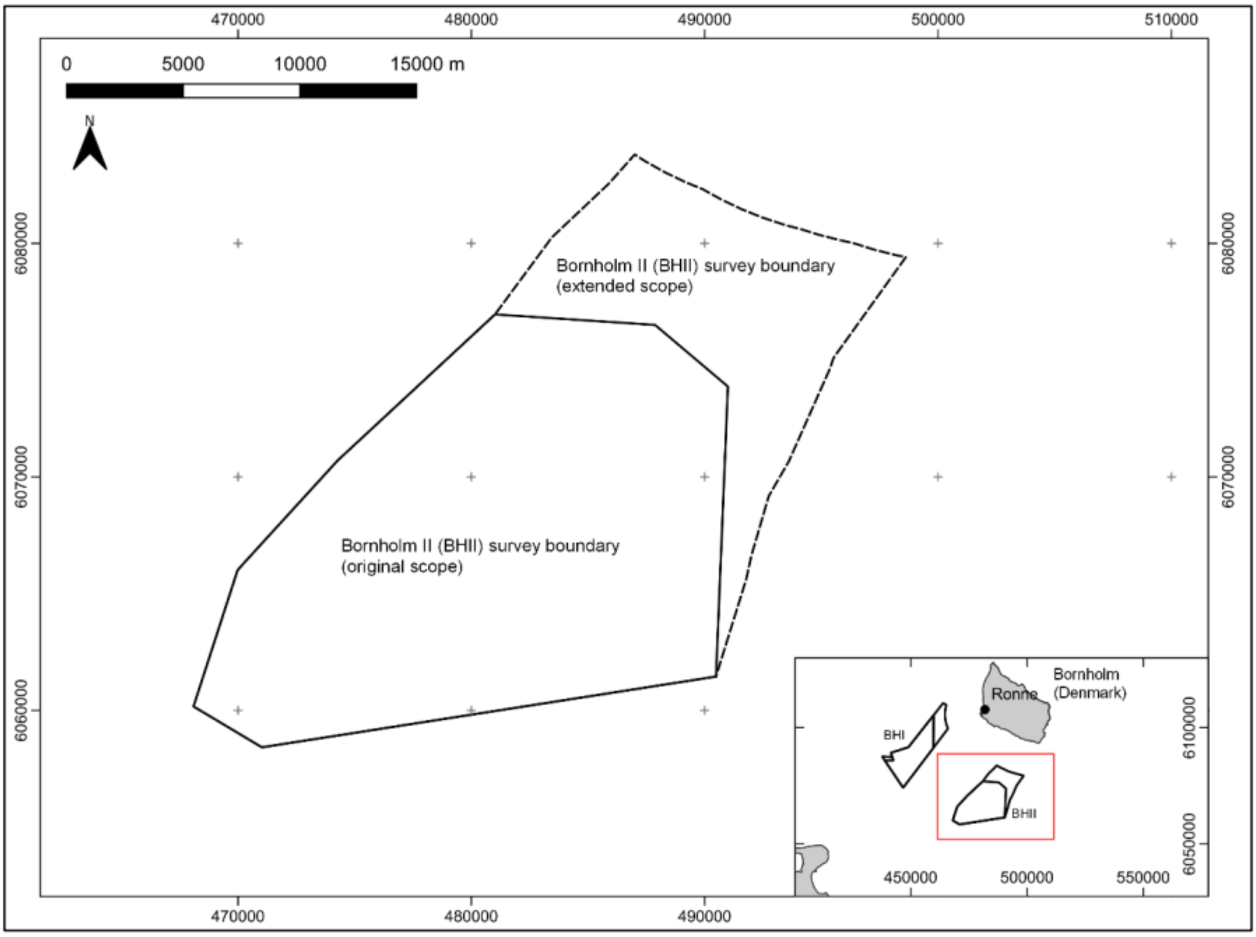


Figure 3-1 Map taken from the geophysical survey report (Energinet, Geophysical Survey Report BHII - Work Package A, 2022) which illustrates the original and extended parts of the BHII site.

Table 3.1 Summary of the site investigations that have been performed at the BHII site.

Investigations	Period	Contractor	Reference
Initial Geophysical Survey	Q3 - Q4 2021	GEOxyz	(GEOxyz, 2022)
Extended Geophysical Survey	Q1 - Q2 2022	GEOxyz	(GEOxyz, 2022)
Geotechnical Survey	Q1 - Q4 2022	Gardline	(Gardline, 2023)

3.2 Existing infrastructure

There are two known infrastructures that cross the BHII site and one close to the BHII site in the southern part. These are the Nordstream I and Baltic Pipe that cross the site. In addition, the Nordstream II is located only approximately 700 m to the south of the site (Figure 3-2).

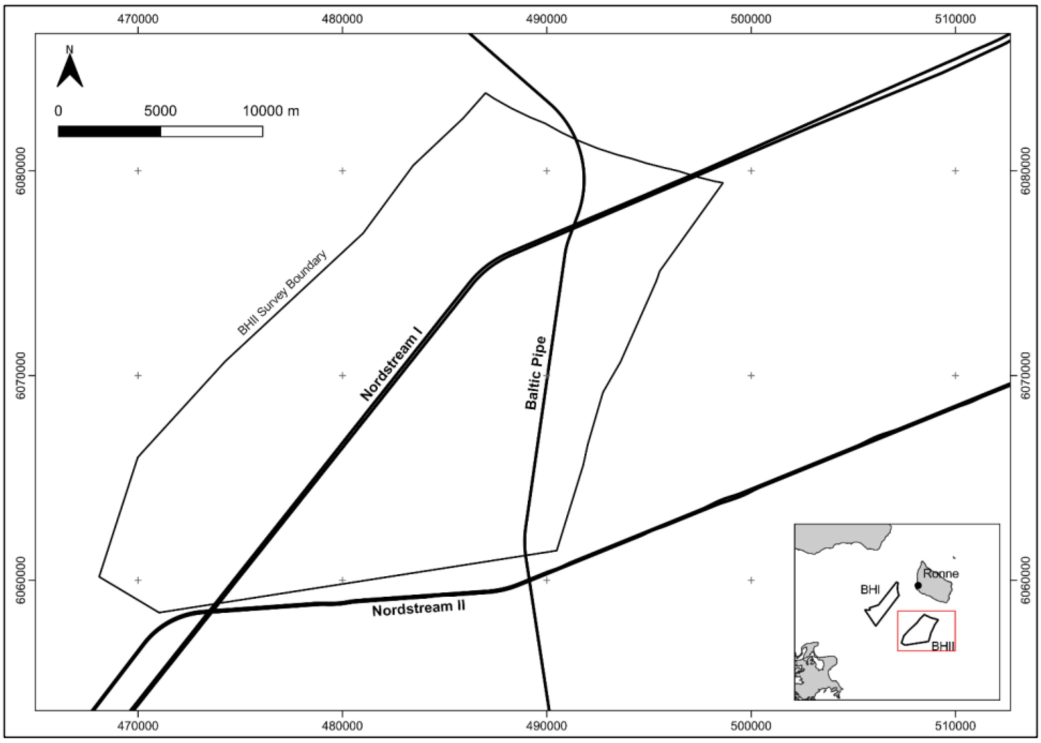


Figure 3-2 Map taken from the geophysical survey report (Energinet, Geophysical Survey Report BHII - Work Package A, 2022) illustrating the existing infrastructure at the BHII site.

4. Databases and data quality

This section summarises datasets that have been utilised in the development of the Integrated Ground Model.

4.1 Applied geodetic systems

Geophysical and geotechnical survey operations including the geological model are based on the coordinate reference system ETRS89 UTM zone 33 N, EPSG:25833. The vertical datum for the project is Mean Sea Level (MSL) as defined by the Technical University of Denmark geoid model DTU21MSL. Height data was acquired relative to the ellipsoid and reduced to the project vertical datum. Full details including the datum and projection parameters are provided in the geophysical survey report (Energinet, Geophysical Survey Report BHII - Work Package A, 2022). Table 4.1 and Table 4.2 summarize the datum and projection parameters for the survey.

Table 4.1 Datum parameters for the survey.

Parameter	Details
Name	European Terrestrial Reference System 1989 (ETRS89)
EPSG Datum Code	6258
EPSG Coordinate Reference System	4258
Spheroid	GRS80
EPSG Ellipsoid Code	7019
Semi-Major Axis	6378137.000
Semi-Minor Axis	6356752.314140
Flattening	1/298.2572221010
Eccentricity Squared	0.00669428002290

Table 4.2 Projection parameters for the survey.

Parameter	Zone 33N
EPSG Coordinate Reference Code	25833
EPSG Map Projection Code	16033
Projection	UTM Zone 33 N
Central Meridian	15° East
Latitude of Origin	0°
False Easting	500000.00 m
False Northing	0.00 m
Scale Factor at Central Meridian	0.9996
Units	Metres

4.2 Data Bases

A desktop study undertaken prior to the start of the data gathering by GEUS (GEUS, 2021) has supported the development of the Integrated Ground Model.

4.2.1 Geophysical Data Base

The geophysical investigations done by GEOxyz included multibeam echo sounder (MBES), Side Scan Sonar (SSS), Magnetometer (MAG), Sub-Bottom Profiler (SBP), 2D Ultra-High Resolution Seismic (2D UHRS). The original geophysical site survey was conducted 28/07/2021 – 27/11/2021, while the extended site survey was conducted 23/03/2022 – 17/05/2022 by GEOxyz for Energinet Eltransmission A/S (Energinet).

An overview of the geophysical survey is summarized in Table 4.3, including sensor type, line spacing and data resolution. The extended geophysical survey had the same survey line spacing as the original survey. The main lines were orientated with the long axis of each survey area with 250 m separation, while cross lines were orientated orthogonal to the primary lines with 1000 m separation. For MBES, SSS, MAG and SBP, secondary survey lines with a separation of 62.5 m were obtained in between the main lines to ensure full seafloor coverage.

Table 4.3 Geophysical data overview

Geophysical Site Investigation		
Sensor Type	Line Spacing	Data resolution
Multibeam Echo Sounder (MBES)	Main lines 250 m Cross lines 1000 m Secondary lines 62.5 m	0.25 m
Sub-Bottom Profiler (SBP)	Main lines 250 m Cross lines 1000 m Secondary lines 62.5 m	< 0.3 m
2D Ultra High Resolution Seismic (2D UHRS)	Main lines 250 m Cross lines 1000 m	0.3 m

4.2.2 Geotechnical Data Base

During the 2022 Geotechnical Campaign ground information was recovered from 20 Boreholes (BHs) and was supplemented with 54 seabed Cone Penetration Tests (CPTs). Figure 4-1 illustrates the locations of the boreholes and CPTs.

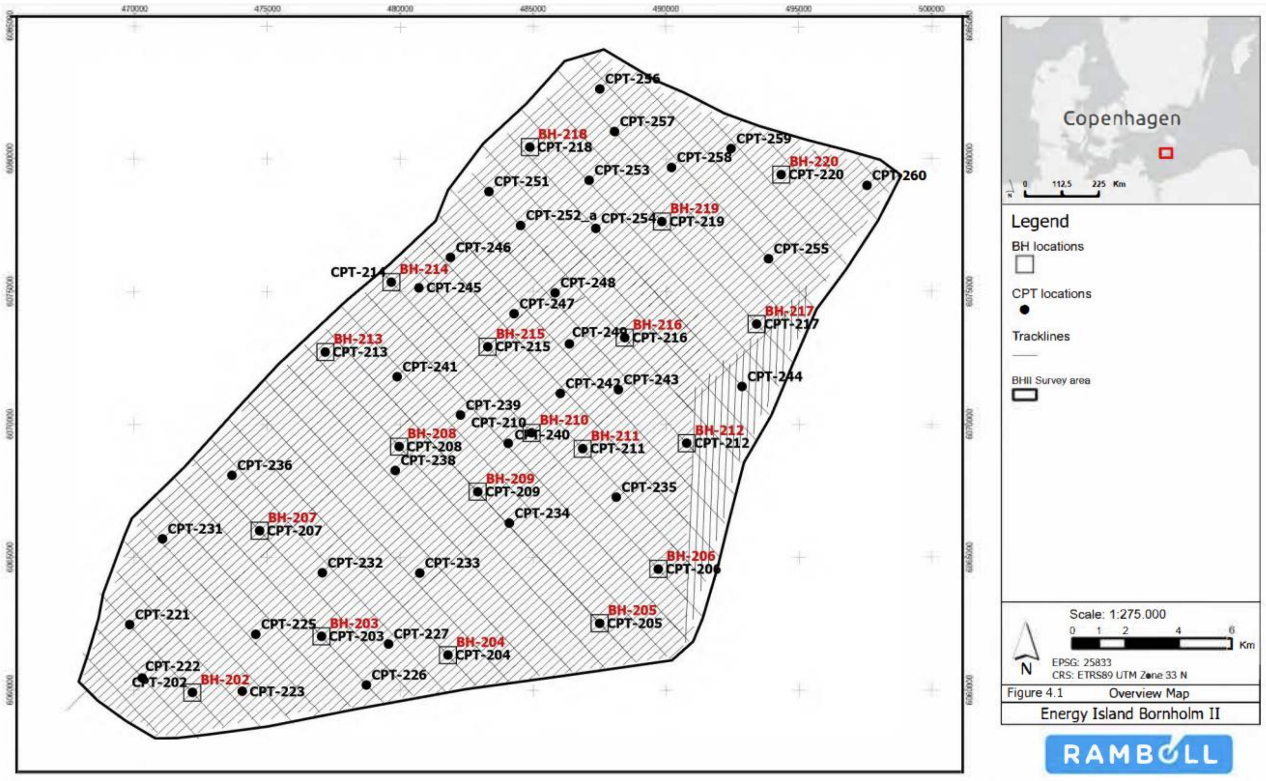


Figure 4-1 Maps illustrating the locations of the Boreholes and CPTs that have been utilised to characterise the geology of the Bornholm II Site.

4.3 Data Quality

This section examines the quality of the provided data within the IHS Kingdom project. Generally, the geophysical data is of good quality, but some issues within the project have been detected and are discussed in subsection below.

4.3.1 Sub-bottom profiler

The SBP data provided is considered to be of good quality with penetration down to approximately 10 m but often much shallower. This was possibly due to a thick succession of soft homogenous sediments found just below the seabed through the entire site. The organic content of these deposits can affect the cable installation. The vertical resolution is 0.3 m. Since most of the sediment succession penetrated by the SBP seismic has been characterised geotechnically as one single soil unit, a re-evaluation of the SBP interpretation has not been in focus. Based on the low depth of penetration of SBP and because similarity of soft units did not require subdivision the focus during this project was on addressing the deeper parts of the stratigraphic succession which was only seen on the UHRS data. Therefore, the SBP data has been left as received within the project.

4.3.2 2D UHRS Seismic

The 2D UHRS data is of good quality with generally low noise levels. The generally good data quality provided the possibility to detect clear seismic events representing potential shifting seismic facies and structural features such as paleovalleys and hummocky features (Figure 4-2).

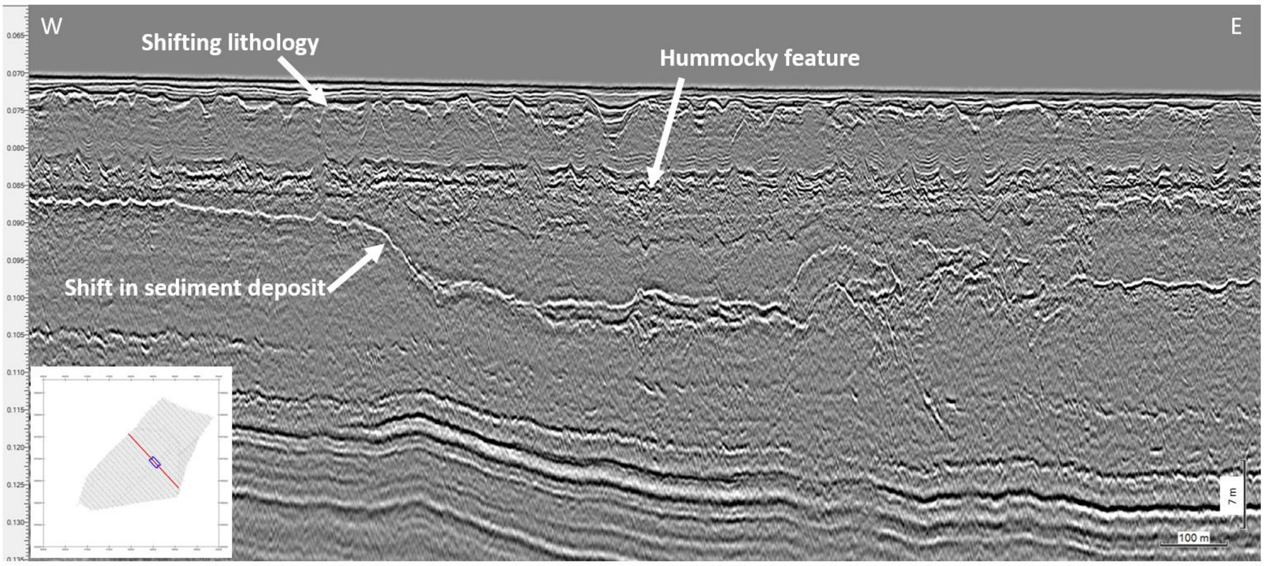


Figure 4-2 Crossline BH2_GO5_X_019_A illustrating the good quality within the UHRS data where distinctions between various seismic facies and structural features can be seen.

Generally, the data allows optimal investigation to be done down to approximately 100 m depth below seabed, which accompanied by geotechnical data allows for interpretation of depth to bedrock with a high degree of confidence. The quality of the seismic data deteriorates below the first seabed multiple. Additionally, selected seismic sections from the north-western part of the site have lower quality, as shown in Figure 4-3.

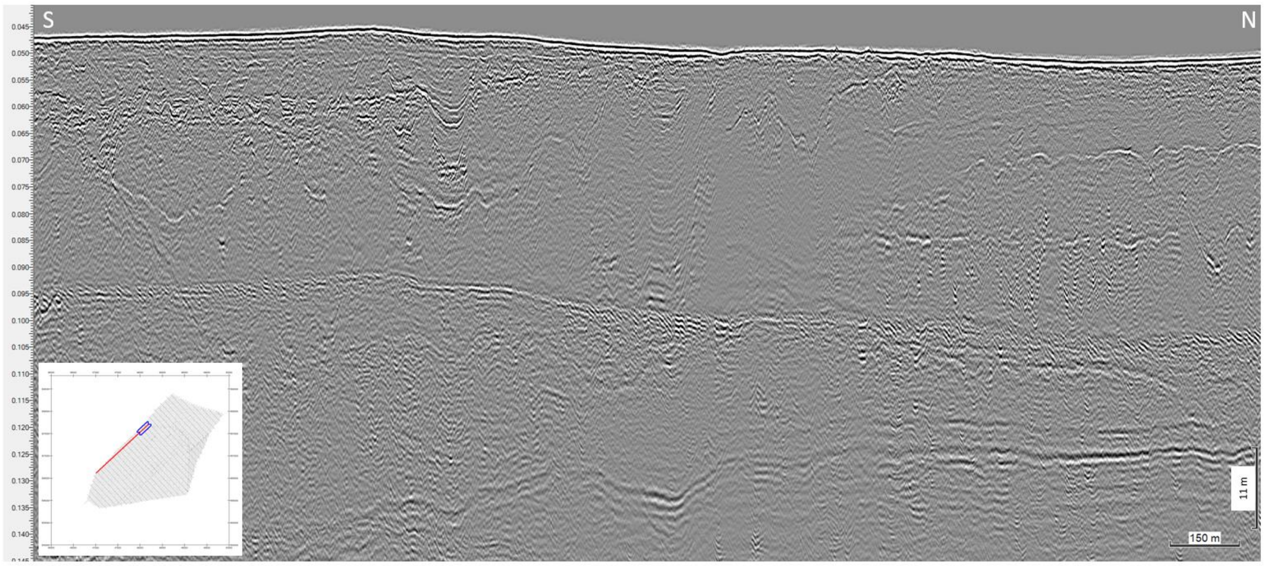


Figure 4-3 Inline BH2_G05_P_003_A illustrating some of the lower quality data within UHRS data where distinction of seismic events and features is harder to accomplish with high degree of confidence.

4.3.3 2D UHRS Offset Issues

Offset issues have been detected within the 2D UHRS dataset (Figure 4-4) between the seismic profiles where misties are detected between the in- and crosslines for the seabed. No specific distribution of these misties has been detected; they occur at random locations. This issue can potentially impact the correlation between the geotechnical and geophysical data, hence resulting in a lower degree of confidence in the correlation. An attempt to increase the confidence has been done with the velocity model (described in detail in Appendix 7), as all data is set to align in the model.

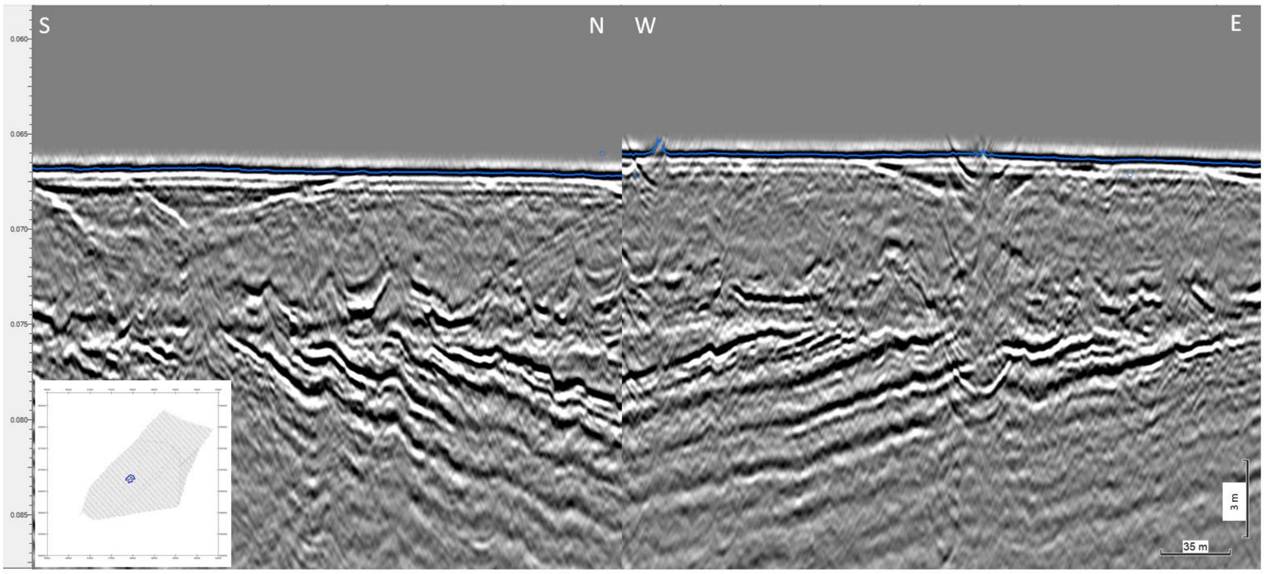


Figure 4-4 Seismic profile from 2D UHRS data. The blue line represents the mapped seabed in the survey area in time domain. A clear offset of approximately 0.9 m (calculated with velocity in the water column of 1500 m/s) is seen between the cross- and inline.

4.3.4 2D UHRS vs. SBP offset

An offset between the mapped seabed depth in the time domain between the 2D UHRS and SBP data was observed (Figure 4-5). A clear distinction in the amount of offset can be seen between the original and extended survey. In the original survey area, the interpreted SBP seabed is generally situated above the interpreted UHRS seabed, hence at shallower depths. While in the extended survey area the interpreted SBP seabed is generally situated below the interpreted UHRS seabed, hence at deeper depths. The offset between the two data is up to 1.3 m. The offset depth was calculated with the water column velocity of 1500 m/s.

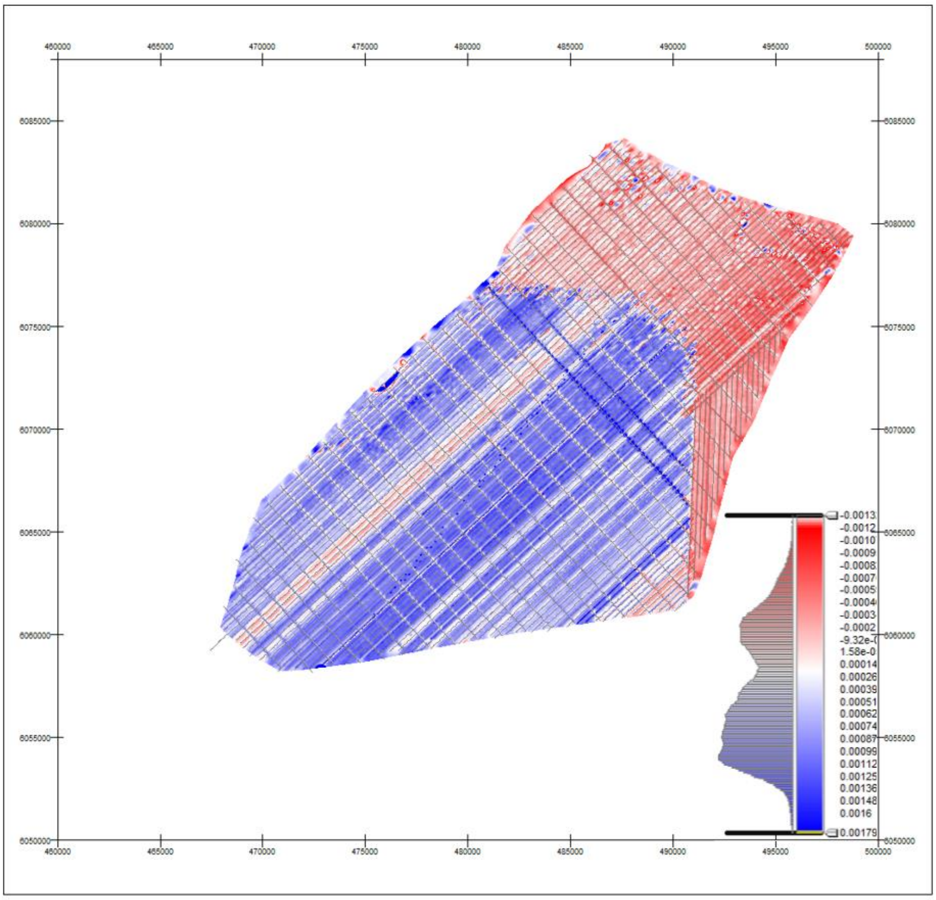


Figure 4-5 Map view of the offset between 2D UHRS seabed in time domain and SBP seabed in time domain. The scale is in TWT [s]. The offset range is from 0.0018 s (1.34 m) to – 0.0013 s (- 0.98 m).

This offset imposed an issue when comparing information, specifically interpreted horizons, from the two data types (Figure 4-6). Figure 4-6 illustrates the interpreted H20_i from SBP data on both the SBP data (A) and UHRS data (B). Here it can be seen that the interpretation done SBP data does not fit the UHRS data. The H20_i interpretation is also not done with a high degree of confidence on the SBP data as the signal becomes weak at depths where the horizon has been interpreted.

A distinct seismic event representing H20_i could also be observed on the UHRS data, therefore it was decided to map the horizon within the 2D UHRS data set. This was also done to minimize the level of uncertainty as the newly interpreted horizon ensured that it would fit with the 2D UHRS data.

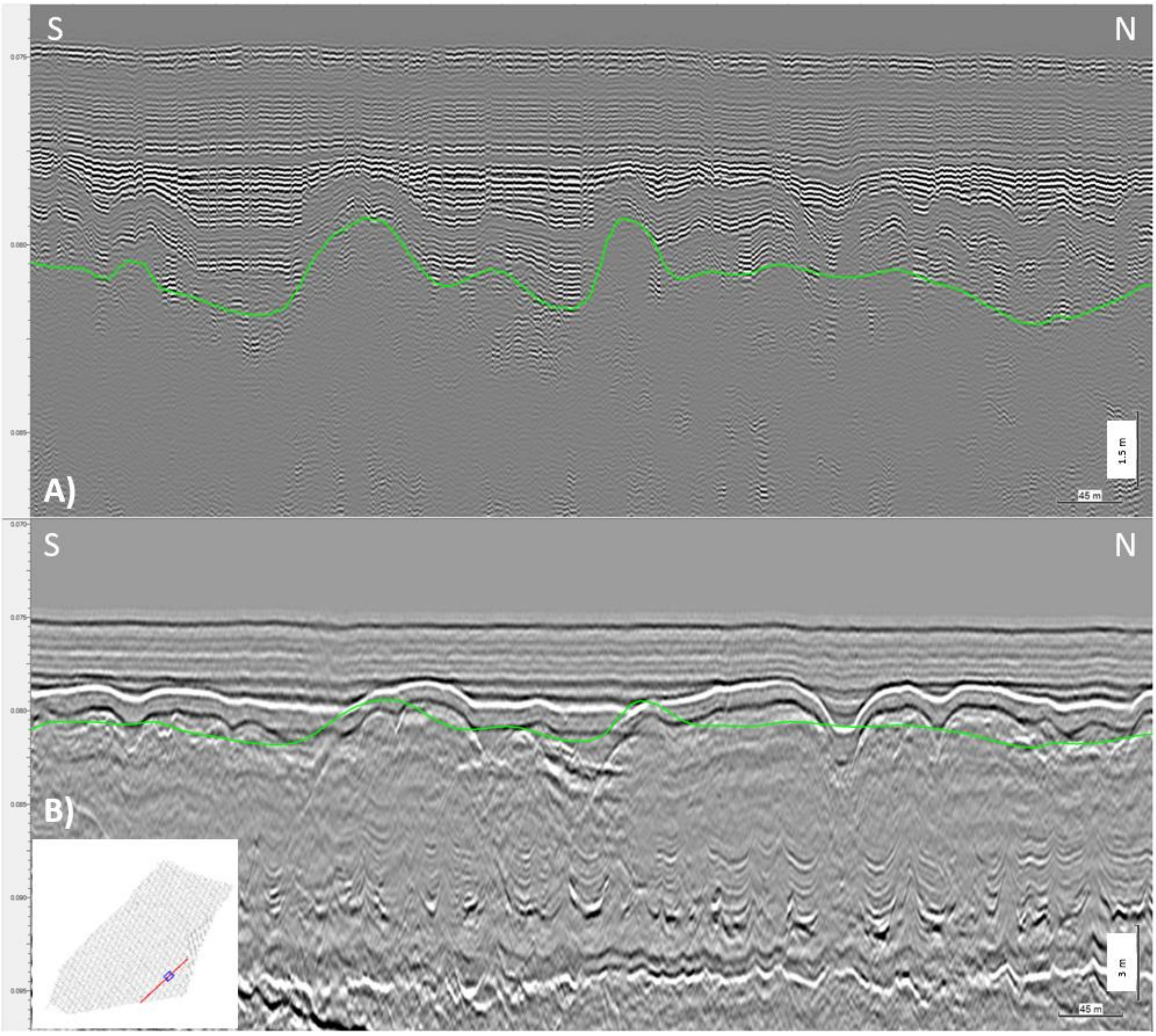


Figure 4-6 Seismic profile displaying the interpreted horizon H20_i on the SBP data. A) Seismic profile in SBP data in time domain displaying H20_i (green line); B) Same seismic profile in UHRS data in time domain displaying H20_i (green line). The displayed H20_i was provided by the client and has not been updated within the SBP data set.

4.3.5 Bathymetry vs. Seabed Depth

An offset between the bathymetry data and the seabed mapped in depth domain in the 2D UHRS was detected (Figure 4-7). The offset ranges from -3.49 to 1.35 m. A clear distinction of the amount of offset can be seen between the original and extended survey. The original survey area generally has a larger offset of approximately -3.49 to 0 m, while the extended survey site generally has a smaller offset of approximately -0.5 to 1.35 m. Generally, the observed misalignments between the seismic and multibeam datasets have been accounted for when building a velocity model in the Kingdom Software and therefore have relatively low impact on the interpretation confidence assessment.

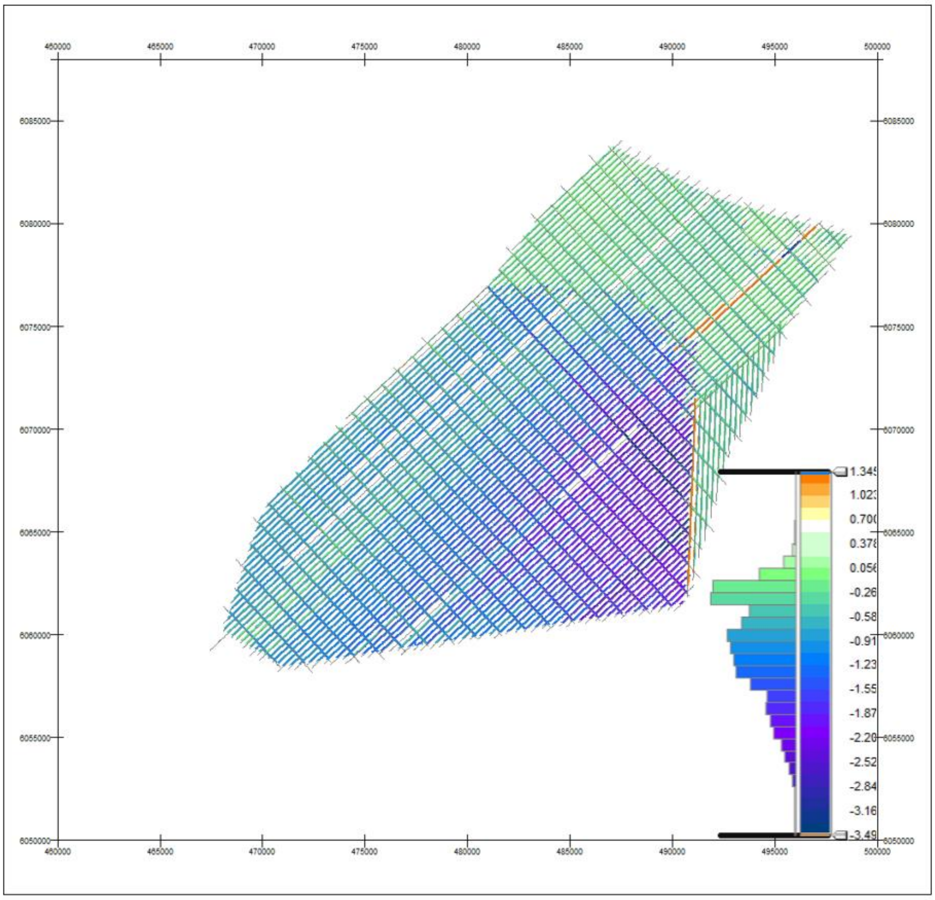


Figure 4-7 Map view of the offset between the bathymetry data and the mapped seabed on seismic data in depth domain. The scale in meters.

5. Bornholm II – Site Setting

This section summarizes the characteristics of the Bornholm II site in terms of the seafloor bathymetry, nature of the seabed sediments and the regional geological setting along with its depositional history.

5.1 Site topography and seabed morphology

Water depth varies across the BHII site from approximately 15 to 57 m with a gradual increase in the water depth from the north-western part of the site towards the south-eastern part of the site (Figure 5-1). This is mainly influenced by a structural high (Arnager Blok) located in between the BHI and BHII sites.

Another distinct bathymetric feature is a dune-like structure observed in the northern part of the site (Figure 5-1). The structure is shown with more detail in Figure 5-2 and Figure 5-3. It has a NW – SE orientation and a slope of approximately 5-10°. Seabed surface classification map (Figure 5-4) created based on the interpretation of the low frequency SSS data and backscatter datasets illustrates that this area is dominated by stones and reefs (Energinet, Geophysical Processing Report BHI & BHII - Work Package A, 2022).

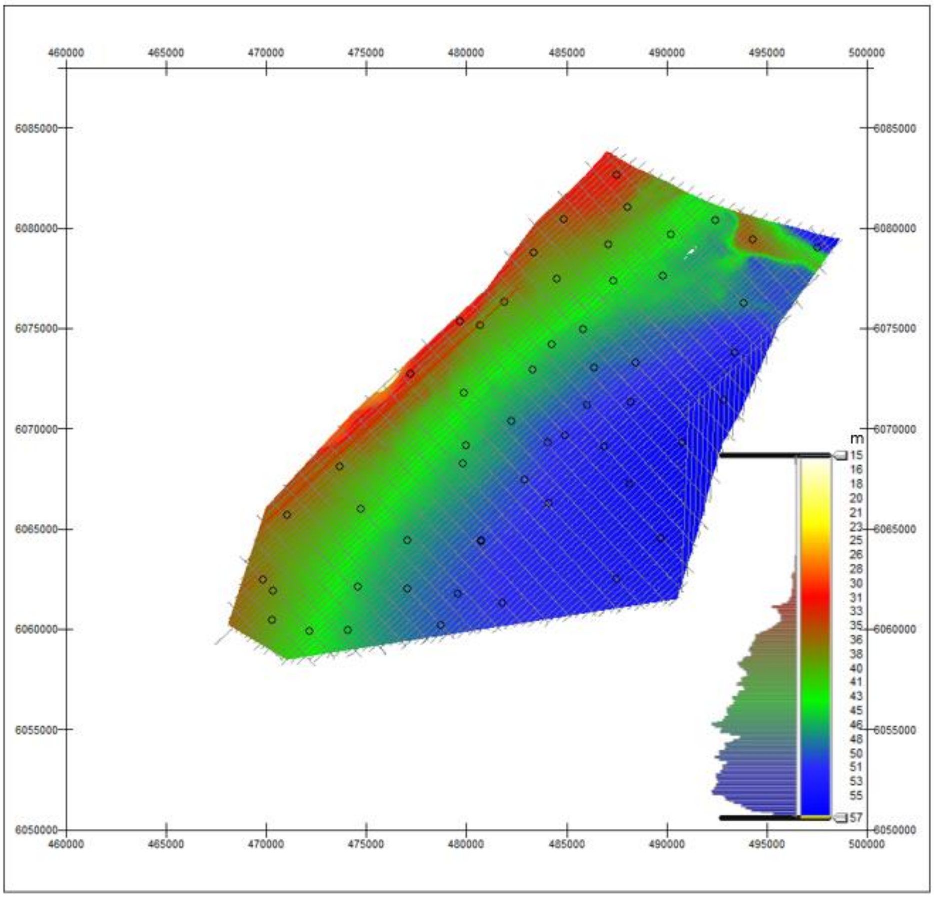


Figure 5-1 Map of the seafloor illustrating how the bathymetry deepens gradually from the north-west towards the south-east. A distinct topographic dune like feature can be seen on the seafloor in the north-eastern part of the site.

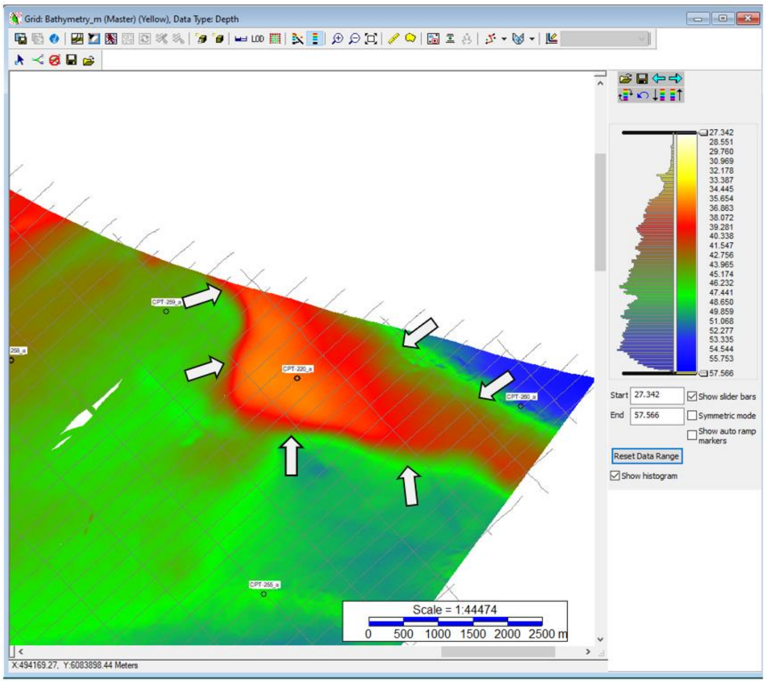


Figure 5-2 A wide dune like feature is seen in the north-eastern part of the area.

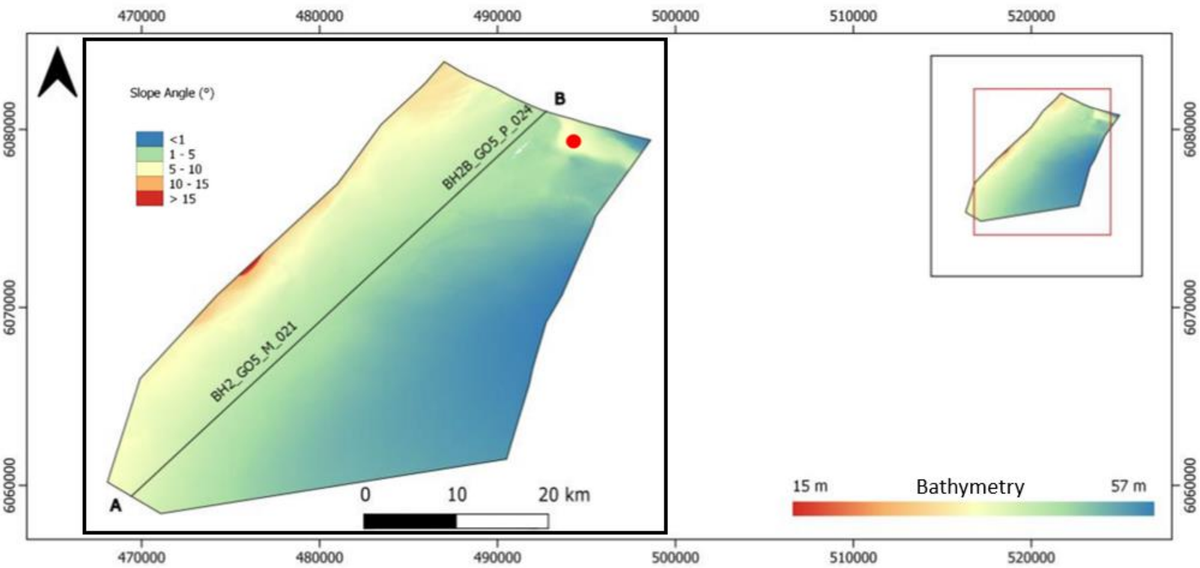


Figure 5-3 Image taken from the geophysical survey report (Energinet, Geophysical Survey Report BHII - Work Package A, 2022) which illustrates the bathymetry and slope angles. The image illustrates that the dune like feature has a slope between 5 and 10˚ (area marked with a red circle).

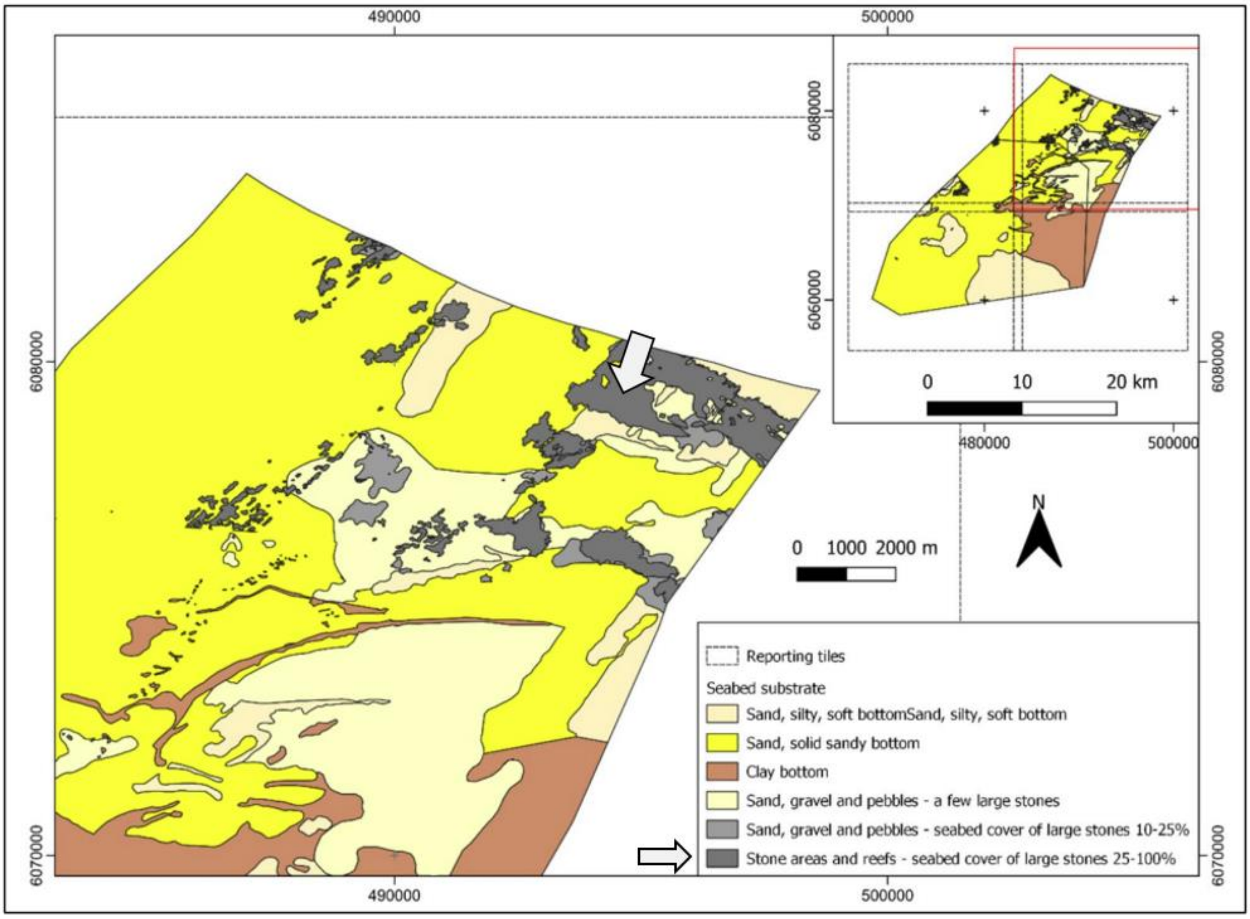


Figure 5-4 Sediment classification map reproduced from the geophysical survey report (Energinet, Geophysical Survey Report BHII - Work Package A, 2022) illustrating how the seafloor across the bathymetric high is dominated by stones, with larger stones covering 25 to 100% of the seabed.

5.2 Seabed – substrate type

An interpretation of the seabed geology for BHII is presented in the Geophysical Survey Report (Energinet, Geophysical Survey Report BHII - Work Package A, 2022). The evaluation was made from interpretation of the acquired low frequency SSS data and backscatter imagery.

Comparison with the bathymetry map (Figure 5-1) indicates that there is a correlation between decreasing grain size with increasing water depth. This is most clearly seen in the NW – SE orientation in the central part of the site where there is a clear transition from sand (solid sandy bottom) to clay substrates with increasing water depth (Figure 5-5). The transition is less obvious in the northern part of the site.

The Geophysical Survey Report notes that the eastern part of the BHII site is heavily trawl scarred with some interspersed pitted areas (Energinet, Geophysical Survey Report BHII - Work Package A, 2022). In the western part of the area numerous erosional features, boulder fields and sand ripples are present.

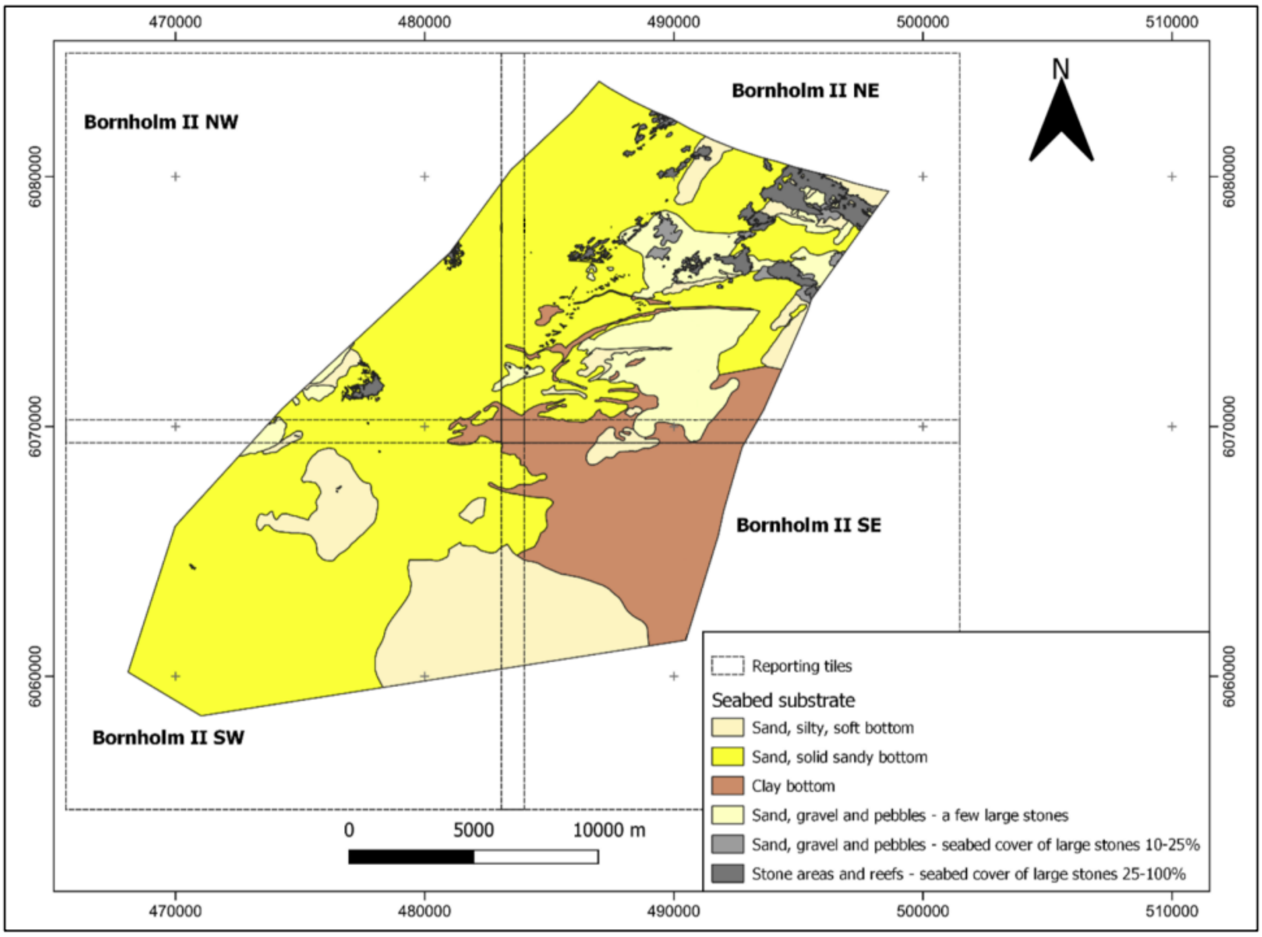


Figure 5-5 BHII seabed surface substrate classification as provided in the final geophysical survey report (Energinet, Geophysical Survey Report BHII - Work Package A, 2022). Note the transition from sand to clay in a NW – SE orientation in the central part of the site that corresponds to the increasing water depth towards the southeast. In the north-eastern part of the site, the area has patches of stone areas and reefs.

5.3 Regional Geology: Context for Bornholm II

GEUS (GEUS, 2021) prepared a geological Desk Top Study (DTS) prior to the start of the data gathering campaigns across the Bornholm Sites. This section reviews the regional geology as described in the report prepared by GEUS in the light of the observations in the BH II area.

Structural setting

The survey site of BHII is located on the border of the Sorgenfrei-Tornquist Zone, extending into both the Risebæk Graben, the Arnager Blok and the Kolobrzeg Graben (Figure 5-7). The Sorgenfrei-Tornquist Zone is an intracontinental fault zone that is between 50-100 km wide extending from Skagerrak in the eastern North Sea Basin towards the southeast to the Black Sea. The Baltic Shield is separated by the zone from the Danish Basin and the North German Basin (Figure 5-6). In the Danish area, this fault zone is divided in to two segments: the Sorgenfrei-Tornquist Zone (STZ) to the northwest and the Teisseyre-Tornquist Zone (TTZ) to the southeast. The two zones overlap at Bornholm, where the NE-SW trending Rønne Graben and Risebæk Graben form lateral ramps between the STZ and the TTZ. These two grabens are divided by the Arnager Blok and both grabens end in the Kolobrzeg Graben (Figure 5-7).

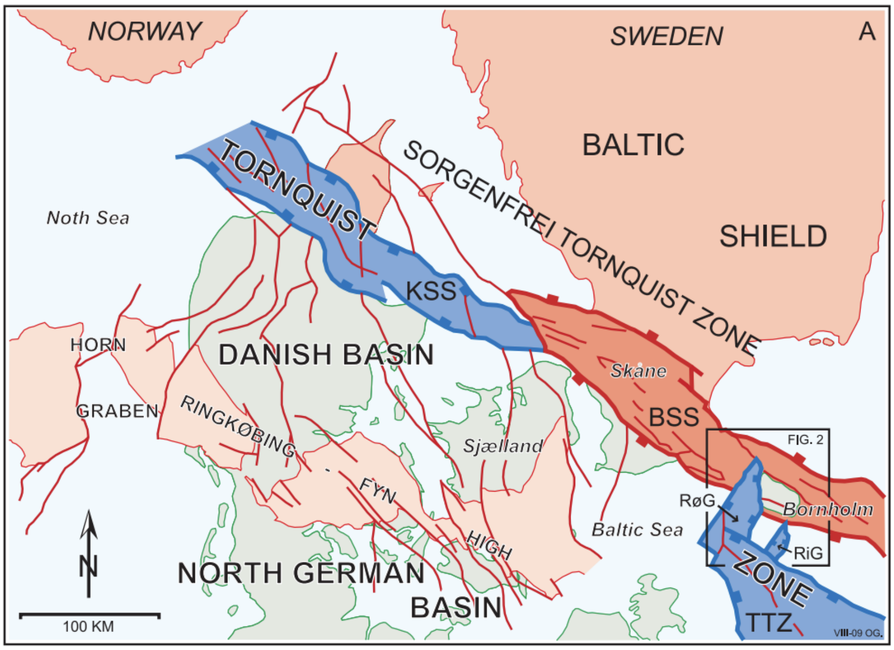


Figure 5-6 Structural map of the Sorgenfrei-Tornquist Zone. RøG: Rønne Graben; RiG: Risebæk Graben; TTZ: Teisseyre-Tornquist Zone; KSS: Kattegat-Skagerrak segment; BSS: Bornholm-Skåne segment (Graversen O, Structural analysis of superposed fault systems of the Bornholm horst block, Tornquist Zone, Denmark, 2009).

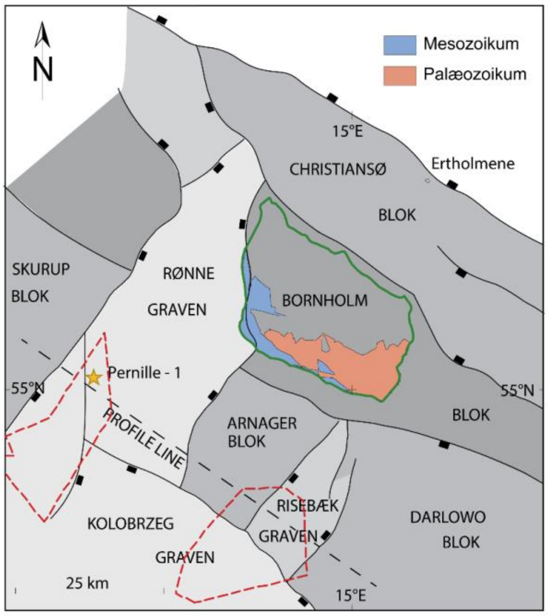


Figure 5-7 Major fault blocks of the Bornholm region. The original BHII survey site is located within the Risebæk Graben and Kolobrzeg Graben (GEUS, 2021).

5.3.1 Palaeozoic – Mesozoic Geology

The preserved Palaeozoic succession in the Risebæk Graben has a thickness of approximately 1 km, thinning towards the west. The thinning has supposedly been caused by recurring erosion during the Late Palaeozoic and most of the Mesozoic.

Repeated vertical fault block movements such as events of rifting and folding dominated the Bornholm area during the Mesozoic. Rifting and subsidence of both the Rønne Graben and the Risebæk Graben occurred during the Mesozoic (Graversen O, Structural analysis of superposed fault systems of the Bornholm horst block, Tornquist Zone, Denmark, 2009).

Towards the end of the Jurassic period limnic sediments were deposited in the area. A large transgression occurred during the Cretaceous period. It reached its peak during Upper Cretaceous time with subtropical oceanic conditions which led to the deposition of chalk layers. Towards the end of the Cretaceous period a large scale regression occurred (Schwarzer K, 2008).

5.3.2 Paleogene – Neogene Geology

The Palaeogene period and the beginning of the Neogene was influenced by several transgression and regression events that covered the entire southern Baltic Sea. At the end of the Neogene period the climate became colder.

5.3.3 Quaternary Geology of the Bornholm region

The Bornholm region was influenced by four glacial events between the Late Saalian to Late Weichselian period, each separated by periods of interstadial marine or glaciolacustrine deposition. The maximum extent of the Scandinavian Ice Sheet in Denmark occurred at 22.000 years BP followed by a stepwise retreat with Bornholm being deglaciated shortly after 15.000 years BP (GEUS, 2021). Generally, the deglaciation occurred rapidly around 12.000 years BP (Bjorck S, 1995).

Figure 5-8 and Figure 5-9 illustrate the gradual deglaciation of the area. At about 18.000 years BP the Scandinavian Ice Sheet had reached its maximum extent, that followed Norwegian and Swedish coastlines, covered the present Zealand and reached down to the northern part of Germany. At about 16.000 years BP the ice had retreated towards the Øresund region and the western part of Skåne, while Lolland-Falster islands were still covered by the ice. The development of local lakes had begun along the ice margin in the south-western part of the Baltic Sea during the ice retreat (GEUS, 2021). Varved clays were deposited in front of the receding ice margin during the ice sheet retreat in the Baltic basin (Bjorck S, 1995).

Investigations done in Polish, German and Danish waters suggest that at about 15.000 years BP the ice margin must have been situated west of Bornholm. Large lakes dammed in front of the ice sheet, received water supply through the Great Belt to Kattegat, that during that time was affected by a regression. Also, the German and Polish rivers contributed with a significant supply of meltwater into the area, which is also supported by the existence of major late glacial delta deposits. As the deglaciation continued an enormous discharge event occurred in the south-central Sweden and the water column in the lake dropped with approximately 25 m (GEUS, 2021).

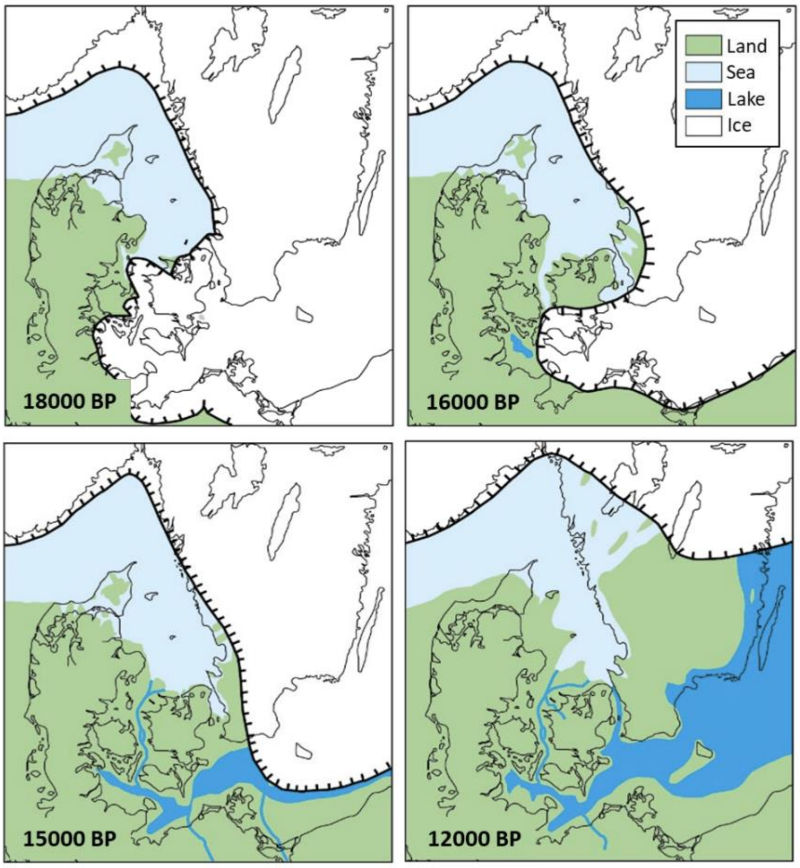


Figure 5-8 Palaeogeographic maps of the Danish area from 18.000 – 12.000 BP (GEUS, 2021).

After the last deglaciation, the Bornholm and Baltic Sea area has gone through two stages of freshwater and two stages of brackish-water periods. 1) The freshwater South Baltic Ice Lake (12.500 – 10.000 years BP); 2) The partly brackish Yoldia Sea (10.000 – 9.500 years BP); 3) The freshwater Ancylus Lake (9.500 – 8.000 years BP); and 4) The brackish Littorina Sea (8.000 – 3.000 years BP). The shifting phases between freshwater and brackish water were a result of isostatic rebound and eustatic sea level changes, which also resulted in deposition of different sedimentary strata (Andren E, 2000).

The Yoldia Sea (10.000 – 9.500 years BP) was formed when a strait was established through the south-central Sweden transforming the Baltic basin into a marine basin. Sea-level was low enough to connect Bornholm with the German mainland. It has been suggested that the Yoldia Sea deposits in the southern Baltic probably consist of reworked Baltic Ice Lake clays. The Yoldia Sea stage consisted of interplay between isostasy and global eustasy (Bjorck S, 1995).

The Ancylus Lake (9.500 – 8.000 years BP) was the result of continuous glacio-isostatic uplift of the south-central Sweden resulting in enclosure of the connection to the ocean hence establishing the last lake phase of the postglacial Baltic. During the Ancylus Lake phase the area experienced calm lake sedimentation followed by gradual transgression and change into brackish conditions finally transitioning into a fully marine environment (GEUS, 2021).

The beginning of the Littorina Sea period is marked by a very rapid sea level rise (2.5 cm/year). This transgression led to a widespread flooding of the south-western Baltic region without any erosion as the landscape was just drowning. The submerged landforms were associated with ice- and glacier- shaped troughs and fjords, including ridges, terminal moraines, basal moraines and imbedded meltwater channels. The rapid sea level rise resulted in all terrain below -5 m of the present mean-sea-level (MSL) being flooded (Schwarzer K, 2008).

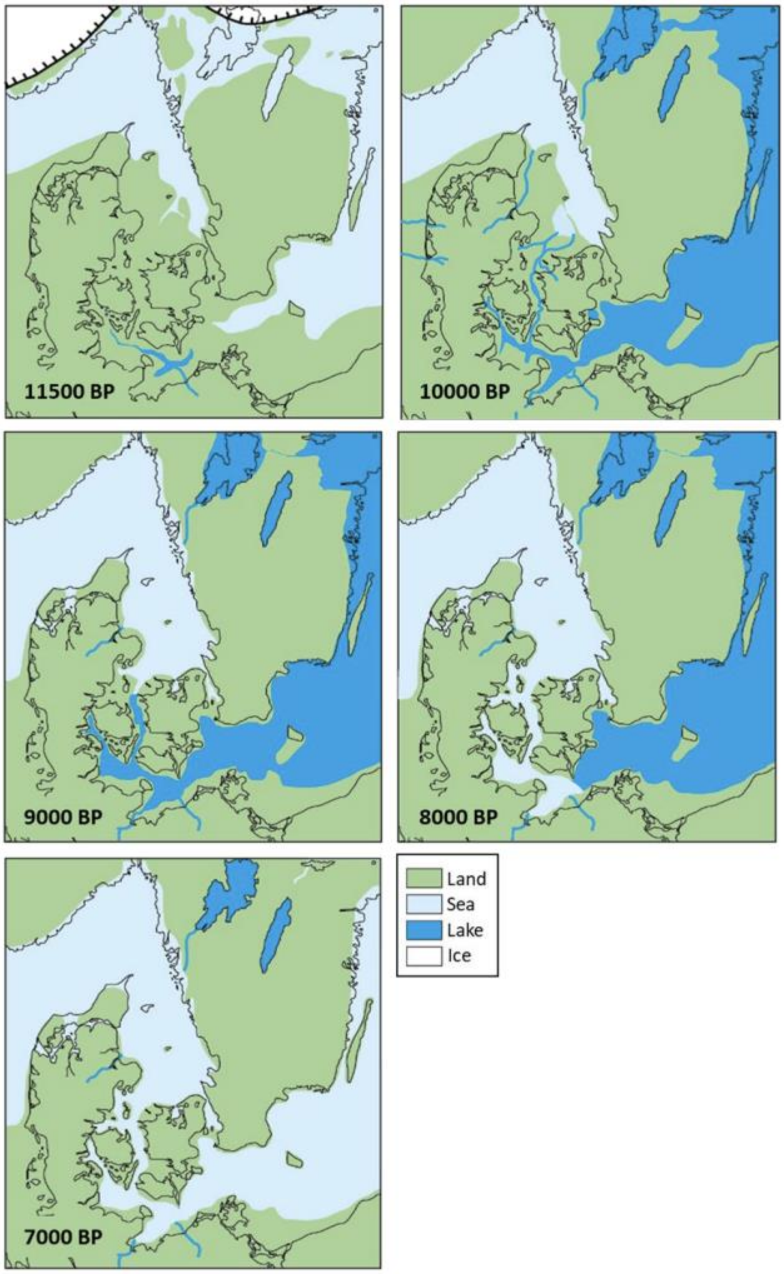


Figure 5-9 Palaeogeopgrahical maps of the Danish area from 11.500 – 7.000 years BP (GEUS, 2021).

5.3.4 Conceptual Geological Model

Two schematic sketches illustrating the geometric relationships between the soil units and seismic units discussed further in the report, are shown in Figure 5-11 and Figure 5-12. An illustration of the stratigraphical subdivision of this ground model as compared to previously published stratigraphy for the Bornholm Basin (GEUS, 2021) is presented in Figure 5-10. The soil units presented in Chapter 8 have been inspired by the Bornholm Basin (GEUS, 2021) but they are not identical.

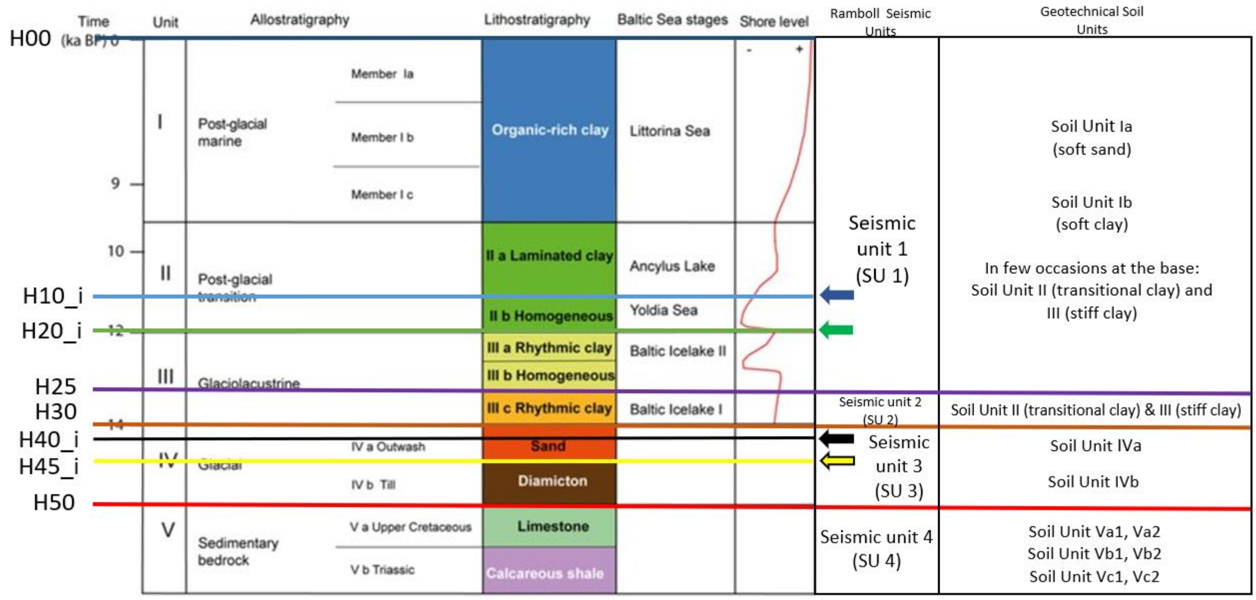


Figure 5-10 Modified stratigraphical subdivision of the Bornholm Basin correlation with observations made in this project (GEUS, 2021)**. Note the seismic horizons marked with arrows can be mapped across the site but do not define separate soil units.**

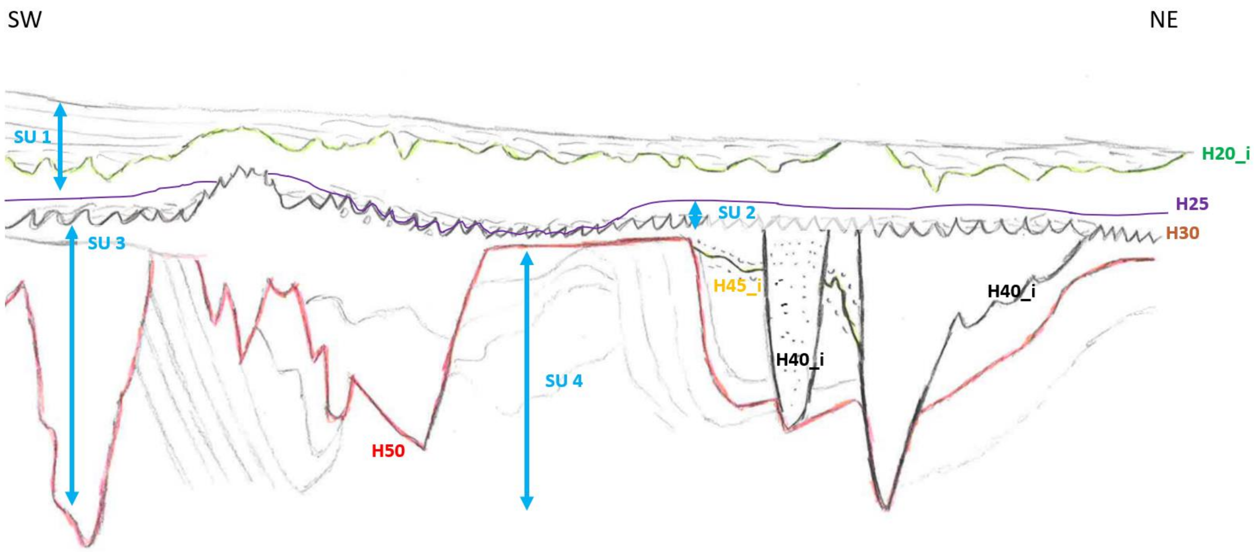


Figure 5-11 Schematic illustration of the seismic unit and horizon distribution throughout the site in a SW – NE orientation. The light green color represents H20_i which is an internal horizon mapped within SU 1. H25 (purple) represents the base of SU 1. H30 (brown) represents the base of SU 2. H40_i (black) is an internal horizon mapped within SU 3 which represents some of the base of paleovalley systems. H45_i (yellow) is an internal horizon mapped within SU 3 which represents the top of the sandy succession. H50 (red) represents the base of SU 3 / top of SU 4.

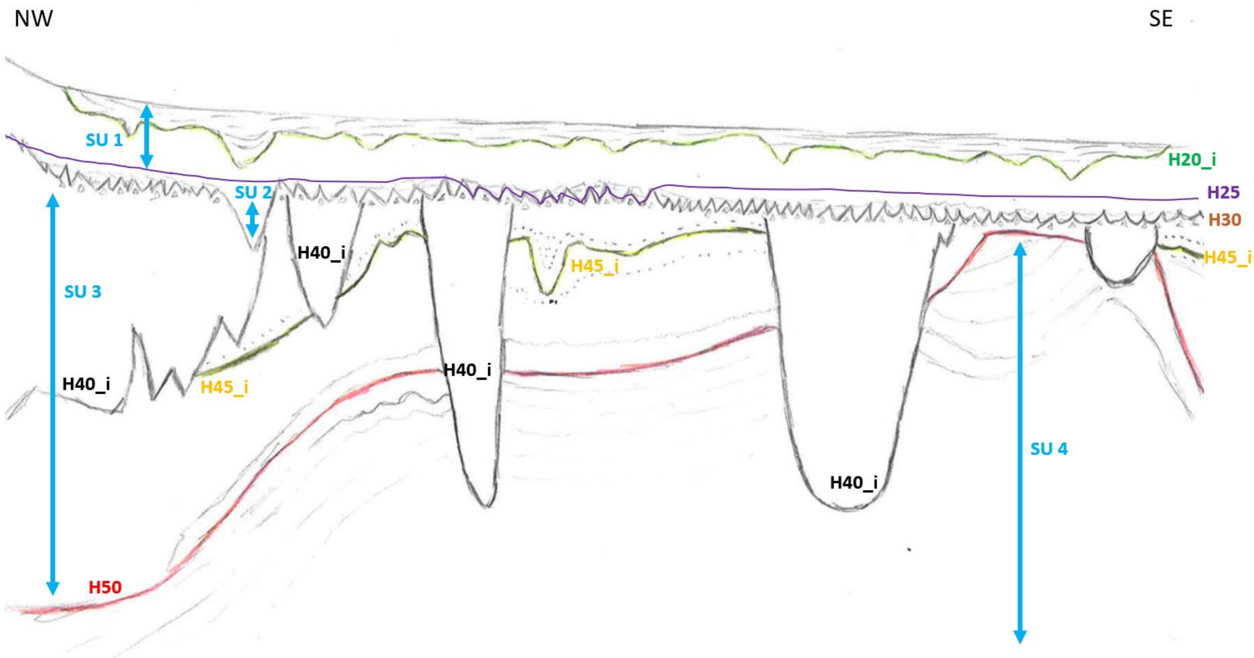


Figure 5-12 Schematic illustration of the seismic unit and horizon distribution throughout the site in a NW – SE orientation. The light green color represents H20_i which is an internal horizon mapped within SU 1. H25 (purple) represents the base of SU 1. H30 (brown) represents the base of SU 2. H40_i (black) is an internal horizon mapped within SU 3 which represents some of the base of paleovalley systems. H45_i (yellow) is an internal horizon mapped within SU 3 which represents the top of the sandy succession. H50 (red) represents the base of SU 3 / top of SU 4.

6. Methodology

6.1 Workflow overview

The provided geophysical and geotechnical data along with corresponding reports and relevant research papers were reviewed and analyzed in detail to get an overview of the site – specific characterization and regional geological setting. Subsequently, the following steps were undertaken to establish an accurate subsurface model. The workflow describing works completed is summarized below.

1. A Kingdom project containing previously mapped horizons was provided to Ramboll. Both UHRS and SBP data were included in the project. It was assessed that all relevant soil unit boundaries (including the shallow soil units) could be interpreted on the UHRS data. It should be mentioned that the penetration depth of SBP data did not allow for an accurate mapping of the shallow horizon (H20_i) across entire site. Therefore, it was decided not to proceed further with the interpretation on the SBP and focus solely on interpreting horizons and unit boundaries in the UHRS data.

2. The horizon H20_i was transferred from SBP data into UHRS and remapped.

3. The geotechnical data (BH, CPTs, logs, soil unit formation tops) were imported into the Kingdom project. Soil unit formation tops enabled a velocity model to be created. Horizons representing main seismic unit's boundaries were used to establish a velocity model with the DDC module in the IHS Kingdom software: H00, H20_i, H30 and H50. Details regarding the velocity model can be found in section 6.2 and Table 6.1.

4. In the first phase the boundaries, where the alignment between the geotechnical and geophysical data was good was not adjusted or only slightly to match the geotechnical data. Firstly, the top bedrock was altered and mapped with support from the geotechnical data with high degree of confidence.

5. During the second phase of correlation between the two datasets, selected misalignments were resolved. For example, a successful correlation of H30 with base of soil unit II and III was accomplished through an iterative process. A correlation between H20_i and soil units could not be achieved but the horizon was kept within the ground model as it was initially thought to represent the base of the organic rich gyttja deposits. Packages of gyttja have been observed in boreholes in intervals that have been assigned to soil unit Ib. An accurate interpolation of the gyttja could not be carried out since gyttja layers are interbedded with organic rich soft clays that do not meet the gyttja definition, however the gyttja and soft clays have the same geotechnical properties. If any seismic horizon should be used to constrain the distribution of the gyttja it should be the H10_i.

6. It has proved to be impossible to seismically define the soft-loose sands (soil unit Ia) from the soft, organic-rich clays and gyttja (soil unit Ib). As a result, these two soil units have been merged to form Integrated Ground Model Unit 1 (IGMU 1). Moreover, the base of this IGMU, where the geotechnical soft soil units pass into transitional soils (soil unit II) is also difficult to define seismically. Therefore, the base of IGMU 1 is a composite surface and has been created in the following manner.

1) In the southern part of the site, the base of soft sediments could be correlated with the top of a laminated seismic package which has been mapped by the H25 seismic horizon.

2) Elsewhere the contact between soil units Ib and II/III was assessed with respect and its relationship to its proximity to H30. In most instances it lies close to this horizon, so the H30 forms the base of IGMU 1 over much of the rest of the site.

3) In those areas where there was a significant difference between the contact of soil units Ib and II/III and the H30 seismic horizon a more pragmatic approach has been taken. In those few areas the contact itself has been gridded and is used to mark the base of IGMU 1. In all these instances this surface merged with the H30 over a distance of several hundred meters.

Table 7.1 in Section 7.2 gives a summary of how the defined seismic, sediment and geotechnical units correlate across the BHII site.

6.2 Velocity model

A velocity model was created to establish a time depth relationship with the Dynamic Depth Conversion tool in the IHS Kingdom Software. This was a required step as offsets were detected throughout the entire site between the provided time and depth domain data. The velocity model was built in a stepwise manner. Firstly, the horizons H00, H30 and H50 were used and subsequently the model was updated to also include the horizon H20_i.

Two definitions are required for the model: A reference in time domain and a matching reference in the depth domain. Table 6.1 presents the defined information for the time and depth relation in the model. The time depth pairs were chosen following two main criteria. Firstly, the horizons represent events also detected on the geotechnical data, hence allowing a correlation between the geotechnical and geophysical data to be made. Secondly, the selected horizons have generally a very broad distribution in the survey area which makes the model more certain.

Additionally, three boreholes; BH-202, BH-206 and BH-216_a, for which PS-log data was available, have been included in the model to increase the confidence of the created velocity model.

The cell size applied for the velocity model was 4x4 m.

Table 6.1 Summary of the input to the Dynamic Depth Conversion in the Kingdom Suite Software

Time Grid	Depth constraint
H00 (Grid)	Bathymetry (Grid)
H20_i (Grid)	H20_i (Formation Top)
H30 (Grid)	H30 (Formation Top)
H50 (Grid)	H50 (Formation Top)
Velocity below last time/depth surface: 1850 m/s	

The Seabed Seismic Horizon (H00) mapped on the UHRS seismic data was tied to the seafloor bathymetry. The bathymetry map was supplied in the Kingdom Project from the geophysical campaign (GEOxyz, 2022) and has an uncertainty of 0.2 m. The bathymetry map was tied to the seismic seabed time grid (Table 6.1) and this time-to-depth tie provides the starting point for the velocity model. A more detailed explanation regarding the steps done for the velocity model is provided in the Appendix 7.

7. Seismic Units and Sedimentology

7.1 Introduction

This section describes how the structural framework of the BHII site has been defined using the mapped Seismic Horizons. Details regarding the observed sedimentological and geological features are also included. Each subsection describes a seismic unit, how it has been picked seismically as well as, its sedimentological features. The relationship between the defined seismic units and the defined geotechnical soil units are presented in detail in section 10.

Seismic units have been defined to be comprised of several soil units as distinction of each soil unit was not possible within the seismic data. Table 7.1 gives an overview of the relationship between the seismic and soil units. A geotechnical characterization of the soil units is given in Chapter 8. Each seismic unit is described below with each section being subdivided into: 1) seismic definitions, 2) sedimentology and geotechnical characteristics and 3) predominant sediment type.

7.2 Terminology

To avoid confusion between the Seismic and Geotechnical soil units, the following system as been used:

- Seismic units are defined using Western Arabic numerals
- Geotechnical soil units and ground model subdivision employs a Roman Numeral system.

Table 7.1 Table summarising how the defined seismic, sediment and geotechnical units correlate across the BHII site.

Integrated Ground Model Unit	Top Seismic Horizon	Bottom Seismic Horizon	Geotechnical Soil Unit	Seismic Unit	Lithology	Depositional Environment	Age
IGMU 1	H00	H25	Interbedded Soil Unit Ib Soil Unit Ia	Seismic Unit 1	Interbedded Soft, organic rich clay and gyttja Loose sand	Marine and lacustrine Distal shoreface or delta front/fan	Post glacial – Late Pleistocene/ Holocene
IGMU 2	H25	H30	Soil Unit II	Seismic Unit 2	Transitional clay	Glaciolacustrine deposits	Late glacial – Pleistocene
			Soil Unit III		Stiff clay	Glacial moraine	Late glacial – Pleistocene
IGMU 3	H30	H50	Soil Unit IVa	Seismic Unit 3	Dense sand	Sandy delta or ice front subaqueous plume fan	Glacial – Pleistocene
			Soil Unit IVb		Glacial till	Glacial till and ice front distal subaqueous fan or distal delta front	Glacial – Pleistocene
IGMU 4	H50	---	Soil Unit V	Seismic Unit 4	Variable	Variable	Jurassic and Cretaceous

The final integrated ground model in the IHS Kingdom Suite project contains a total of ten seismic horizons that have been mapped by GEOxyz and Ramboll. These include four main seismic horizons (H00, H25, H30 and H50) delivered by the client and in some cases remapped by Ramboll, as well as four additional seismic horizons (H10_i, H20_i, H40_i and H45_i). Two of these (H40_i and H45_i) have been mapped during the work of integrating seismic and geotechnical data into this Integrated Ground

Model. H20_i has been mapped on both sets of data. Ramboll has worked almost exclusively on the UHRS seismic since most of the geotechnical soil units have been defined at depths that are generally greater than the SBP data can image.

Figure 5-11 and Figure 5-12 show a schematic illustration of the seismic units in NW to SE and NE to SW across the site, as well as their spatial relationship.

7.3 SU 1

SU 1 is the shallowest unit and is defined at its top by horizon H00 which follows the seabed reflector and by the H25 horizon at its base. Generally, the SU 1 is composed entirely of soft clays and/or soft sands. Transitional and stiff clays can be encountered at the base of the unit. Seismic horizon H20_i was mapped within the SU 1 as it was thought to potentially represent the base of organic rich gyttja deposits. After closer examination, based on solely borehole description, it was concluded that the base of gyttja has a better fit with the H10_i interpretation. Gyttja is constituting an integral component of the organic and soft material within Soil Unit Ib.

The thickness of SU 1 is largest in the northern part of the site along with a few other areas local sites where it reaches up to 39 m (Figure 7-1**Error! Reference source not found.**). Otherwise, the unit has generally thickness between 0 – 14 m throughout the site and it was deposited in a marine environment.

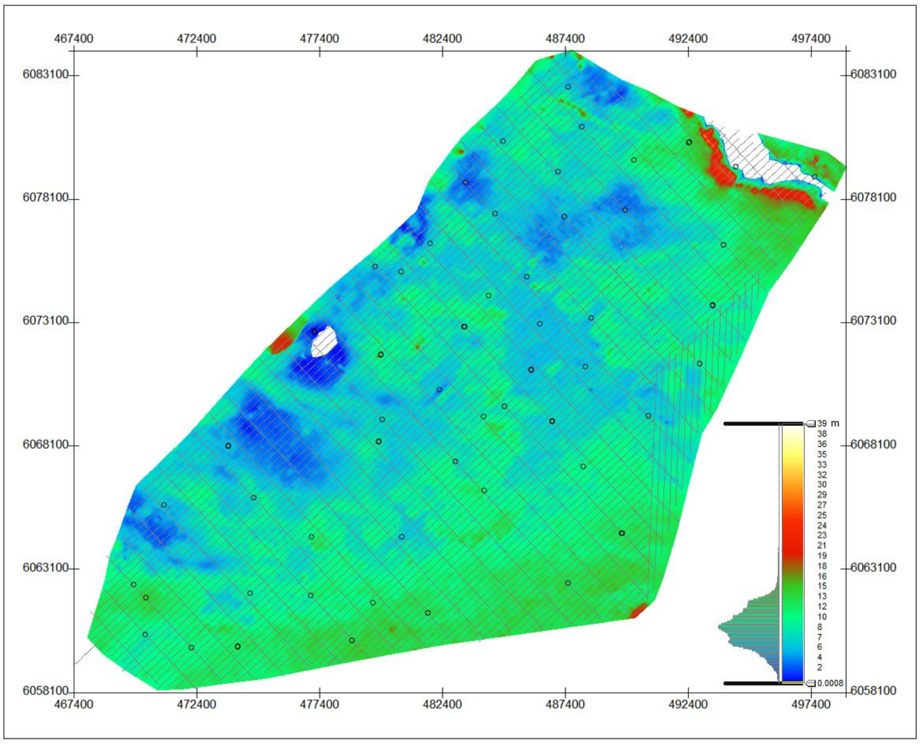


Figure 7-1 Isochore map of SU 1. The map represents a combined thickness of the soft organic rich clays (soil unit Ib) and soft loose sands (soil unit Ia) that are interbedded within SU 1. Grey lines represent the 2D UHRS survey lines. Black circles represent the location of the borehole and CPTs. Color scale shows thickness in meters (m).

7.3.1 Seismic definition – H00 and H25

The top of SU 1 is defined by horizon H00, which is the seabed and first seismic reflector. The seabed is generally a smooth surface throughout the entire survey site except in the north-eastern part of the survey area where a large dune like feature can be observed. No other major seabed features such as sand waves or ripples have been detected on the seismic data.

The base of the unit is defined by the H25 horizon which posed difficulties during the mapping. The best correlation between the geotechnical information and seismic data could be accomplished in the southern part of the site, where a laminated package of varved clays can be observed in the seismic data at the base of soft sediment deposits (Figure 7-2). The extent of the mapped H25 based on a successful correlation between the geotechnical information and seismic data can be seen in Figure 7-3.

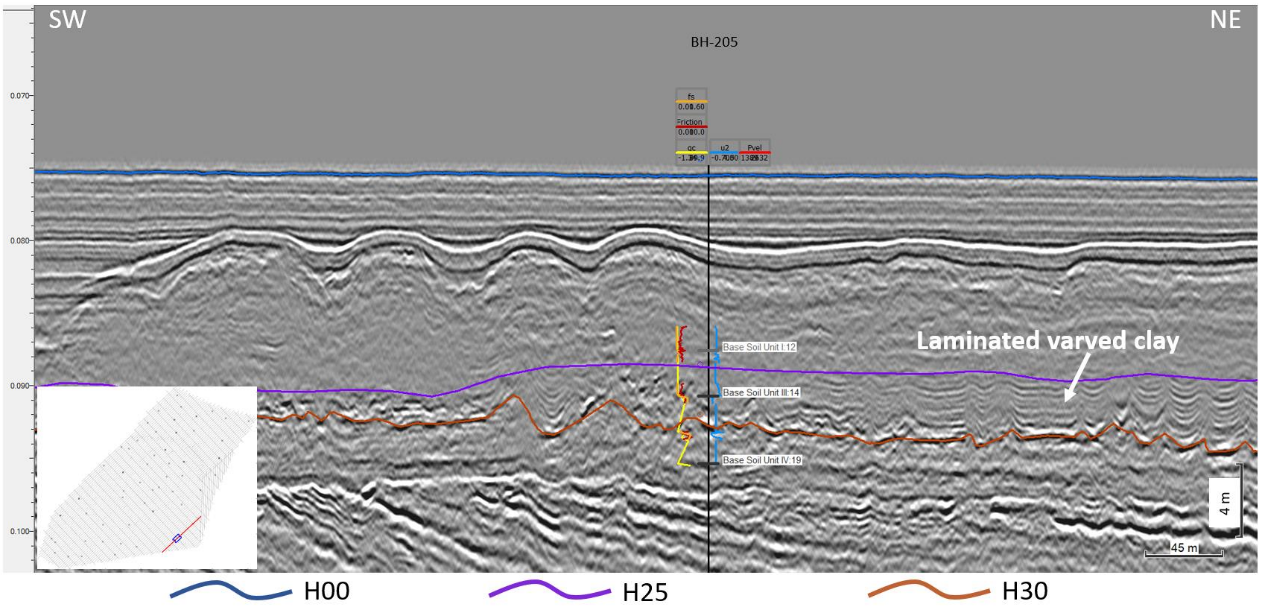


Figure 7-2 Inline BH2_G05_P_061 illustrating the mapped base of soft sediments (marked by H25) above laminated varved clay package in the southern part of the site.

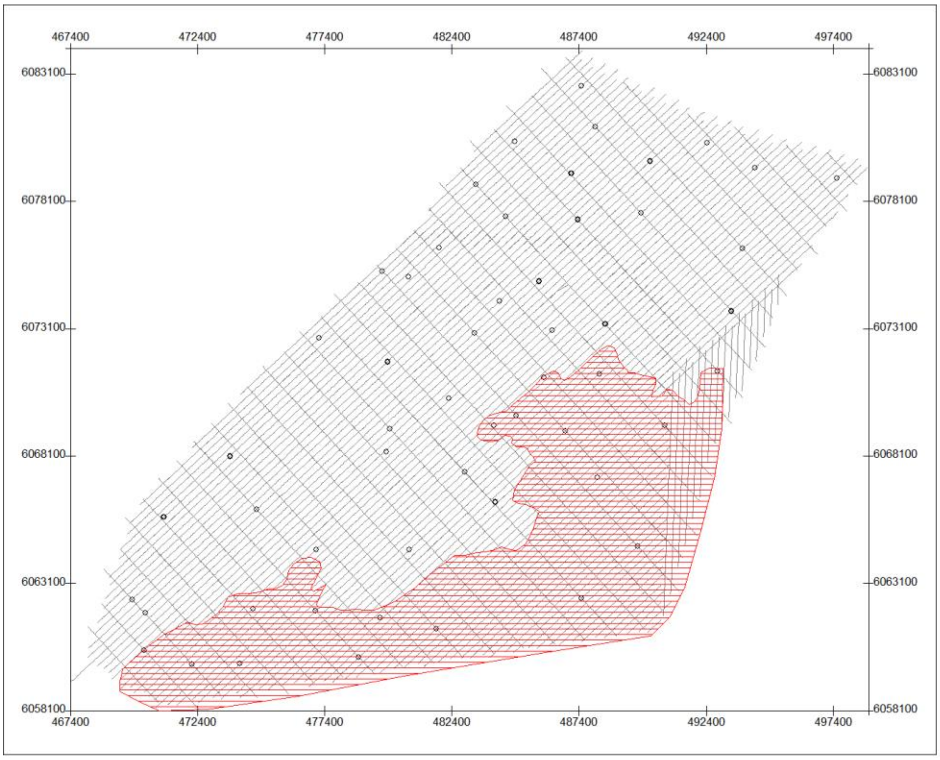


Figure 7-3 Overview map illustrating the extent of H25 which was mapped (marked by the red polygon) in the southern part of the site, based on the seismic data.

As the thickness of soil unit II and III which has been merged together into one unit, often has a relatively little thickness it was decided that the base of this unit, marked by H30 horizon, could be used to define the base of soft sediments in areas where soil unit II and III have a thickness below 3 m. Figure 7-4 illustrates a CPT where a thin thickness of soil unit III was seen and therefore merged into the soft sediment unit.

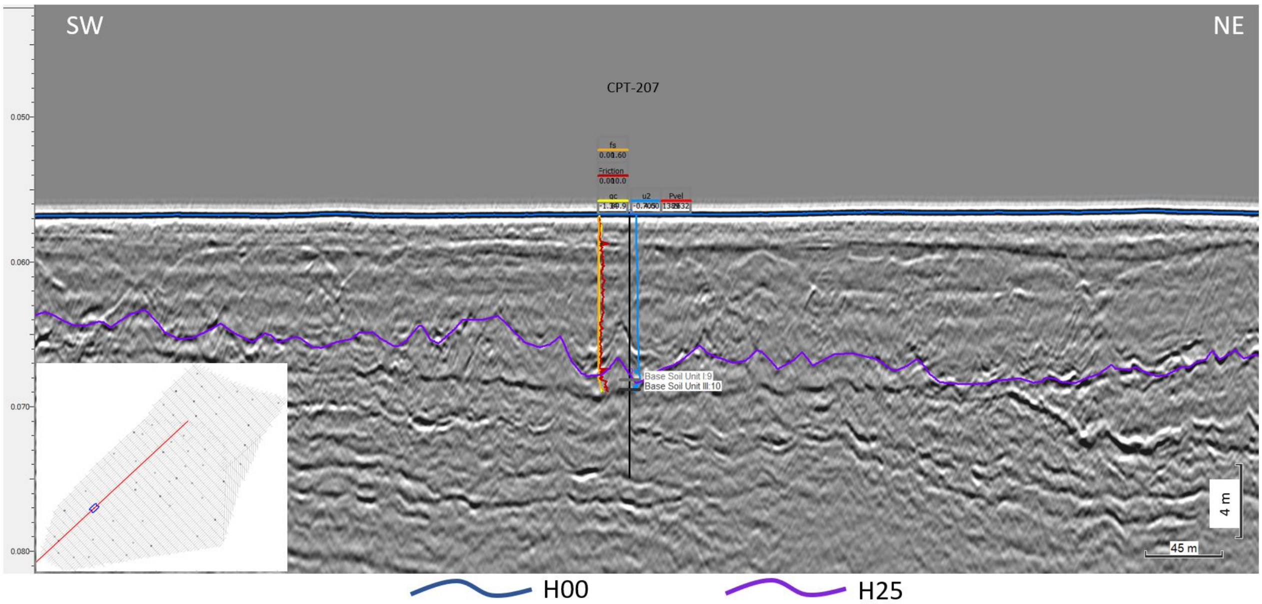


Figure 7-4 Inline BH2_G05_P_016 illustrating that soil unit III has a thickness below 1 m for CPT-207. Therefore, the unit has been included within the soft sediment (SU 1) interpretation marked by the H25 horizon.

Lastly there were eight local areas throughout the site (Figure 7-5), where neither of the two previously mentioned approaches could be used. Therefore, an interpolated grid created between the formation tops within borehole and CPTs was used to define the base of soft sediment deposits. An example of a borehole where the interpolated approach was used is illustrated in Figure 7-6. The figure shows that the H30 interpretation has been mapped approximately 5 m below the soft sediment marker and this was deemed too high of an uncertainty to include. Therefore, the interpolated grid was used instead to mark the base of soft sediments (soil unit I).

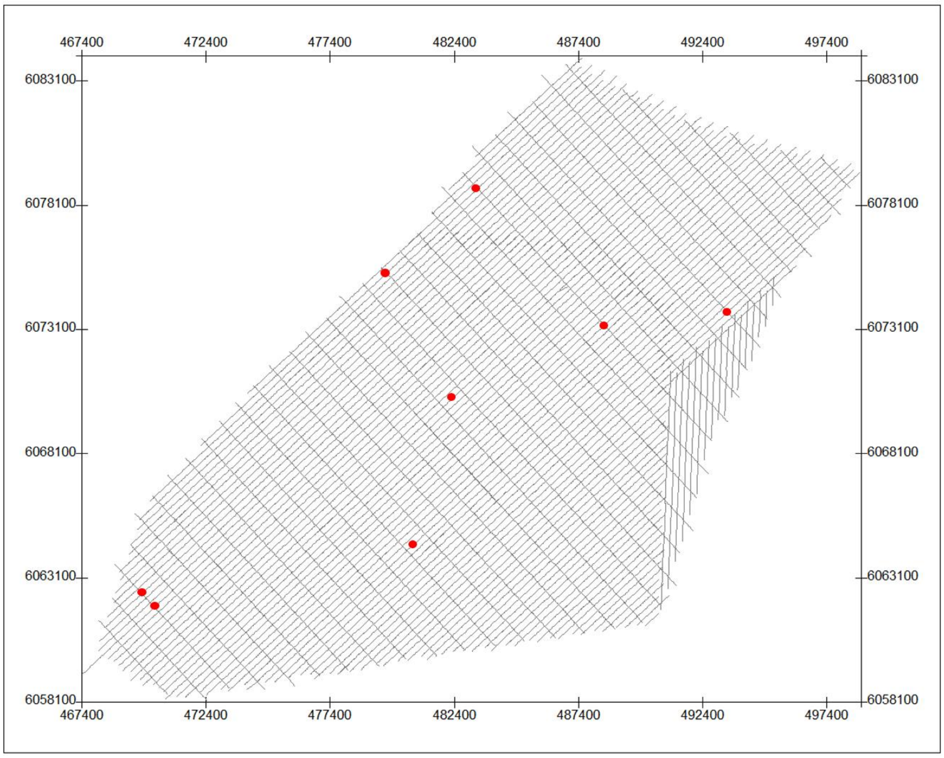


Figure 7-5 Overview map of the eight local sites (marked by red circles) where an interpolated grid between borehole and CPTs was used to guide the interpretation for base of soft sediments. These eight local sites are: BH-217, BH-216, CPT-251, BH-214, CPT-239, CPT-233, CPT-221 and BH-201.

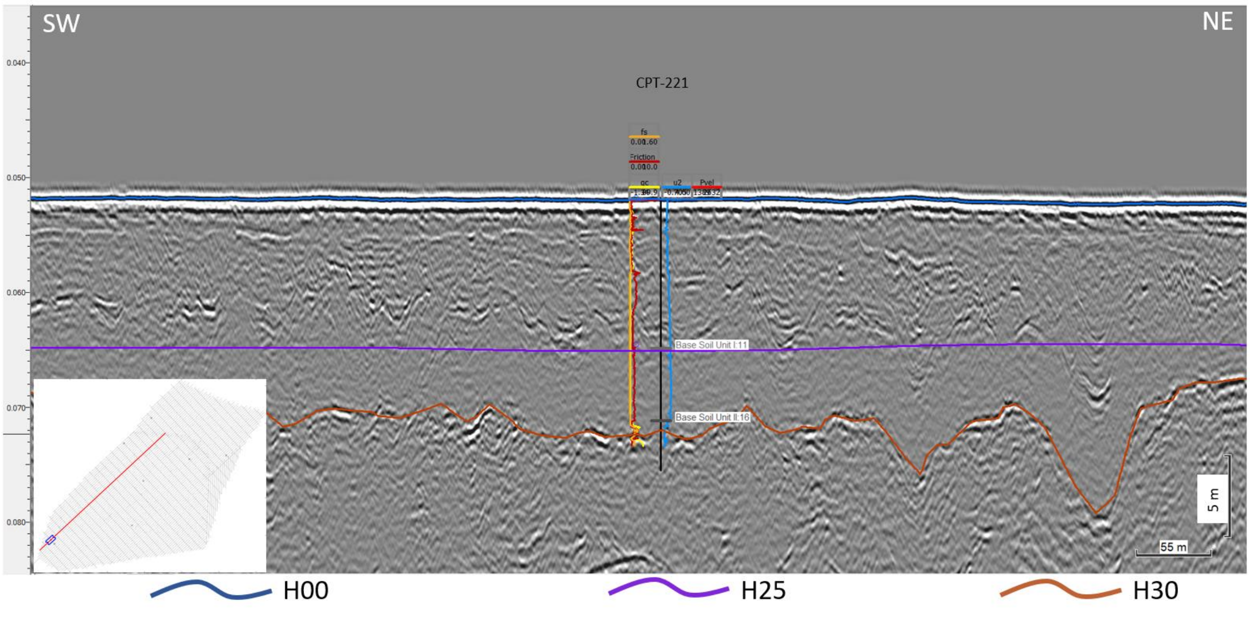


Figure 7-6 Inline BH2_G05_P_013 illustrating the south-western part of the site, where an interpolated grid between boreholes was used to guide the base of soft sediment interpretation (purple, H25 horizon) as the thickness of soil unit III exceeded 3 m.

7.3.2 Internal Seismic Characteristics

The upper parts of SU 1 show a low amplitude parallel lamination that becomes stronger with depth. Very low amplitude reflectors may suggest that this unit has an acoustic impedance closer to that of seawater rather than other geological units. Thus, indicating that it is very soft/weak. The lower part of SU 1 shows homogenous seismic facies (below H20_i) as shown on Figure 7-7. Thickness of the upper well laminated part of SU 1 is larger in the south-eastern part of the site.

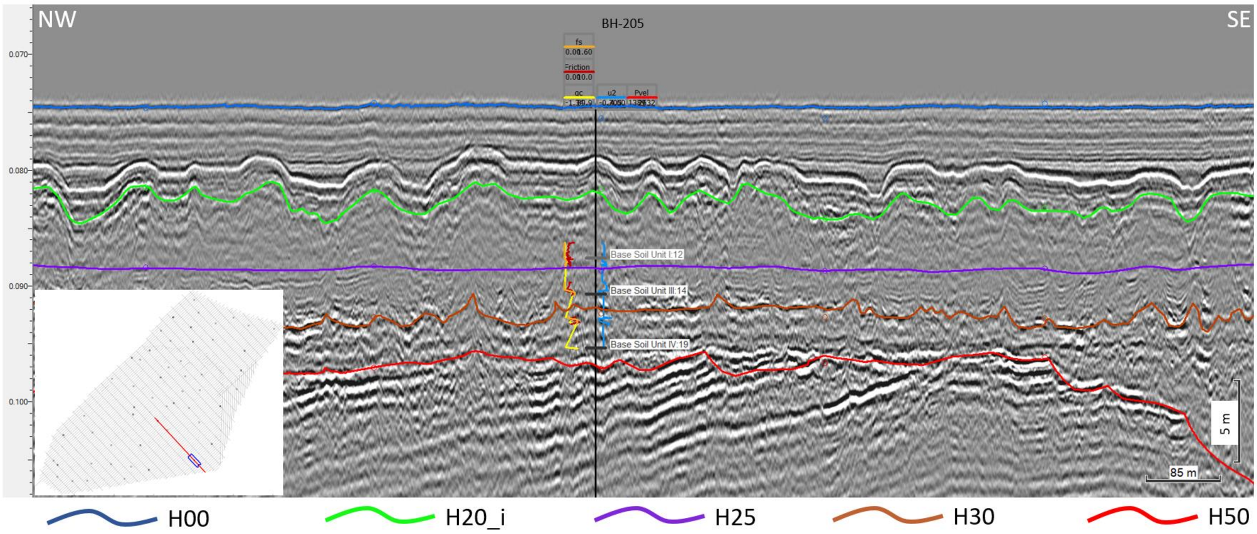


Figure 7-7 Crossline BH2_G05_P_059_A illustrating the interpreted horizons and BH-205. The base of SU 1 is marked by H25 and a shift in seismic facies is marked with H20_i. Formation tops in BH-205 illustrate the base of soil units. The upper part of SU 1 has clear horizontal laminations.

7.3.3 Sedimentology and Geotechnical Characteristics

SU 1 comprises both loose sand (soil unit Ia) and soft, organic rich clays (soil unit Ib) in the upper part. Near the base of this unit stiffer clays (soil unit II and III) can potentially be encountered at the base. Packages of soil unit Ia and soil unit Ib are interbedded and often no seismic data can be used to map the units separately (Figure 7-8). Therefore, the two soft sediment units have been merged into a single seismic unit. There is however a general increase in the volume of the soft organic rich clays and gyttja towards the south-east.

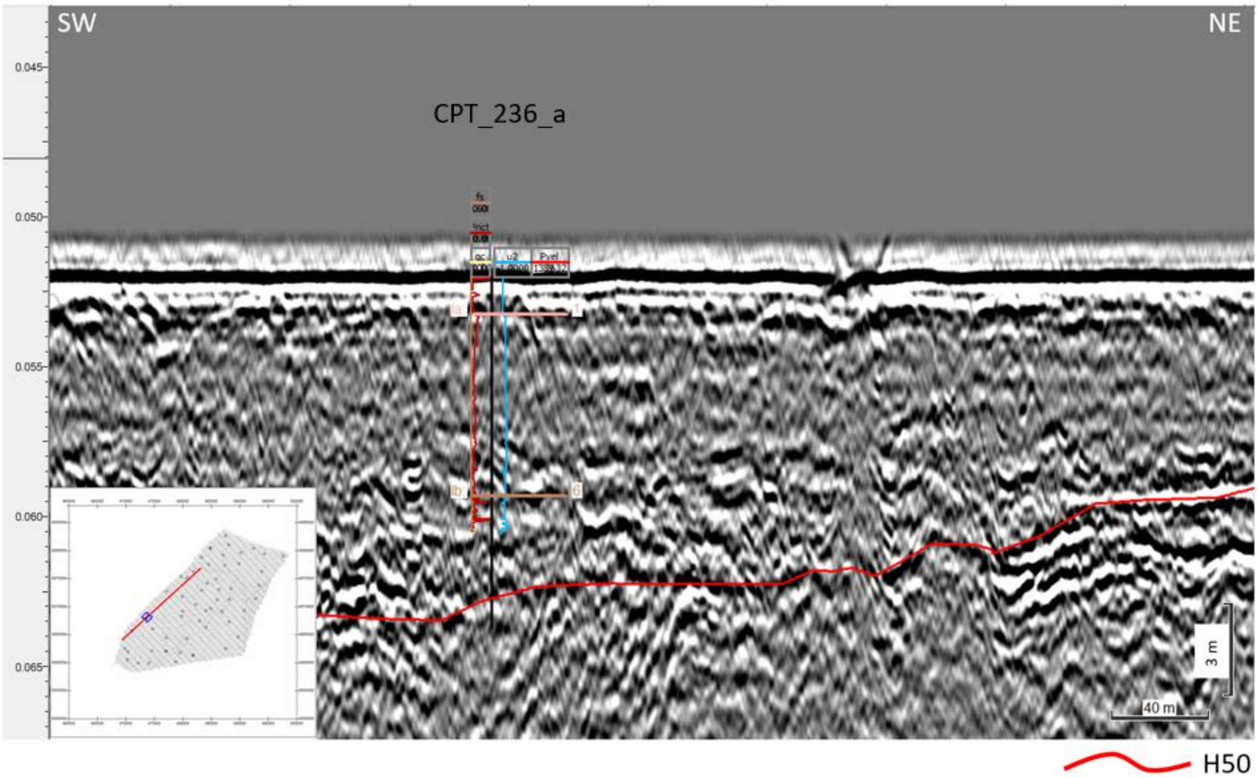


Figure 7-8 An inline BH2_G05_P_007_Q with CPT-236 and the bases of the interpreted soil units. The figure illustrates that a subdivision between the soft units Ia and Ib (the geotechnical boundary is marked with Ia) was not possible on the seismic data as no distinct seismic reflector could be mapped between the two units.

SU 1 represents the post-glacial transition clay and post-glacial marine sediments at the upper part, along with recent Holocene deposits according to (GEUS, 2021). The upper part was deposited during the Littorina Sea stage, the Ancylus Lake stage, the Yoldia Sea stages and last part of the Baltic Ice Lake stage. The base of the unit can represent glaciolacustrine sediments deposited as depositional environment in the area shifted from glacial to glaciolacustrine (Baltic Ice Lake) as the Weichselian glacier retreated (GEUS, 2021). The clay in the base of the unit is generally of very high strength or becoming high strength with increasing depth.

7.3.4 Internal Horizon (H10_i)

Horizon H10_i mapped by survey contractor was not incorporated in the Ground Model by Ramboll as it does not represent a relevant geotechnical boundary, as concluded by the geotechnical team. According to GEOxyz (GEOxyz, 2022) horizon H10_i was defined in the SBP data as a base of a section composed of laminated clay with increasing silt/sand fraction (Figure 7-9). Potentially, this seismic event may represent the shift in sediment deposits from the Yoldia Sea into the Ancylus Lake. During the deposition of these sediments the area experienced calm lake sedimentation. In other areas the seismic event can be identified on seismic data, but the lamination representing the calm lake sedimentation is not clearly seen.

After additional investigation, comparing the borehole descriptions with the mapped horizons it was determined that the base of gyttja deposits follow the H10_i interpretation more accurately within the seismic. Therefore, it is thought that H10_i can potentially represent the base of gyttja formation. Based on the geotechnical interpretations, gyttja formations constituting an integral component of the organic and soft material within Soil Unit Ib.

7.3.5 Internal Horizon (H20_i)

Horizon H20_i was provided within the SBP data to Ramboll (Figure 7-9) but was not originally mapped on the UHRS data. It was decided that the horizon was of potential relevance as clear seismic facies could be seen within the seismic data. H20_i has been mapped as a soft seismic reflection below clearly laminated deposits (Figure 7-7).

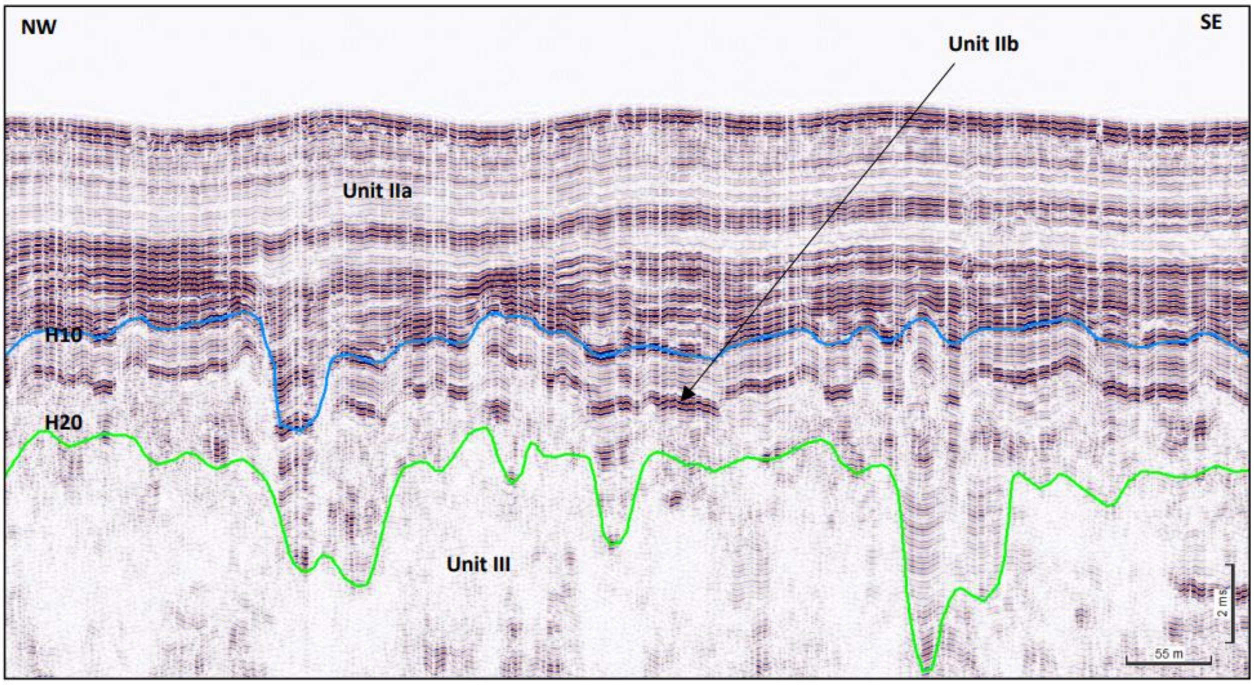


Figure 7-9 Line X_015 in SBP data illustrating the mapped H10_i and H20_i (Energinet, Geophysical Survey Report BHII - Work Package A, 2022).

7.4 SU 2

SU 2 is a very thin unit within the model as it is defined by H25 at the top and H30 at its base. The unit is composed of transitional (soil unit II) to stiff clays (soil unit III). Due to the varying mapping approaches done for SU 1, the thickness of SU 2 has some uncertainty as small thicknesses below 3 m have been included into SU 1. Therefore, the distribution of the unit is also relatively sparse as many parts are not represented by this unit.

The thickness of SU 2 is largest in a paleovalley system in the south-western part of the site where it reaches up to 37 m (Figure 7-10). Otherwise, the unit has generally thickness between 0 – 5 m throughout the site.

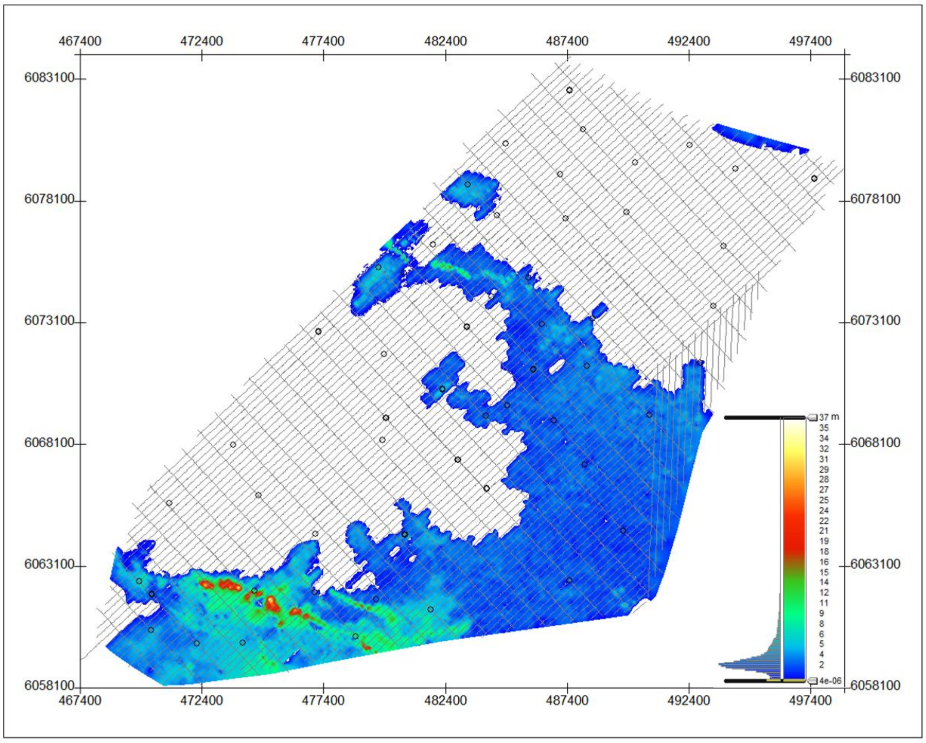


Figure 7-10 Isochore map of SU 2. The map represents a combined thickness of the transitional clays (soil unit II) and stiff clays (soil unit III) that are within SU 2. Grey lines represent the 2D UHRS survey lines. Black circles represent the location of the borehole and CPTs. Color scale shows thickness in meters (m).

7.4.1 Seismic definition

Mapping approaches done for H25, which defines the top of SU 2 are explained in section 6.1. The base of the unit is defined by the highly irregular H30 which was mapped on a hard seismic event (amplitude peak) beneath hummocky features (Figure 7-11) encountered in the site, but the seismic event was often laterally discontinuous.

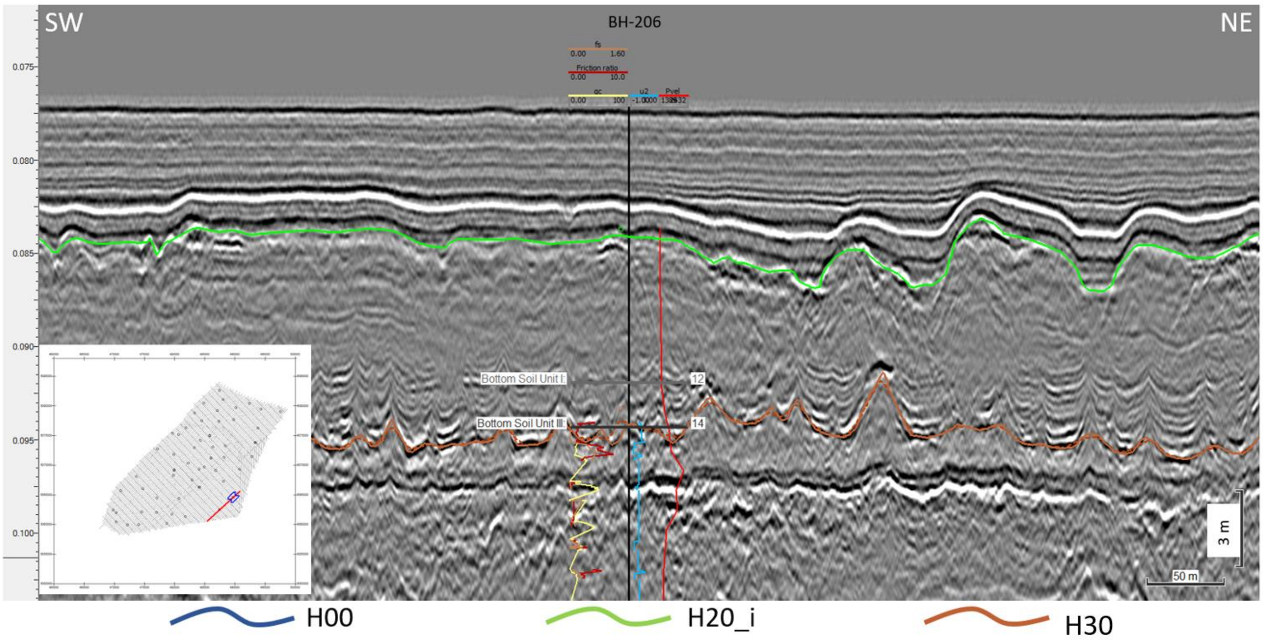


Figure 7-11 Inline BH2_G05_P_061 with BH-206 showing a good correlation between the base of SU 2, marked by the H30 horizon, and the base of soil unit III. Formation tops represent base of soil units.

7.4.2 Internal Seismic Characteristics

As the unit SU2 is generally very thin ranging from 0 – 5 m, the internal seismic characteristics are very limited. However, very distorted lamination package of rhythmically layered clay sediments of three to four high amplitude reflections, can be observed within the unit above the hummocky features in parts of the site (Figure 7-7). The hummocky feature marks the last of the ice-sheet influenced sediments. These are onlapped and draped by the Baltic Lake succession, so they mark the transition from glacial to post glacial, lacustrine sediments.

7.4.3 Sedimentology and Geotechnical Characteristics

H30 horizon marks the base of the unit and has successfully been correlated with the base of either soil unit II or soil unit III within the site. The unit represents transitional to stiff clays increasing their strength with the depth.

7.5 SU 3

SU 3 is the thickest of the seismic units depicted in this area. Where H30 represents the top of SU 3, but in a local site in the north-central part of the site, when this horizon is absent the top of SU 3 is represented by the seabed reflector (H00). The base of SU 3 is defined by horizon H50.

The thickness of SU 3 is largest in the central part of the site in a NW – SE orientation and some local sites in the south and north, where it reaches a thickness of 104 m (Figure 7-12). Otherwise, the unit generally has a thickness between 0 – 40 m throughout the site. SU 3 buries the topography of the underlying bedrock, together with presence of channels it results in dramatically variating thicknesses.

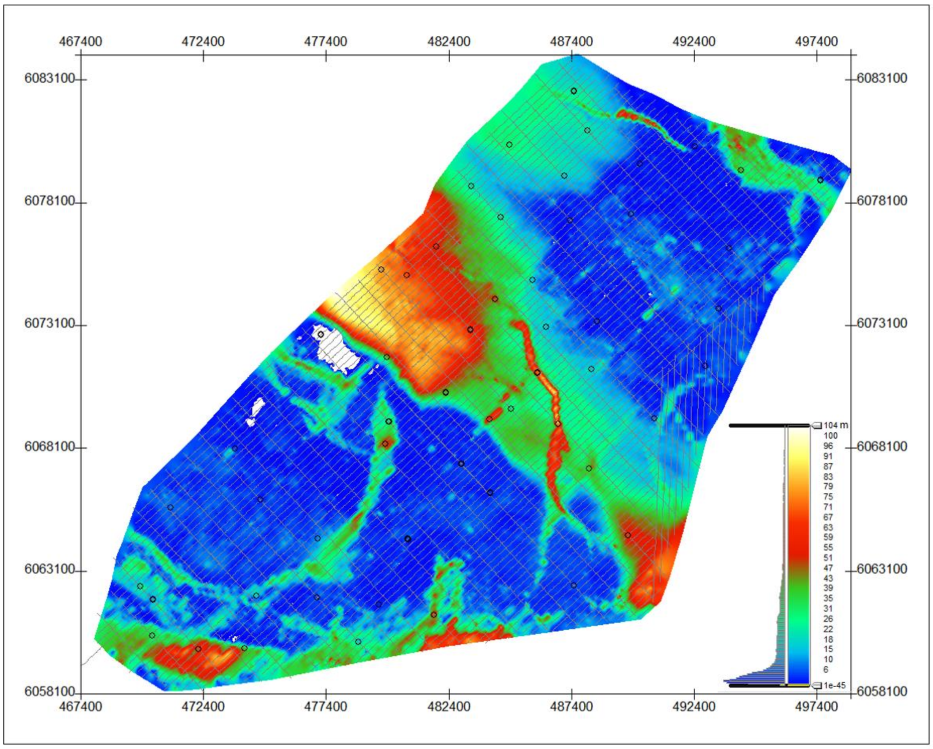


Figure 7-12 Isochore map of SU 3. The map represents a combined thickness of the dense sand (soil unit IVa) and clay till (soil unit IVb) that are within SU 3. Grey lines represent the 2D UHRS survey lines. Black circles represent the location of the borehole and CPTs. Color scale shows thickness in meters (m).

7.5.1 Seismic definition

Ramboll has remapped the seismic horizon H30 in large parts of the site. The seismic horizon H50 is also one of the most important horizons as it not only represents the base of SU 3 and therefore base of soil units IVa and IVb, but also the top of soil unit V (bedrock). H50 was also remapped by Ramboll in large parts of the site and is examined in more detail in section 7.6.1.

H40_i represents base of paleovalley systems mapped within SU 3, the horizon H45_i has been correlated with the geotechnical information and is interpreted to represent a distinct sand succession within the SU 3.

7.5.2 Internal Seismic Characteristics

Generally, the SU 3 shows a homogeneous, seismically transparent seismic facies. A distinct soft seismic event is seen in the central part of the site where the thickness of the unit is thickest. This soft seismic event was mapped as horizon H45_i and is described with more details in the section 7.5.5. SU 3 can be characterized by presence of pronounced paleovalley systems developed during the last glacial event. Along the channel axis, SU 3 can therefore reach significant thicknesses. H40_i marks the base of the paleovalley system which is described further in section 7.5.4. In the central part of the site the unit is relatively thin due to presence of bedrock at shallow depths.

7.5.3 Sedimentology and Geotechnical Characteristics

SU 3 is comprised of alternating layers of soil unit IVa (dense sand) and IVb (clay till). Therefore, it proved difficult to map these soil units separately based on the seismic data. Generally, soil unit IVa is found above soil unit IVb.

Figure 7-13 shows BH-210 with a seismic line from the central part of the site where SU 3 has the largest thickness. Here the main sediment type comprising SU 3 is dense sand (soil unit IVa). Figure 7-14 shows BH-202 located in the southern part of the site where SU 3 deposits consist of both dense sand (soil unit IVa) and clay till (soil unit IVb).

SU 3 represents glacial sediments which were deposited and reworked several times during the last glacial event. As the ice eventually started to melt large quantities of outwash sand were deposited across the site. Soil unit IVa is interpreted to represent packages of outwash sands deposited on top of glacial tills. The thickness of till is relatively low towards the northern part of the site which suggests that it has been eroded before the deposition of outwash sands. The observed hummocky features likely represent field of moraine deposits after the gradual retreat of the last glacial maxima (LGM) ice sheet.

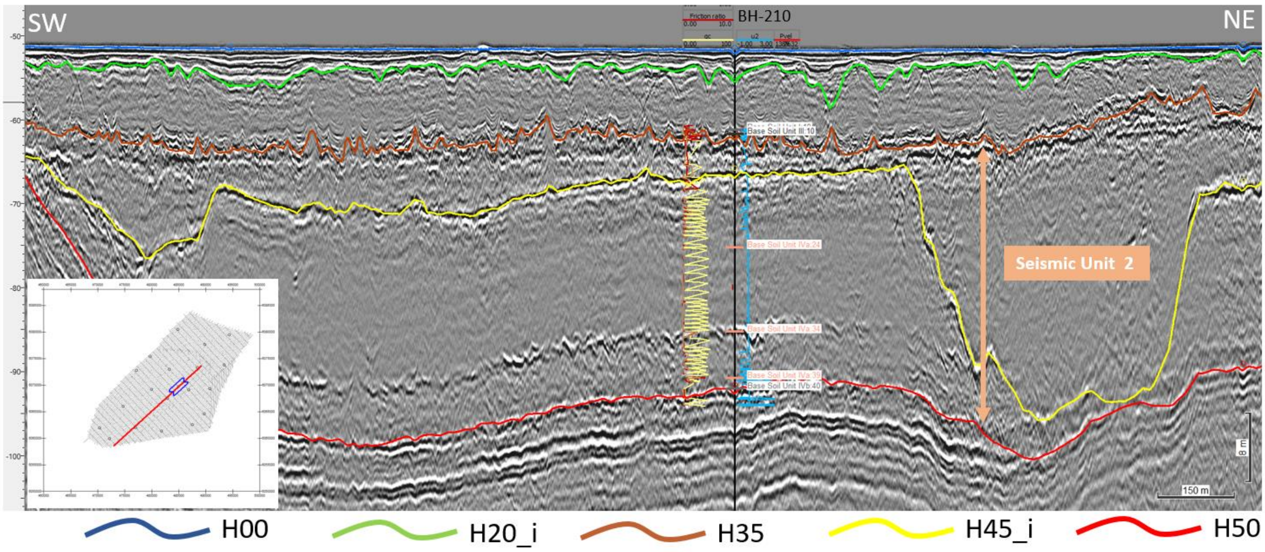


Figure 7-13 Inline BH2_G05_P_033_A showing BH-210 with the base of the interpreted soil units displayed. The figure shows that the SU 2 (defined between H30 and H50) comprises mainly of soil unit IVa. Note: Label "Base Soil Unit III" covers the label for "Base Soil Unit Ib". Soil unit III has a very thin thickness in BH-210.

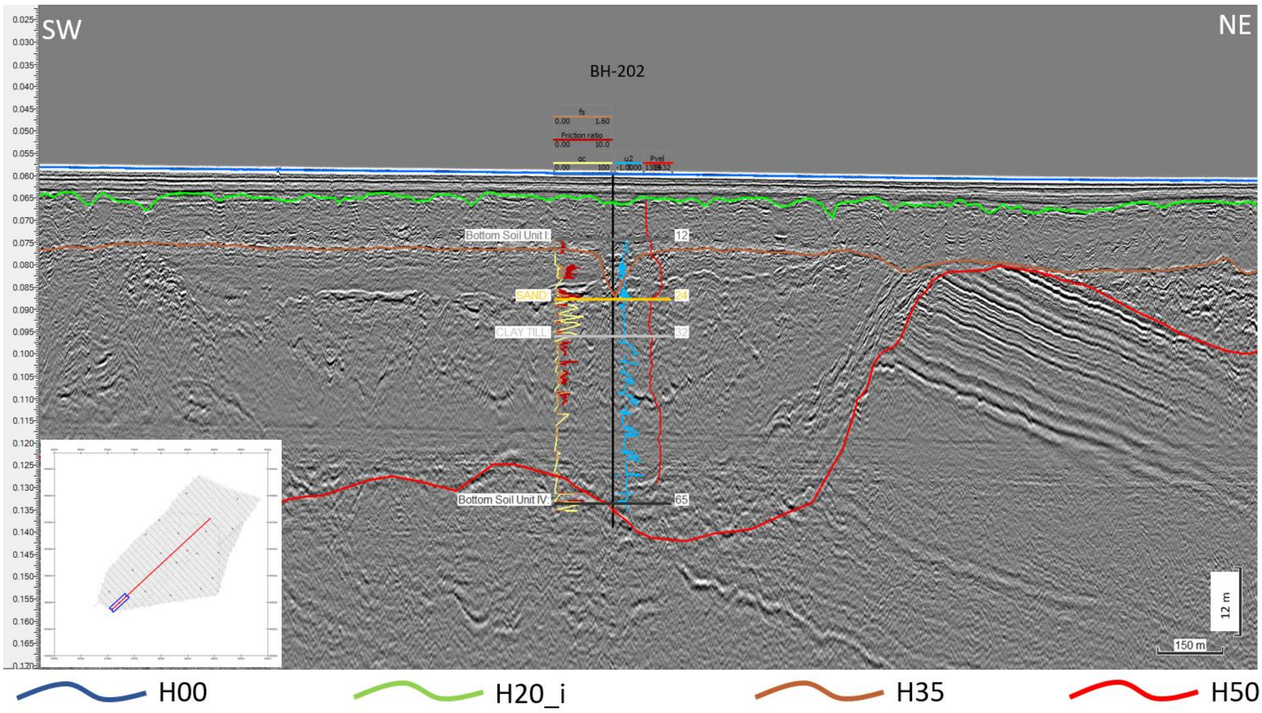


Figure 7-14 Inline BH2_G05_P_027 showing BH-202 with the base of the interpreted soil type displayed, showing that in the southern part of the site, SU 2 comprises sand (soil unit IVa) in the upper part and clay till (soil unit IVb) in the lower part. Formation top representing the sand and clay till are showing the top of these deposits.

7.5.4 Internal horizon H40_i

Horizon H40_i was mapped in the 2D UHRS data by Ramboll as a structural feature horizon. The survey site is heavily influenced by channel and paleovalley systems developed as a result of the glacial retreat. Detailed mapping of the channels and glacial paleovalleys is essential to the OWF site and therefore H40_i horizon represents the base of paleovalley systems observed across the site.

Figure 7-15 shows a depth below seabed for the H40_i gridded horizon. Depths are varying from 0 to 97 m below seabed. The figure shows also that the presence of H40_i is limited to the central part of the site and has a NW – SE orientation. H40_i is also present within a relatively small area in the northern end of the site. The paleovalley system has not been observed on the seismic data in the south-western part of the site due to presence of the Kolobrezeg Graben (Figure 5-7). At the area of Kolobrzeg Graben the bedrock becomes extremely shallow (it can be found as shallow as 1 m below the seafloor). This most likely prevented formation of pronounced channels, although paleovalley systems are also observed to cut down into the bedrock (Figure 7-16).

The base of paleovalley system marked by H40_i vary in depths. The mapping of paleovalleys is less straightforward in the northern part of the site due to lower quality of seismic data, hence the uncertainty is higher in that part of the site.

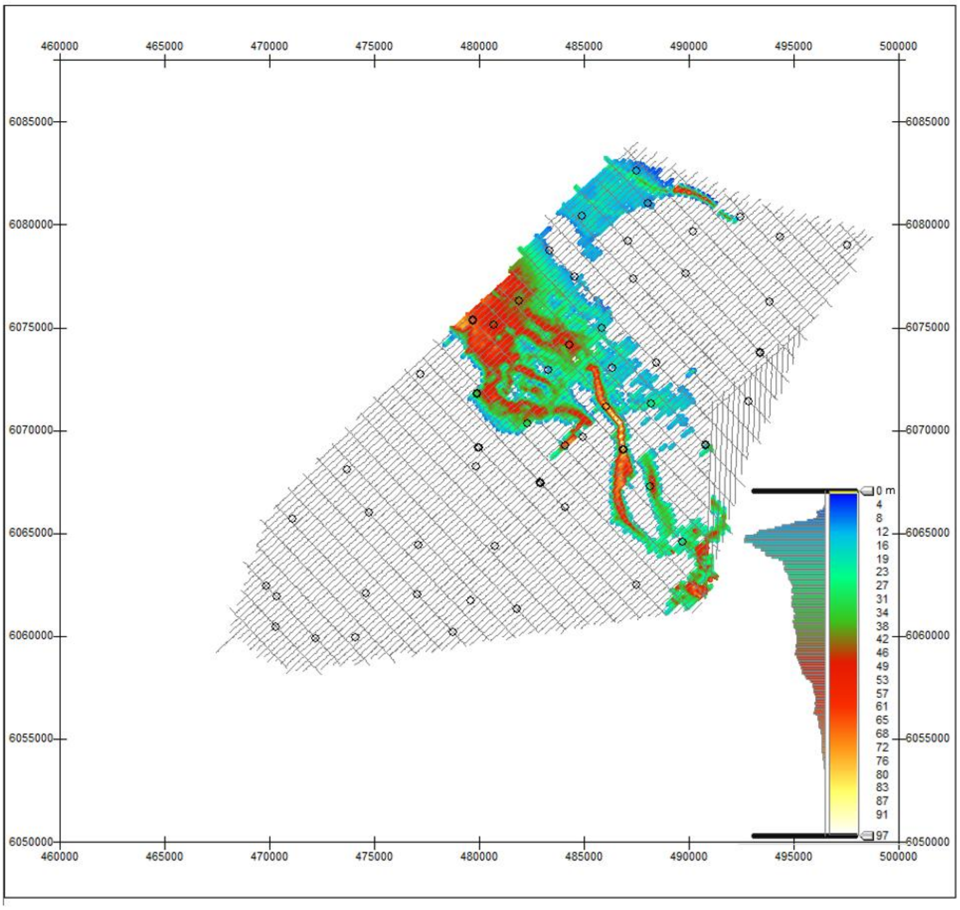


Figure 7-15 Depth below seabed map for H40_i. Grey lines represent the 2D UHRS survey lines. Black circles represent the location of the borehole and CPTs. Colorscale is depth below seabed in meters (m).

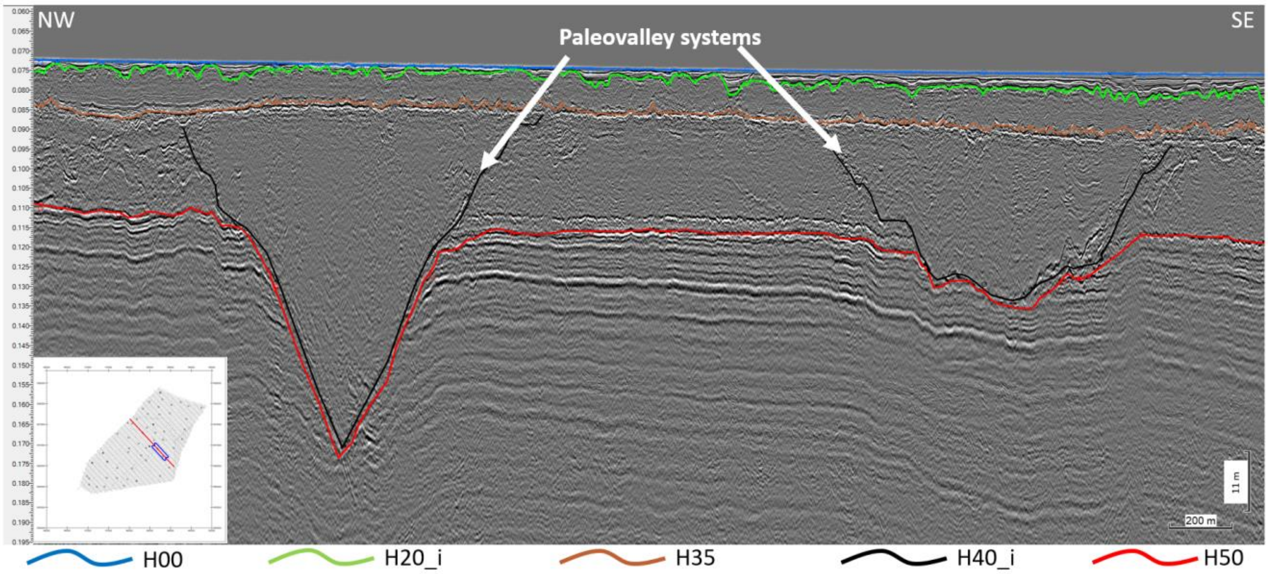


Figure 7-16 Crossline BH2_GO5_X_020_A illustrating the mapped paleovalley systems in the site.

7.5.5 Internal horizon H45_i

The seismic horizon H45_i was mapped in the 2D UHRS data by Ramboll as it represents distinct seismic reflector. It has been mapped relatively locally with a similar distribution as seen for H40_i showing a general NW – SE orientation in the central part (Figure 7-17). H45_i was picked as a very soft reflector, as shown on Figure 7-18. The distinct soft event has been interpreted to represent a sand succession within the glacial deposits. This interpretation is supported by the geotechnical data (Figure 7-19). The horizon has depth below seabed between 7 - 62 m.

At selected areas the seismic data has lower quality making the mapping of H45_i difficult and therefore the interpretation less confident. Moreover, numerous paleovalley systems found in those areas made the distinction between H40_i and H45_i difficult. It was therefore decided to map the H45_i horizon only within areas where the corresponding seismic reflector could have been mapped with certainty.

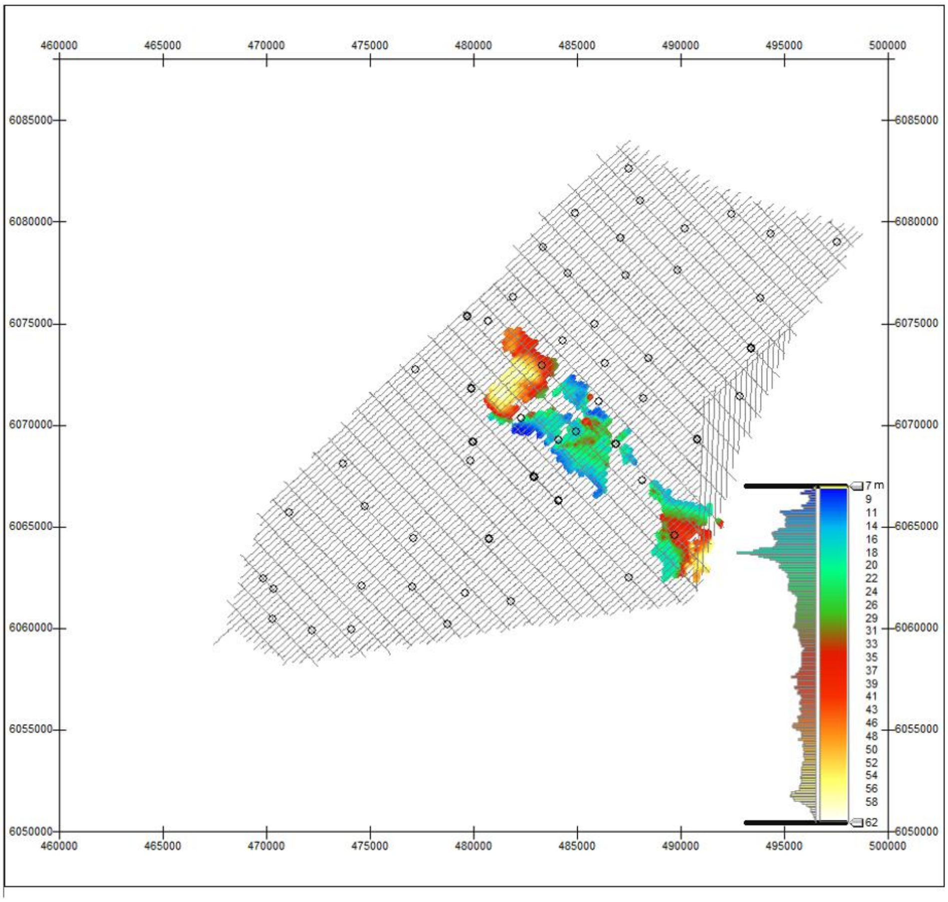


Figure 7-17 Depth below seabed map of H45_i. Grey lines represent the 2D UHRS survey lines. Black circles represent the location of the borehole and CPTs. Colorscale is depth below seabed in meters (m).

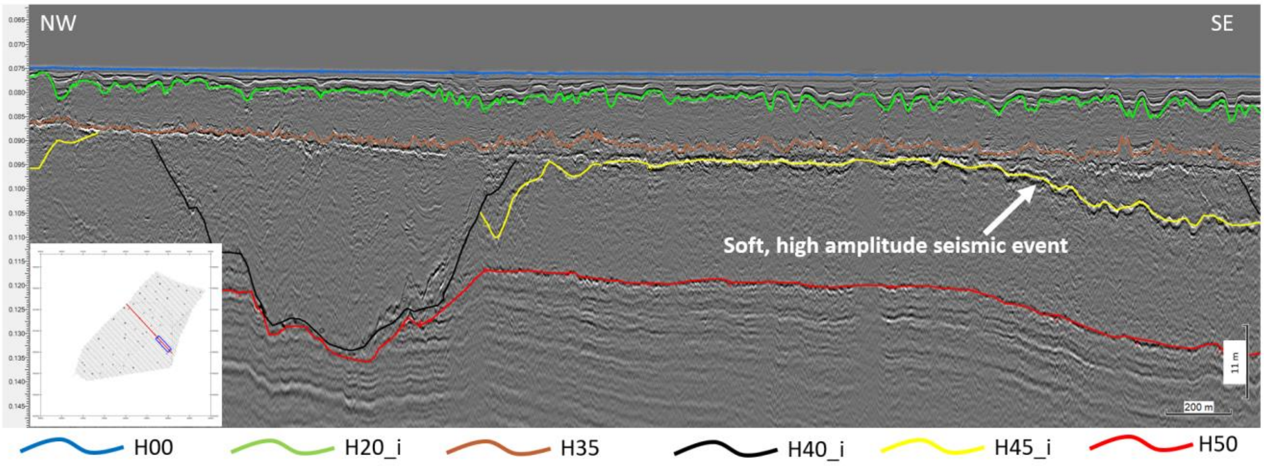


Figure 7-18 Crossline BH2_GO5_X_020_A illustrating the mapped H45_i on a very distinct soft, high amplitude seismic event. The mapped paleovalley cuts into the bedrock.

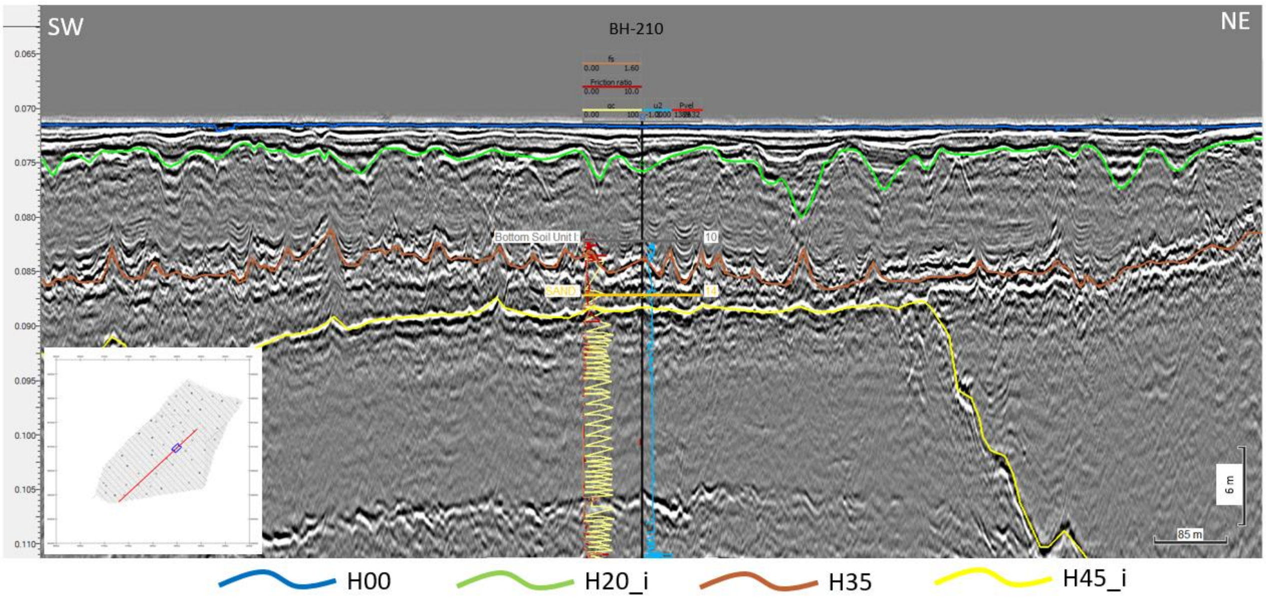


Figure 7-19 Inline BH2_G05_P_033_A illustrating BH-210 on the seismic data in time domain. The top of a sand package belonging to soil unit IV is shown. The top of this package correlates relatively well to the soft reflector H45_i mapped through the site.

7.6 SU 4

SU 4 is the deepest defined unit within the site. Its top is defined by the horizon H50 throughout the entire site. The base of the unit is not determined as it exceeds depths depicted on the seismic data. SU 4 comprises the bedrock which has a complex character with different rock types described from boreholes across the area (see section 8.6 below and Table 8.22). The most typically encountered bedrock type is limestone/mudstone. However, sandstone and chalk has also been encountered.

Figure 7-20 shows the depth below seabed map for top bedrock. In the "flat" areas the depth ranges from slightly above 0.05 m (very local) to 35 m, whereas maximum depths of up to 91 m are reached where channels are mapped.

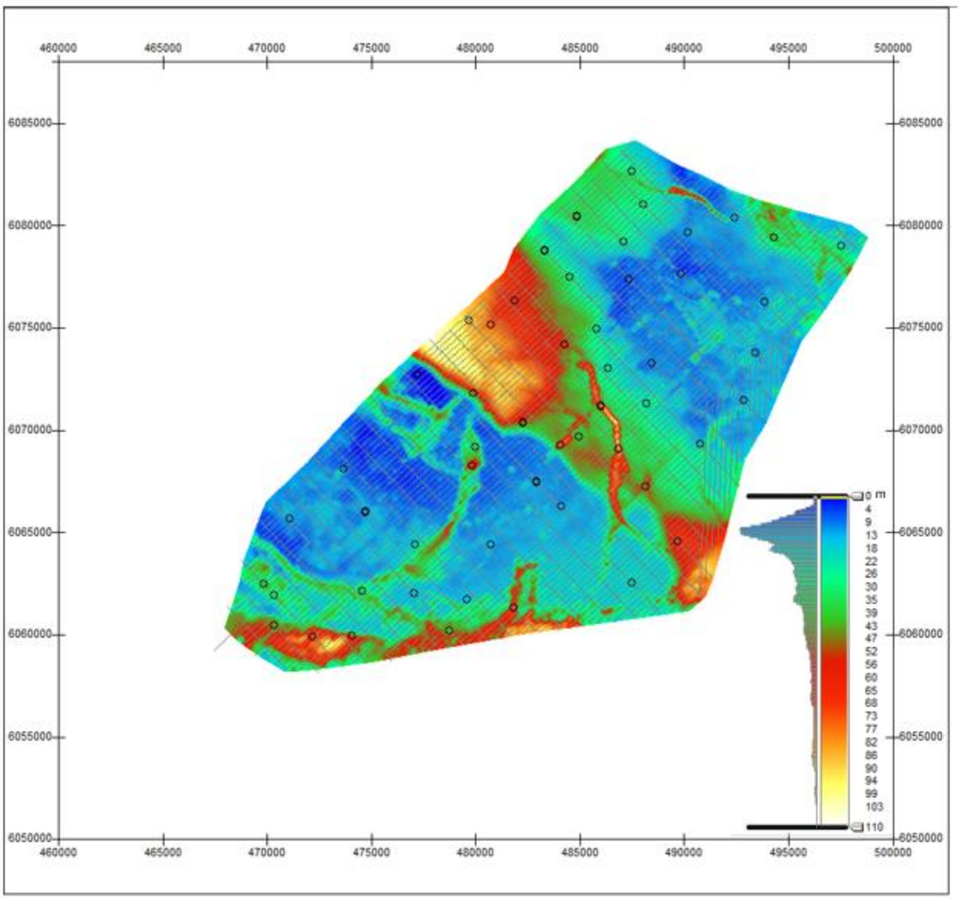


Figure 7-20 Depth below seabed map of top bedrock. Grey lines represent the 2D UHRS survey lines. Black circles represent the location of the borehole and CPTs. Colorscale is depth below seabed in meters (m).

7.6.1 Seismic definition

Figure 7-21 shows the depth below seabed for top bedrock interpretation carried out by GEOxyz compared to the interpretation updated by Ramboll. The maps were created by converting the data from time domain into depth domain in the established velocity model. The updated interpretation shows that at selected locations the top bedrock surface can be found at larger depths than originally interpreted (the elevation in areas where bedrock is deepest has been altered from 98 to 110 m). This is especially noticeable in the central part of the site, along a NW-SE running feature that can be correlated with the edge of Risebæk Graben (see Figure 5-7 and Figure 7-20).

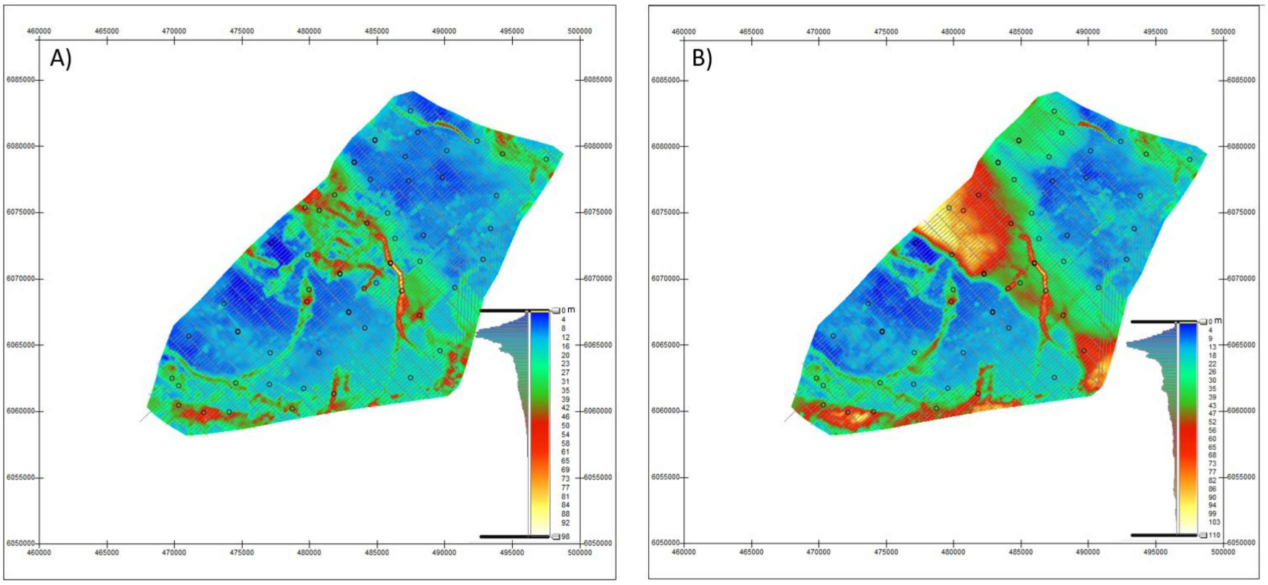


Figure 7-21 Depth below seabed for top bedrock. A) The mapped H50 (which represents the top bedrock) by GEOxyz; B) Remapped H50 by Ramboll. Grey lines represent the 2D UHRS survey lines. Black circles represent the location of the borehole and CPTs. Colorscale is depth below seabed in m.

This horizon has been mapped on a distinct reflector (generally high amplitude soft seismic event or locally as a hard seismic event) (Figure 7-22). The reflector correlates very well with top bedrock identified in the geotechnical data. In selected areas the horizon has been picked at the termination of dipping bedrock strata (Figure 7-23). The top of bedrock was mapped where the visible bedding terminates upwards.

One of the challenges while picking the top bedrock was related to the fact that the lithology of the sub-cropping bedrock is highly variable and thus has inhomogeneous seismic facies. However, it can be concluded that, with support from the geotechnical investigations (see more in section 7.6.3), the depth to the top bedrock was determined with a high degree of confidence.

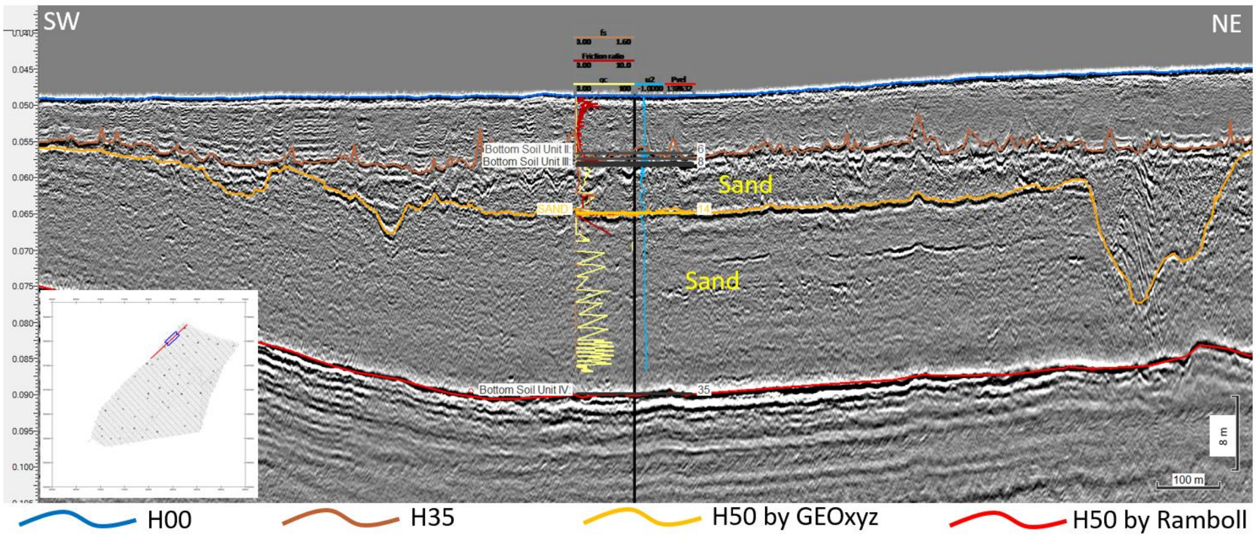


Figure 7-22 Inline BH2B_G05_P_004_V2 illustrating BH-218 the original H50 picked by GEOxyz and the updated version by Ramboll. The horizon H50 mapped by GEOxyz is interpreted as H40_i, an internal horizon within SU 3.

7.6.2 Internal Seismic Characteristics

The bedrock has been strongly deformed with a large-scale folds clearly visible (Figure 7-23). Generally, the bedrock is also easily distinguished by its closely laminated seismic facies.

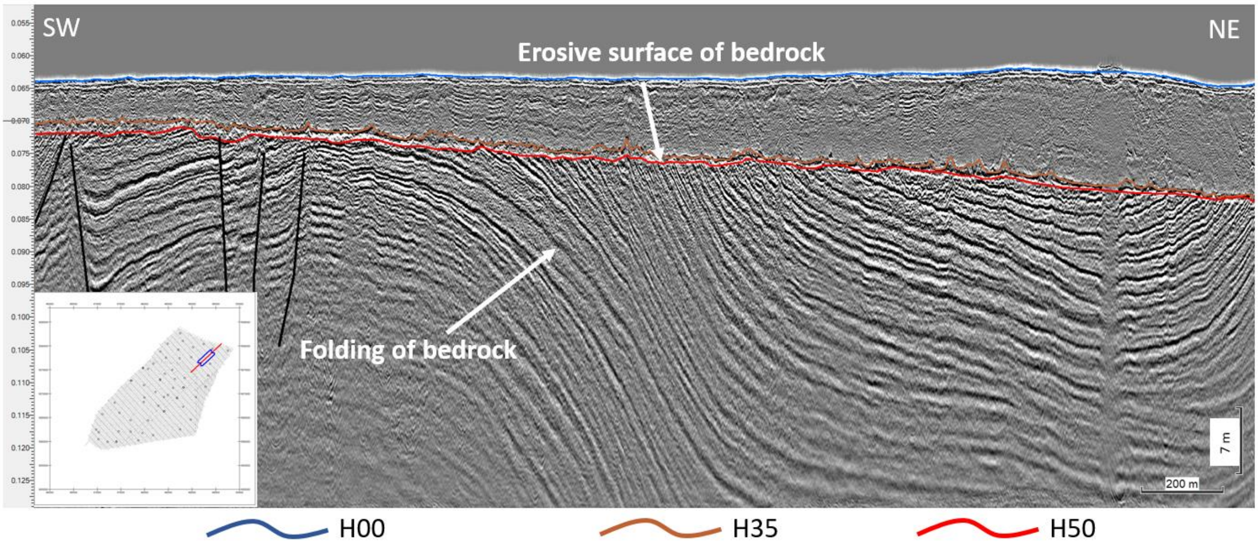


Figure 7-23 Inline BH2B_G05_P_035_V2 illustrating the pronounced folding of the bedrock along with a clear erosive surface.

7.6.3 Sedimentology and Geotechnical Characteristics

SU 3 represents the bedrock which varies in type throughout the site and is composed of Cretaceous and Jurassic rocks. Correlation between the seismic unit and the geotechnical soil units has been successful in 13 out of 20 boreholes at the site. The most typically encountered type of bedrock is limestone/mudstone (soil units Va1 and Va2) (Figure 7-13) but other types such as sandstone (Vc1 and Vc2) and chalk (Vb1 and Vb2) have also been encountered. Borehole BH-217 penetrated soft chalk (soil unit Vb1) and soft sandstone (soil unit Vc1) (Figure 7-24).

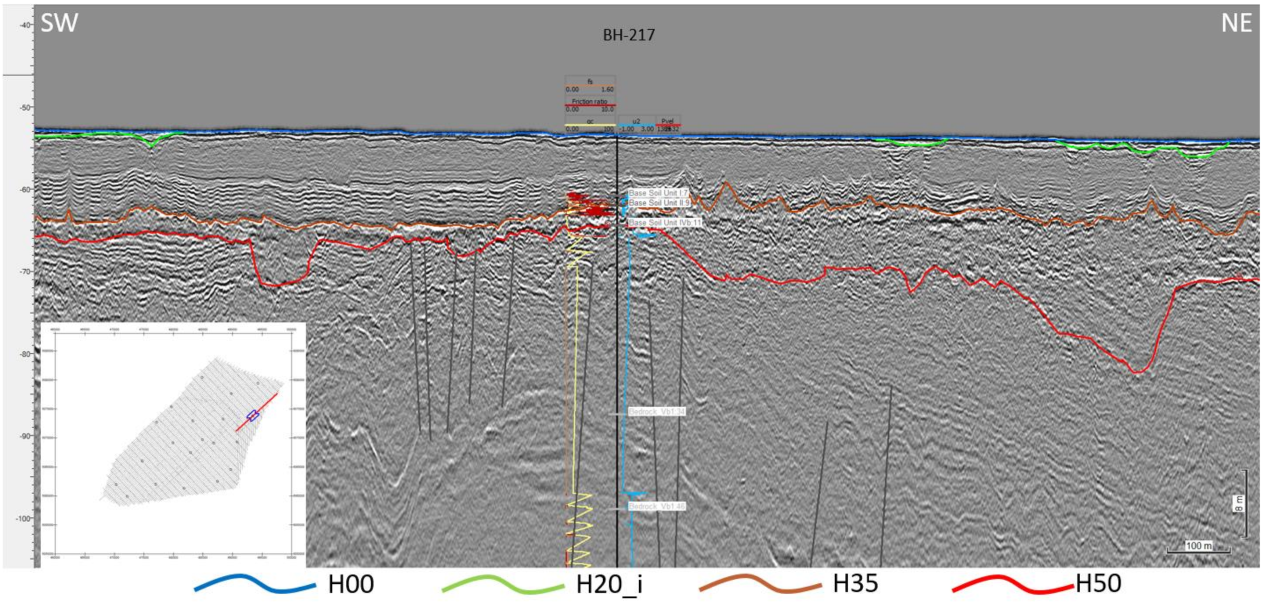


Figure 7-24 Inline BH2B_G05_P_047_V2 showing BH-217 with the interpreted geotechnical soil units. Numbers in the borehole show depth below seabed for the soil unit base. The figure shows the varying type of bedrock throughout the borehole: soft chalk (soil unit Vb1) and soft sandstone (soil unit Vc1) beneath. Faults interpreted by the survey contractor can be observed close to BH-217.

8. Geotechnical Interpretation

The evaluation of the geotechnical data to characterize the soils at the site and the layering of soil units at each geotechnical location is explained in this section. For each location, a definition of soil layers and stratigraphy based on CPT, borehole logs and laboratory data has been carried out. Moreover, a determination of the geotechnical properties has been done including the assessment of these propertied to each soil unit. The assessment of the ground model and the soil provinces throughout the entire site has been supported by the layering and soil characterization interpreted at survey locations.

8.1 Geotechnical data

A geotechnical site investigation was carried out by Gardline (Gardline, 2023) in the BH I and BH II OWF areas. A summary of the geotechnical investigation for Bornholm II is provided below in Table 8.1. A total number of 20 boreholes and 54 shallow CPTs were performed. The maximum depth of the boreholes is 71 m and the depth of the CPT is generally less than 5 m, and occasionally up to 20 m. The geotechnical interpretation is based on the final version 2 factual report (Gardline, 2023) which comprises both areas. The data from both sites is used to derive geotechnical parameters. The Soil Profiles and geotechnical sections only specific to the BH II area are presented in this report.

Table 8.1 Summary of geotechnical site investigation data at Bornholm II.

Location [-]	Maximum Depth [m]	North [m]	East [m]	Location [-]	Maximum Depth [m]	North [m]	East [m]
BH-201	70.23	6061941	470335.9	CPT-219	4.91	6077640	489833.7
BH-201_a	7.94	6061935.9	470341.3	CPT-219_a	4.48	6077645	489834.4
BH-202	66.59	6059907	472183.8	CPT-220	0.25	6079409.9	494318.4
BH-203	29.4	6062023.2	477039.6	CPT-220_a	0.32	6079414.8	494317.4
BH-204	17.39	6061314.8	481793.4	CPT-221	18.17	6062465.9	469832.5
BH-204_a	32.21	6061315	481798.1	CPT-222	15.31	6060454.8	470304.1
BH-204_b	69.74	6061309.9	481793.1	CPT-223	12.21	6059956.7	474063
BH-205	70.43	6062518.1	487496	CPT-223_a	0	6059945.9	474063.9
BH-205-a	9.92	6062516.5	487499.1	CPT-223_b	10.92	6059951.6	474068.9
BH-206	60.04	6064562.3	489703.8	CPT-225	9.54	6062099.9	474569
BH-207	69.15	6066001.2	474719	CPT-226	13.45	6060191.7	478728.1
BH-207_a	7.97	6065996.1	474713.9	CPT-227	12.59	6061735.1	479562.4
BH-208	18.97	6069164	479959.1	CPT-231	8.3	6065694.4	471064.1
BH-208_a	25.36	6069169.1	479954.2	CPT-231_a	8.26	6065689.3	471068.9
BH-208_b	70.11	6069165.6	479955.4	CPT-232	0.4	6064417.3	477073.5
BH-208_c	5.92	6069172.5	479962.8	CPT-232_a	0.41	6064421.4	477073.7
BH-209	70.16	6067470	482909.1	CPT-233	8.46	6064405.8	480734.6
BH-209_a	4.88	6067465	482903.2	CPT-233_a	9.07	6064399.8	480739.4
BH-210	63.4	6069683.3	484940	CPT-233_b	8.67	6064395.1	480734.4
BH-211	70.4	6069082.3	486858	CPT-234	9.06	6066291.2	484100.7
BH-212	31.4	6069295.5	490770	CPT-234_a	0.9	6066286.5	484105.5
BH-212_a	51.25	6069290.6	490765.3	CPT-234_b	9.3	6066281.6	484101.1
BH-213	1.78	6072727	477185.9	CPT-236	5.84	6068085.7	473675.3

Location [-]	Maximum Depth [m]	North [m]	East [m]	Location [-]	Maximum Depth [m]	North [m]	East [m]
BH-213_a	6.67	6072721.9	477181	CPT-236_a	7.32	6068090.9	473675.4
BH-213_b	9.88	6072727.3	477176	CPT-236_b	8.46	6068081.1	473675.4
BH-213_c	69.63	6072730.5	477177.7	CPT-238	7.95	6068268.8	479810.9
BH-213_d	68	6072730.7	477184.6	CPT-238_a	0.36	6068263.7	479816.1
BH-214	69.66	6075361.1	479669	CPT-238_b	7.55	6068258.8	479811.1
BH-214_a	9.89	6075355.7	479664	CPT-239	2.74	6070356.3	482266.2
BH-215	15.5	6072925.7	483279.8	CPT-239_a	7.83	6070361.4	482266.2
BH-215_b	60.3	6072922.1	483281.2	CPT-239_b	7.97	6070352.8	482269.9
BH-216	6.7	6073270.4	488437.5	CPT-240	10.49	6069290.5	484059.3
BH-216_a	50.5	6073270.6	488441.8	CPT-241	8.38	6071798	479884.2
BH-217	69.64	6073781.9	493399.8	CPT-241_a	8.25	6071789.3	479887.9
BH-218	31.64	6080445.2	484874.5	CPT-242	6.59	6071169.4	486018
BH-218_a	21.72	6080440.3	484869.4	CPT-242_a	7.34	6071174.1	486018.1
BH-218_b	70.12	6080444.9	484864.5	CPT-243	7.59	6071313	488200.8
BH-219	70.4	6077640.3	489839.2	CPT-243_a	6.33	6071304.4	488206.1
BH-220	62.12	6079409.9	494323.2	CPT-244	9.48	6071432.4	492846.5
CPT-201	13.36	6061936.3	470336	CPT-244_a	9.37	6071436.8	492845.8
CPT-202	11.06	6059911.8	472188.9	CPT-245	11.76	6075145	480702.7
CPT-203	1.09	6062023.7	477043.4	CPT-246	10.02	6076291.9	481889.5
CPT-203_a	1.08	6062027.8	477042.7	CPT-246_a	5.76	6076296.6	481889.5
CPT-204	15.42	6061320.6	481793.4	CPT-247	5.51	6074171.4	484278.1
CPT-206	14.03	6064554.3	489698.1	CPT-247_a	8.16	6074176	484278.1
CPT-207	9.6	6066001.3	474714.7	CPT-248	1.39	6074956.7	485819.7
CPT-207_a	9.48	6066005.7	474714.1	CPT-248_a	1.4	6074961	485819.9
CPT-208	8.66	6069169.3	479958.8	CPT-249	0.25	6073034.8	486357.9
CPT-208_a	8.06	6069173.8	479958.9	CPT-249_a	0.45	6073039.7	486357.8
CPT-208_b	8.04	6069168.8	479964.1	CPT-251	6.06	6078770.7	483334.4
CPT-209	8.2	6067465.5	482914.1	CPT-251_a	6.56	6078774.6	483333.8
CPT-209_a	9.36	6067459.5	482909	CPT-252_a	6.32	6077493.7	484524.4
CPT-210	10.33	6069688.9	484935	CPT-253	4.74	6079194.5	487101.2
CPT-211	8.42	6069092.3	486858.4	CPT-253_a	4.73	6079198.7	487099
CPT-211_a	7.99	6069086.7	486862.9	CPT-254	5.28	6077383.5	487351.5
CPT-212	7.9	6069296.6	490765.8	CPT-254_a	4.85	6077387.3	487351.1
CPT-212_a	9.1	6069300.7	490764.5	CPT-255	8.98	6076240.9	493842
CPT-213	2.18	6072727.6	477181.1	CPT-255_a	9.44	6076245.5	493841.4
CPT-213_a	0.66	6072732	477181	CPT-256	1.21	6082633.2	487501.3
CPT-214	15.56	6075360.5	479664.2	CPT-256_a	1.11	6082637.4	487500.2
CPT-214_a	16.58	6075366.3	479664.1	CPT-256_b	1.86	6082632.8	487505.4
CPT-215	6.24	6072927	483290.1	CPT-257	0.71	6081031.1	488053.2

Location [-]	Maximum Depth [m]	North [m]	East [m]	Location [-]	Maximum Depth [m]	North [m]	East [m]
CPT-215_a	6.37	6072920.6	483285	CPT-257_a	0.64	6081036	488053.3
CPT-216	6.97	6073270.5	488437	CPT-258	1.71	6079676.1	490195.9
CPT-216_a	6.22	6073274.3	488437.2	CPT-258_a	1.34	6079681	490196.4
CPT-217	8.37	6073782.7	493395.4	CPT-259	0.71	6080391	492434.6
CPT-217_a	8.49	6073786.8	493394.7	CPT-259_a	0.7	6080395.8	492435
CPT-218	7.53	6080445.2	484869.7	CPT-260	1.53	6079003.2	497544.5
CPT-218_a	7.82	6080450.1	484868.6	CPT-260_a	0.6	6079007.8	497544.8

The soil investigation from the locations of Bornholm II is presented in Figure 8-1.

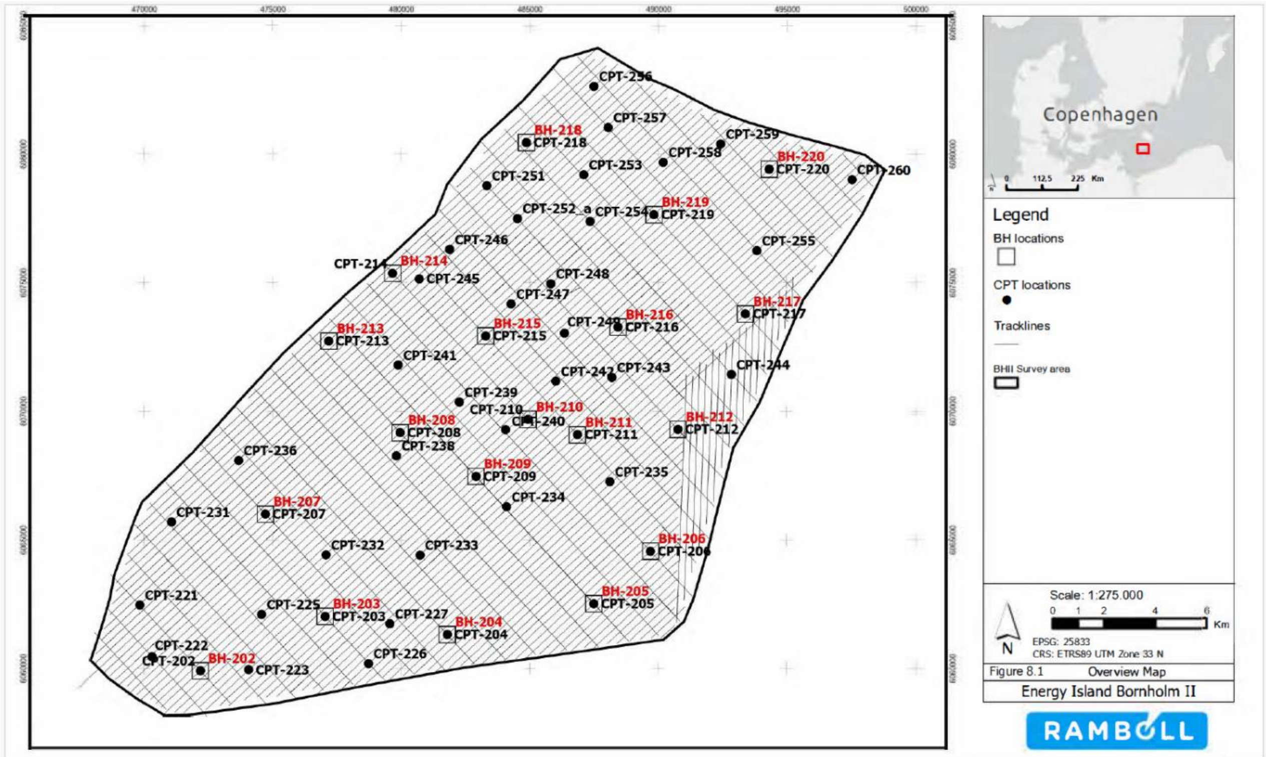


Figure 8-1 Geotechnical data available at Bornholm II.

8.2 Geotechnical units

The geotechnical description and characterisation of the Geotechnical Units is defined in this section. Besides the identification of soil layers based on the geological description of soil samples retrieved as well as interpretation of the geophysical surveys, the formations are also identified by means of the in-situ cone penetration testing carried out. This interpretation is based upon the available geotechnical data for the soil and rock at the site and geotechnical engineering judgement.

Therefore, in order to gain a higher level of understanding of the in-situ conditions CPT tests can also be utilised in the classification process. Empirical correlations such as that outlined by the Robertson (Robertson & Cabal, 2022) approach can be used to understand the soil behaviour types encountered at each location and are considered to have a stronger link to fundamental in-situ behaviour. Appendix 1 shows the normalised soil behaviour type index for each soil unit, based on Robertson (Robertson &

Cabal, 2022) classification. Therefore, the geotechnical units are classified based on normalised soil behaviour type index from CPT, BH description and lab data.

The geotechnical units identified consist of six soil units and six rock units. Soil unit Ia comprises loose to medium dense silty sand found in the upper layers of Late glacial/Post glacial- Pleistocene/ Holocene. Similarly, soil unit Ib, encountered in the top layers, consists of very soft clay, organic silty material with high plasticity, also from the Post glacial-Holocene age. Soil unit Ib represents also the gyttja formations in the area, since gyttja is constituting an integral component of this organic and soft material within Soil Unit Ib. Following these, soil units Ia and Ib precede either soil unit II or III. Soil unit II is characterized by soft to firm clay material of Late glacial-Pleistocene age, while soil unit III consists of firm to stiff clay material also from the Late glacial-Pleistocene age. Beyond these soils, soil units IVa and IVb emerge with a Glacial-Pleistocene age. Soil unit IVa represents medium dense to very dense silty sand, while soil unit IVb is constituted by very stiff to very hard sandy clay till, occasionally containing shell fragments. Table 8.2 provides a summary of the geotechnical soil units and their relationship to the geophysical seismic units.

Regarding the rock units, Va1 and Va2 are composed of limestone/mudstone. Va1 is identified as soft, ranging from very weak to medium weak limestone/mudstone, whereas Va2 is characterized as hard, ranging from weak to extremely strong limestone/mudstone. For rock units Vb1 and Vb2, which are chalk, Vb1 is soft chalk, while Vb2 is hard chalk. Finally, rock units Vc1 and Vc2, both consisting of sandstone, feature Vc1 as soft, extremely weak to weak sandstone, and Vc2 as hard, medium-strong to strong sandstone.

Table 8.3 provides a summary of the geotechnical rock units and their relationship to the geophysical seismic units.

Table 8.2 Geotechnical soil units at Bornholm area.

Unit	Soil Type	Description	Age and Seismic units	Colour
Ia	Sand	Loose to medium dense sand	Post glacial. Late Pleistocene / Holocene – SU 1 (south-west)	
Ib	Clay and/or Gyttja	Very soft organic clay and/or Gyttja	Post glacial. Late Pleistocene / Holocene – SU 1	
II	Clay	Transition layer of clay with soft to firm strength	Late glacial – SU 2	
III	Clay	Firm to stiff clay	Late glacial – SU 2	
IVa	Sand	Medium dense to very dense sand	Glacial – SU 3	
IVb	Clay Till	Very stiff to very hard clay till	Glacial – SU 3	

Table 8.3 Geotechnical rock units at Bornholm area.

Unit	Rock Type	Description	Age and Seismic units	Colour
Va1	Limestone/Mudstone	Soft, very weak to medium weak	Cretaceous – SU 4	
Va2	Limestone/Mudstone	Hard, weak to extremely strong	Cretaceous – SU 4	
Vb1	Chalk	Soft Chalk	Cretaceous – SU 4	
Vb2	Chalk	Hard Chalk	Cretaceous – SU 4	
Vc1	Sandstone	Soft, extremely weak to weak	Jurassic – SU 4	
Vc2	Sandstone	Hard, medium strong to strong	Jurassic – SU 4	

There are differences between Gardline's (Gardline, 2023) and Rambøll's interpretations of age and soil units. Rambøll has done a fit to purpose interpretation of age and units considering the interpretation of geophysical data together with the geotechnical data and their future use in foundation design.

Appendix 2 shows the measured and derived parameters from the CPT for each location together with soil behaviour type index of Robertson (Robertson & Cabal, 2022).

The correspondence between the seismic horizons and the sedimentological units is explained in Section 7. However, it should be noted here that the soils and rocks at the Bornholm sites are complex, and there is not a simple one-to-one correspondence between the geophysical and geotechnical units due to lateral variation in the mechanical behaviour of the sediments. Several iterations between geotechnical and seismic data have been required to define the geotechnical units. The site's geology requires boreholes to identify both soil and rock unit since continuous CPTs are generally only available for the shallow, very soft soil units. As a consequence, the structurally deeper clay tills are not well identified in the down the hole CPTs.

8.3 Geotechnical cross sections

Geotechnical cross-sectional profiles were produced to illustrate the lateral variability of the units encountered across Bornholm II. Six cross sections were produced to present as many locations as possible. The locations of these can be seen in Figure 8-2. For each cross section, the boreholes and the CPTs are presented separately in Appendix 3.

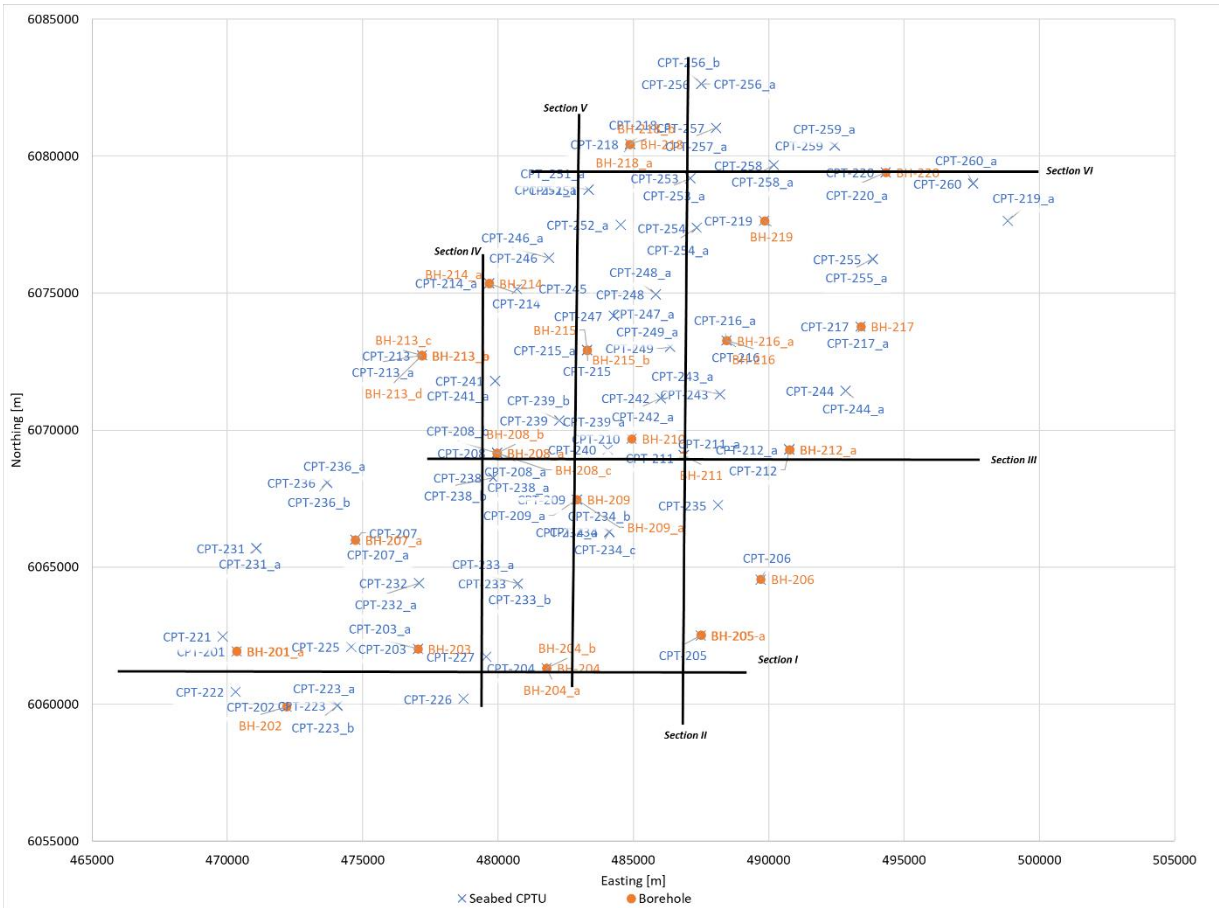


Figure 8-2 Geotechnical cross sections locations.

8.4 Geotechnical derivation of soil parameters

The engineering parameters for design is interpreted from the field and factual site investigation data obtained for the project. Some parameters will be location specific (local) while others will be formations specific (global). The reason for specifying some of the data as formation specific is to have as large a data set as possible to derive the parameters and furthermore to be able to determine these parameters at locations where only CPT's are available.

A statistical assessment according to DNVGL-RP-C207 (DNVGL-RP-C207, 2019) is performed where all soil parameters are taken as cautious mean values. A cautious mean value can be taken as a value with a confidence greater than 50 %. In the present report a confidence greater than 75 % has been used unless specifically stated in the text. The lower and upper bounds are given for some parameters and are taken as one or half standard deviation from the cautious best estimate or based on engineering judgment.

Outliers are defined as data that are located more than two standard deviations from the mean value this is in accordance with DNVGL-RP-C207 (DNVGL-RP-C207, 2019). The outliers will not be used in the analyses of the design values and the number of the test presented in the tables below for each parameter are without the outliers. However, outliers are displayed in the figures below.

8.5 Detailed Geotechnical Interpretation of the soil units

8.5.1 Particle Size Distribution

The particle size distributions, PSD, for each engineering soil unit is determined through laboratory testing. The primary compositions are listed in Table 8.4.

Table 8.4 Primary composition for each soil units based on PSD's.

Soil unit	Primary Composition
Ia	Fine sand to medium sand, silty
Ib	Clay, silty
II	Clay, silty, slightly sandy
III	Clay, silty, sandy
IVa	Medium sand to coarse sand, silty
IVb	Clay, very sandy

Fine and gravel contents are derived for each soil unit and summarized in Table 8.5 and Table 8-6. Moreover, Figure 8-3 presents the fines and gravel content with the depth for each soil unit for comparison.

Table 8.5 Fines content for each soil unit.

Soil unit	Mean [%]	Max [%]	Min [%]	75% Confidence [%]	Test number
Ia	15.1	65	4	10.2	8
Ib	93.9	100	60	93.2	59
II	61.4	76	51	59.7	10
III	56.7	93	34	54.9	28
IVa	20.7	64	1	19.4	72
IVb	61.3	100	30	59.5	55

Table 8.6 Gravel content for each soil unit.

Soil unit	Mean [%]	Max [%]	Min [%]	75% Confidence [%]	Test number
Ia	0.3	2	0	0.1	8
Ib	0.3	3	0	0.2	61
II	3.4	7	0	2.9	11
III	3.6	11	0	3.2	27
IVa	2	13	0	1.8	72
IVb	4.8	16	0	4.4	54

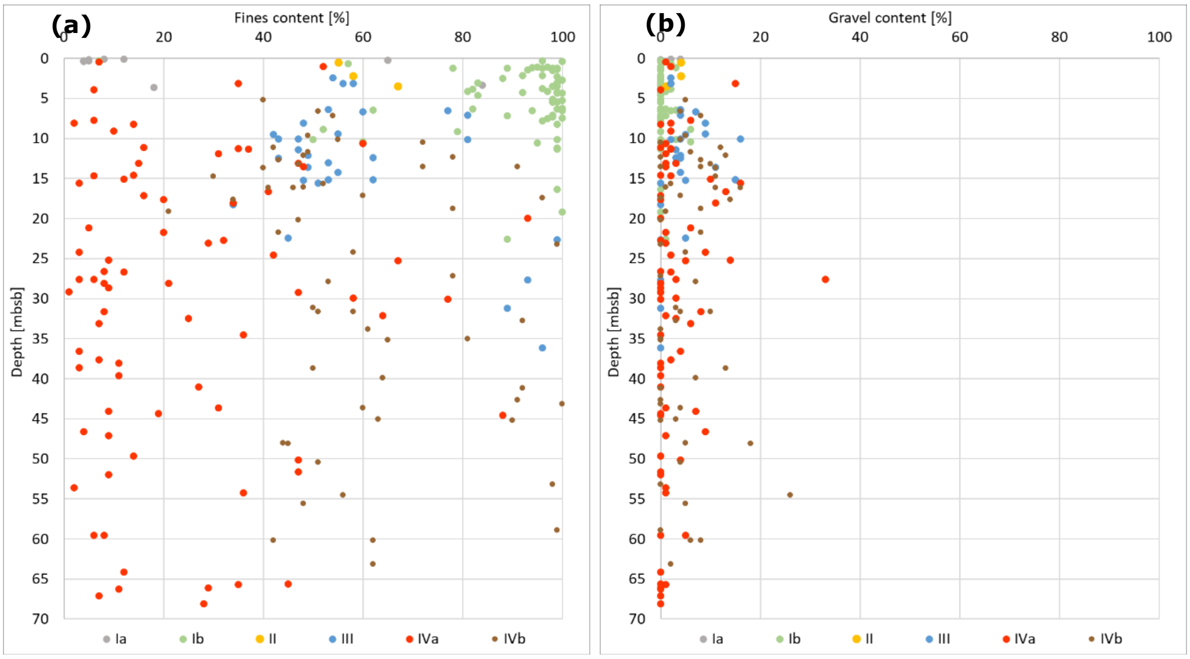


Figure 8-3 Fines (a) and gravel (b) content.

8.5.2 Maximum and Minimum Dry Unit Weight

A total of 3 maximum and minimum dry unit weight, γ_d, determination tests have been performed for soil unit Ia and a total of 12 for soil unit IVa. The results of these tests are summarised in Table 8.7.

Table 8.7 Maximum and minimum unit weight.

Soil unit		$\gamma_{d,max}$ [kN/m^3]	$\gamma_{d,min}$ [kN/m^3]
Ia	Average	15.5	11.9
	Minimum	15	11.8
	Maximum	15.8	12.1
	75% Confidence	15.3	11.9
IVa	Average	17	13.9
	Minimum	15.7	12.8
	Maximum	18.4	15.2
	75% Confidence	16.9	13.7

8.5.3 Specific Gravity, d_s

The specific gravity, d_s, has been determined from a total of 197 tests that have been performed (including outliers). The results are depicted in Figure 8-9-Figure 8-9.

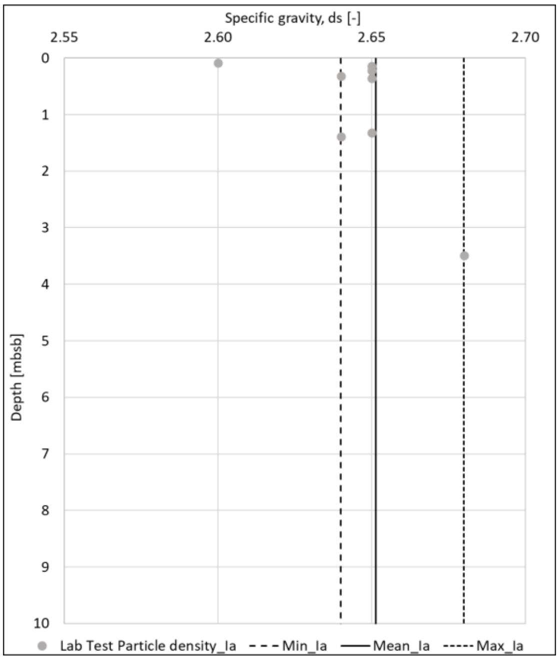


Figure 8-4 Specific gravity for unit Ia.

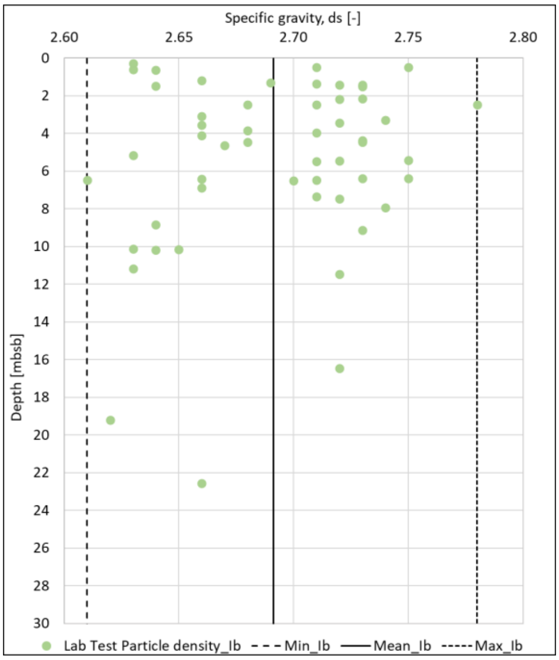


Figure 8-5 Specific gravity for unit Ib.

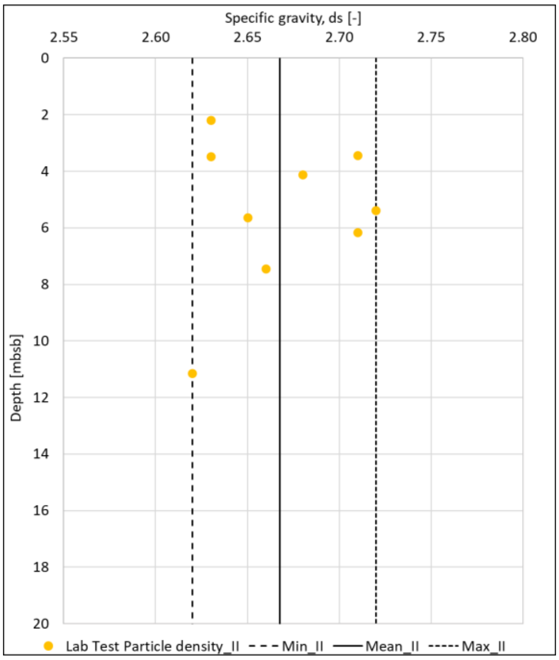


Figure 8-6 Specific gravity for unit II.

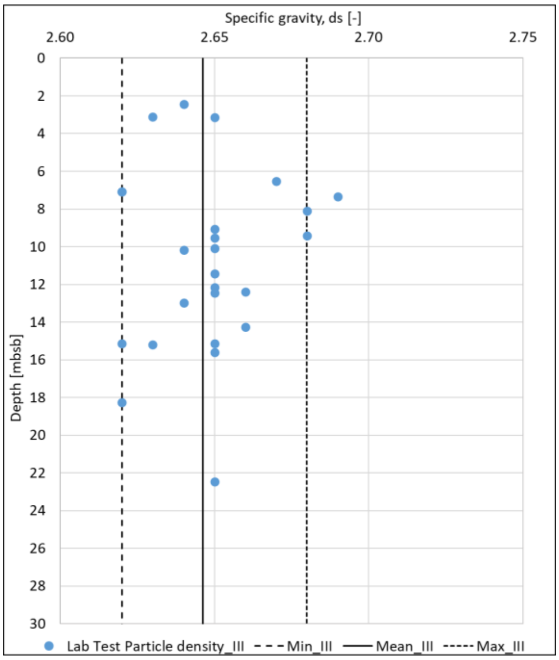


Figure 8-7 Specific gravity for unit III.

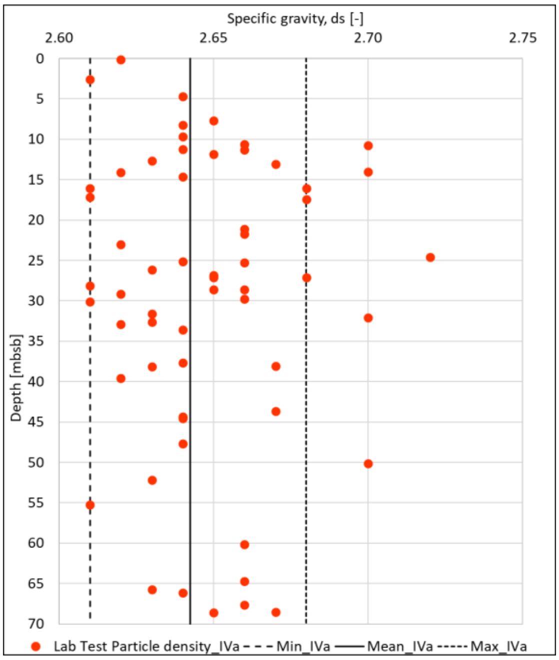


Figure 8-8 Specific gravity for unit IVa.

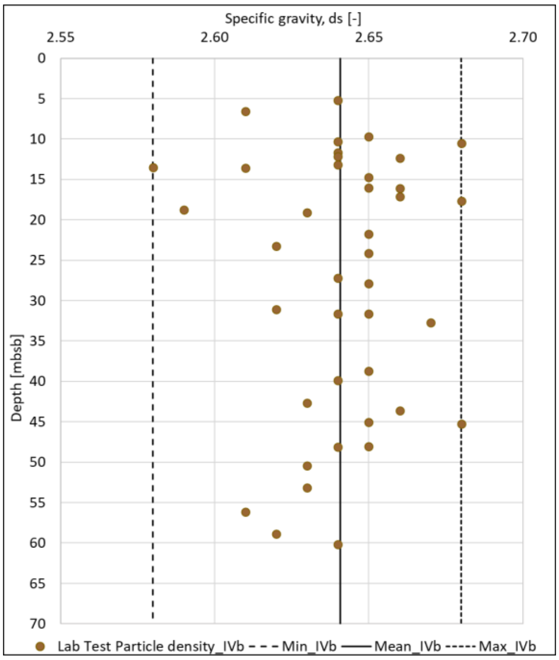


Figure 8-9 Specific gravity for unit IVb.

As seen in the figures, the specific gravity for the site varies between 2.58 to 2.78. The results are summarized in Table 8.8.

Table 8.8 Specific gravity for each soil unit.

Soil unit	Mean [-]	Max [-]	Min [-]	75% Confidence [-]	Test number
Ia	2.65	2.68	2.64	2.65	7
Ib	2.69	2.78	2.61	2.69	52
II	2.67	2.72	2.62	2.66	9
III	2.65	2.68	2.62	2.64	24
IVa	2.64	2.68	2.61	2.64	54
IVb	2.64	2.68	2.58	2.64	40

8.5.4 Unit Weight

The total unit weights are computed based on the bulk density laboratory test results. It has been assumed that the bulk unit weight is equal to the saturated unit weight, γ_{sat}. The submerged unit weight, γ_{sub}, for each soil unit is taken as the average value with 75% confidence, see Figure 8-10-Figure 8-15. The submerged unit weight is presented in Table 8.9.

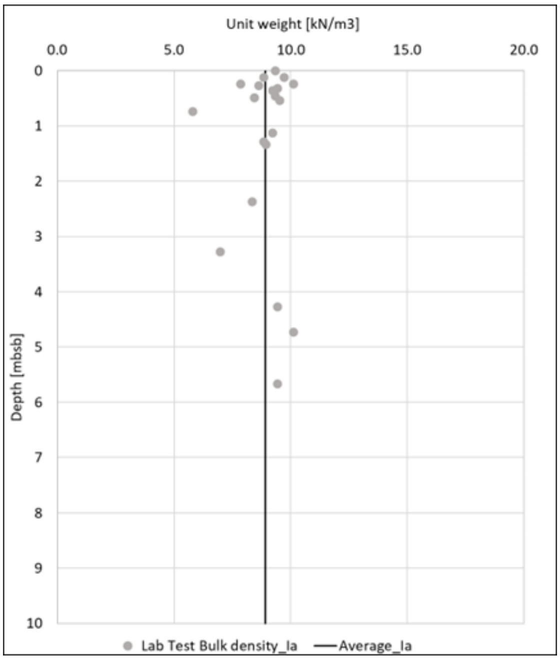


Figure 8-10 Submerged unit weight for unit Ia.

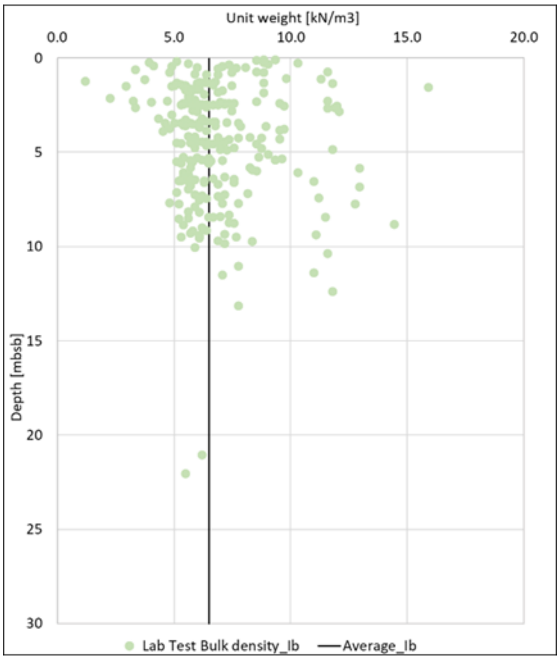


Figure 8-11 Submerged unit weight for unit Ib.

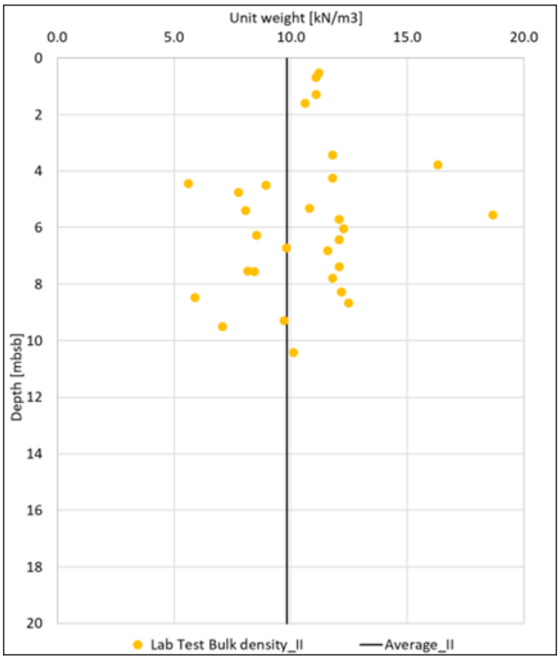


Figure 8-12 Submerged unit weight for unit II.

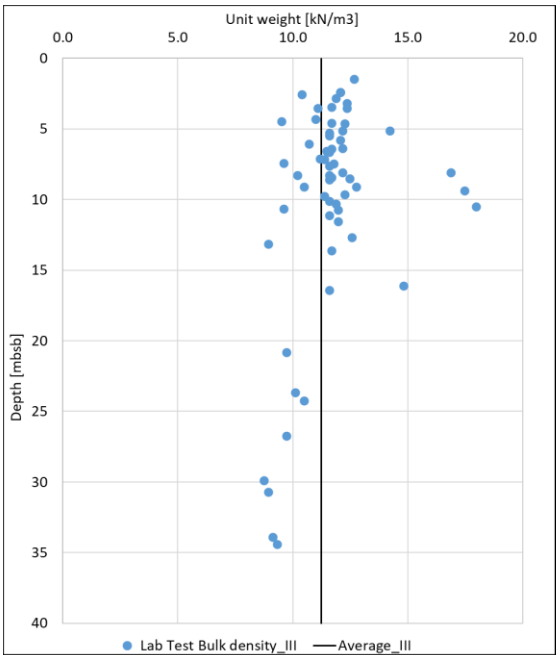


Figure 8-13 Submerged unit weight for unit III.

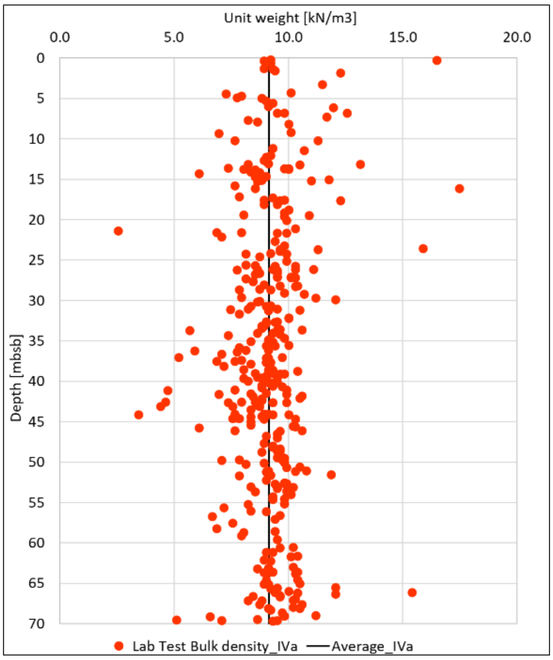


Figure 8-14 Submerged unit weight for unit IVa.

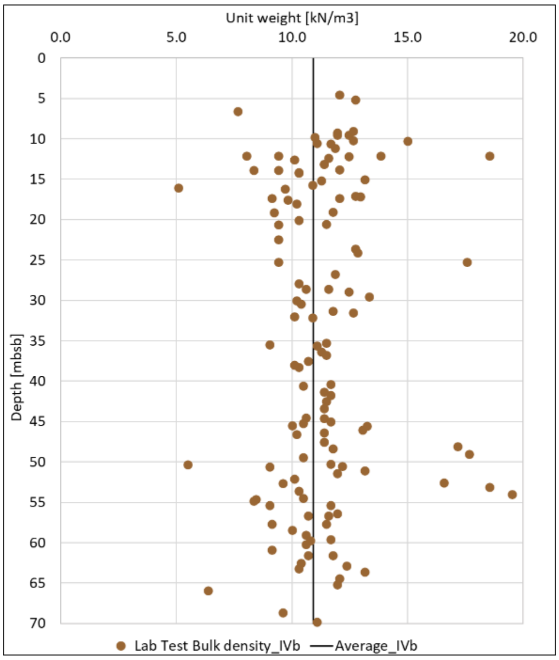


Figure 8-15 Submerged unit weight for unit IVb.

Table 8.9 Submerged unit weight for each soil unit.

Soil unit	γ_{sub} [kN/m3]
Ia	8.9
Ib	6.5
II	9.8
III	11.2
IVa	9.1
IVb	10.9

8.5.5 Moisture content

Measurements of the moisture content has been performed for the available boreholes. The main results are listed in Table 8.10. The results can also be seen in Figure 8-16-Figure 8-21. The highest moisture content is met in the soil unit Ib demonstrating that it is an organic material with high plasticity such as gyttja.

Table 8.10 Moisture content for each soil unit.

Soil unit	Mean [%]	Max [%]	Min [%]	75% Confidence [%]	Test number
Ia	43.5	76	26	34.6	5
Ib	54.1	111	13	53.2	177
II	25.8	50	14	23.9	17
III	16.3	29	8	16.0	58
IVa	27.7	42	12	27.3	165
IVb	17.3	37	4	16.8	132

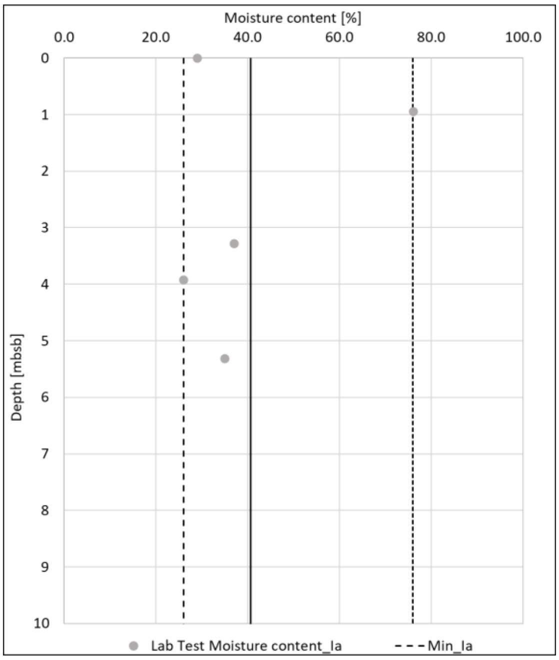


Figure 8-16 Moisture content for unit Ia.

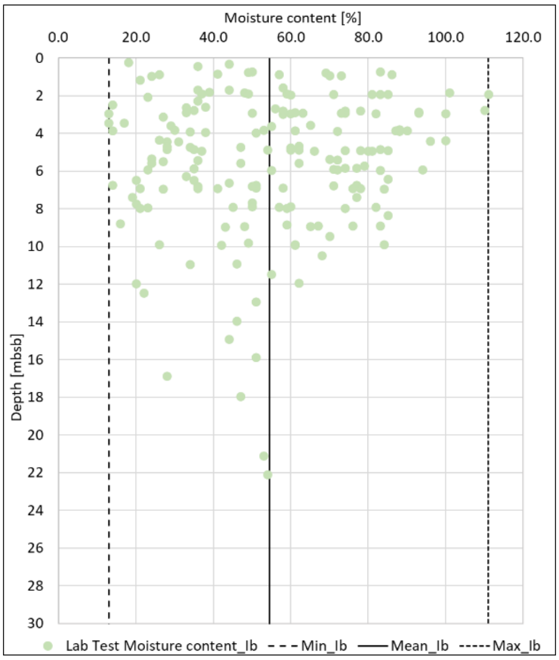


Figure 8-17 Moisture content for unit Ib.

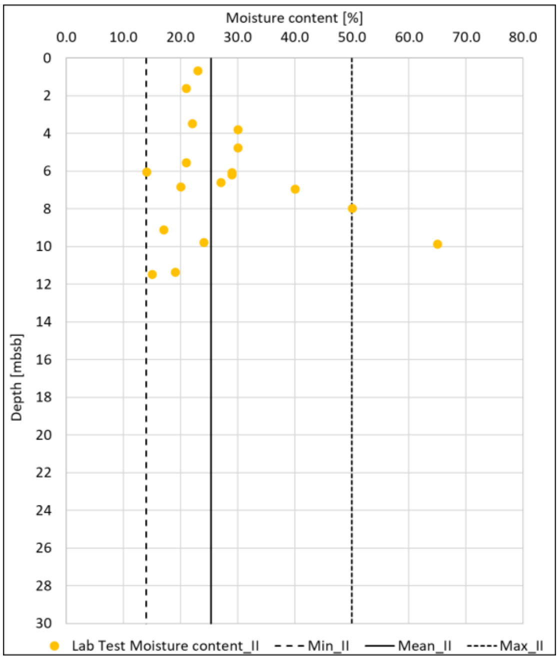


Figure 8-18 Moisture content for unit II.

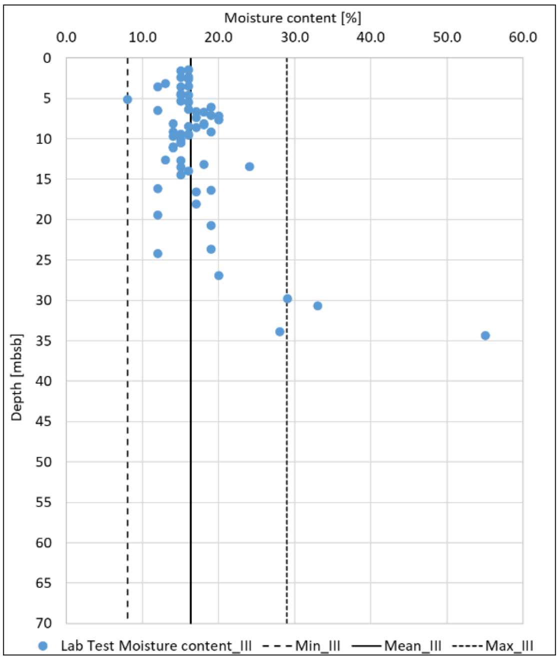


Figure 8-19 Moisture content for unit III.

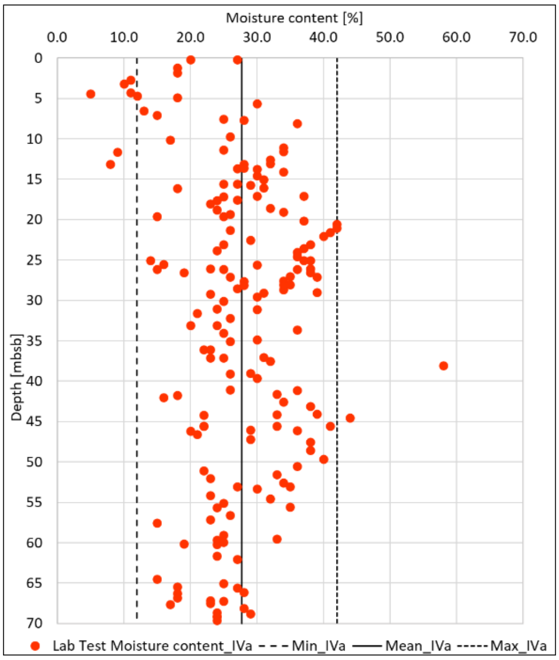


Figure 8-20 Moisture content for unit IVa.

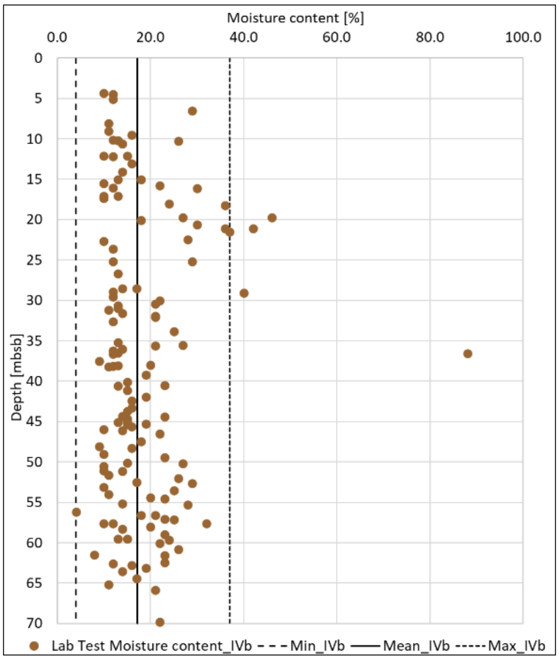


Figure 8-21 Moisture content for unit IVb.

8.5.6 Plasticity Index and Atterberg Limits

Plasticity indices for each engineering soil unit have been determined through traditional laboratory testing for the available boreholes. The plasticity chart from the results is presented in Figure 8-22.

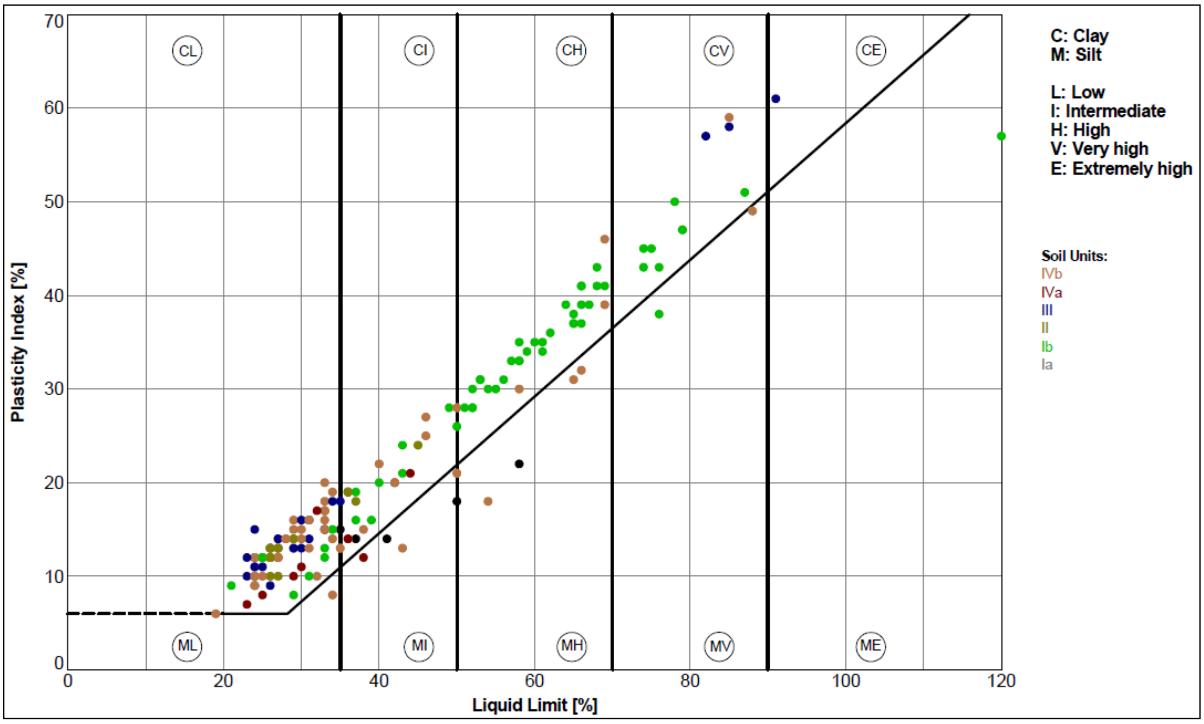


Figure 8-22 Plasticity chart of the soil units.

For soil unit Ib a total of 61 tests have been performed and the unit is identified as clay with plasticity varying from low to extremely high but with most of the tests indicating very high plasticity. A total of 11 tests have been undertaken on samples recovered from soil unit II and its plasticity is deemed to be low from the test results. Soil unit III had a total of 26 tests, the results of which indicate a clay with low to intermediate plasticity. Finally, for soil unit IVb, a total of 55 tests were performed with the data indicating that the unit is mostly clay with low to intermediate plasticity, with only a few tests below the A-line. As expected, the most plastic Soil is the shallow Ib Unit. Table 8.11 presents the results for the Plasticity Index (PI) and the Atterberg limits (Liquit Limit-LL and Plastic Limit-PL).

Table 8.11 Plasticity results for each soil unit.

Soil unit	Index	Mean [%]	Max [%]	Min [%]	75% Confidence [%]	Test number
Ib	PI	31	57	8	30	58
II	PI	13	19	9	12	10
III	PI	14	20	9	13	23
IVb	PI	16	32	6	15	51
Ib	LL	55	87	21	54	57
II	LL	28	37	24	27	10
III	LL	29	42	23	28	23
IVb	LL	34	66	19	33	51
Ib	PL	24	38	12	24	57
II	PL	15	19	13	15	10
III	PL	15	25	9	15	24
IVb	PL	18	30	12	17	51

8.5.7 Organic content and chemical composition content

Different chemical and organic contents are found. These are summarised in Table 8.12 to Table 8.15 and the outliers are not included.

Table 8.12 Carbonate content for each soil unit.

Soil unit	Mean [%]	Max [%]	Min [%]	75% Confidence [%]	Test number
Ia	0.09	0.18	0	0.03	2
Ib	11.87	25	0	11.07	32
II	9.1	9.1	9.1	9.1	1
III	16.29	23	10	15.13	7
IVa	3.57	13	0	2.85	13
IVb	27.68	54	9.1	22.09	6

The carbonate content in unit IVb is high, which also corresponds with the borehole descriptions of soil unit IVb; it is described as calcareous in some samples.

Table 8.13 Organic content for each soil unit.

Soil unit	Mean [%]	Max [%]	Min [%]	75% Confidence [%]	Test number
Ia	1.13	1.3	0.95	1	2
Ib	5.97	9.7	2.6	5.78	31
II	5.2	5.2	5.2	5.2	1
III	3.53	5.6	1.8	3.16	7
IVa	1.55	7.6	0.28	1.16	12
IVb	1.7	1.7	1.7	1.7	1

As seen in Table 8.13 the organic contents for the soil units are small so there is little risk for elevated organic content in the Soil Successions.

Table 8.14 Sulphate content for each soil unit.

Soil unit	Mean [%]	Max [%]	Min [%]	75% Confidence [%]	Test number
Ia	0.11	0.13	0.08	0.09	2
Ib	0.1	0.2	0.02	0.1	29
II	0.06	0.06	0.06	0.06	1
III	0.08	0.16	0.04	0.07	8
IVa	0.07	0.34	0.03	0.05	13
IVb	0.07	0.11	0.05	0.06	5

Table 8.15 Chloride content for each soil unit.

Soil unit	Mean [%]	Max [%]	Min [%]	75% Confidence [%]	Test number
Ia	0.15	0.15	0.15	0.15	2
Ib	0.18	0.47	0.02	0.16	31
II	0.44	0.44	0.44	0.44	1
III	0.09	0.17	0.01	0.08	8
IVa	0.07	0.13	0.02	0.07	13
IVb	0.07	0.11	0.04	0.06	5

8.5.8 In-Situ Stress State

8.5.8.1 Pre-consolidation Pressure and OCR

A total of 45 incremental (IL) oedometer tests have been performed. From these tests the pre-consolidation pressure σ_{pc} has been determined and the over consolidation ratio (OCR) determined, see Figure 8-23.

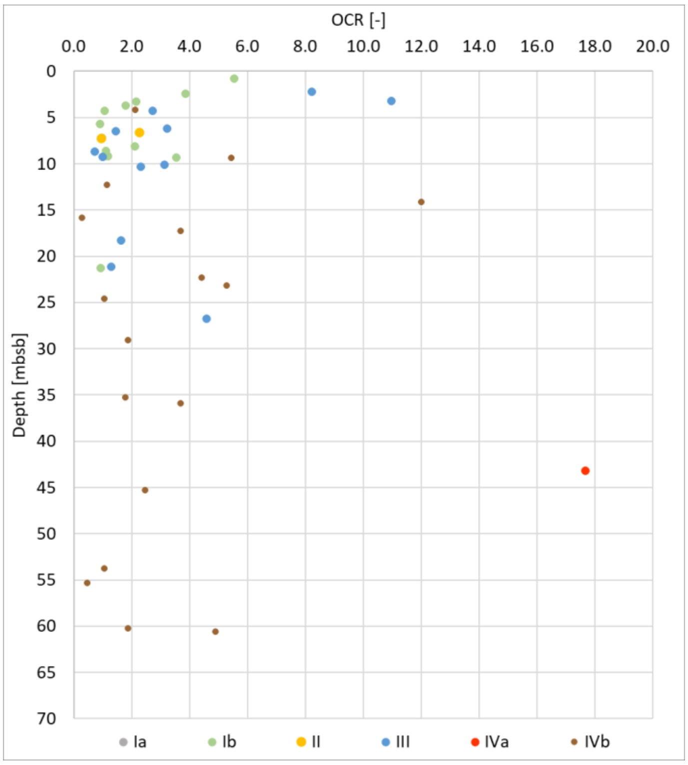


Figure 8-23 OCR from IL.

The over consolidation ratio, OCR, defines the clay stress history comparing the past maximum effective pressure, σ'_{pc}, with the present effective pressure of the soil, σ'_{v0}. The OCR is defined as stated in Equation (8.1) and summarized in Table 8.16:

$$OCR = \frac{\sigma'_{pc}}{\sigma'_{v0}} \tag{8.1}$$

Table 8.16 OCR per soil unit.

Soil unit	Min OCR [-]	Max OCR [-]	Average OCR [-]	75% Confidence [-]	Test number
Ib	0.89	3.87	1.72	1.52	12
II	0.93	2.26	1.6	1.13	2
III	0.72	8.22	2.75	2.32	11
IVb	0.3	5.44	2.6	2.31	16

8.5.8.2 Effective In-Situ Stress

The horizontal effective in-situ stress, σ'_{h0} is calculated based on the coefficient of earth pressure at rest, K_0. K_0 is calculated based on the assumption that the soil is normal consolidated corresponding to the non-cohesive units of Ia and IVa. The normal consolidation is used as this is the most conservative approach:

$$K_{0,nc} = (1 - \sin \varphi) \tag{8.2}$$

Where φ is peak angle of internal friction.

The horizontal effective stress is used in the calculation of the relative density, D_r. In Figure 8-24 the calculated values of K_0 are shown for soil unit IVa, since there are not available CID tests for the soil unit Ia to determine the K_0.

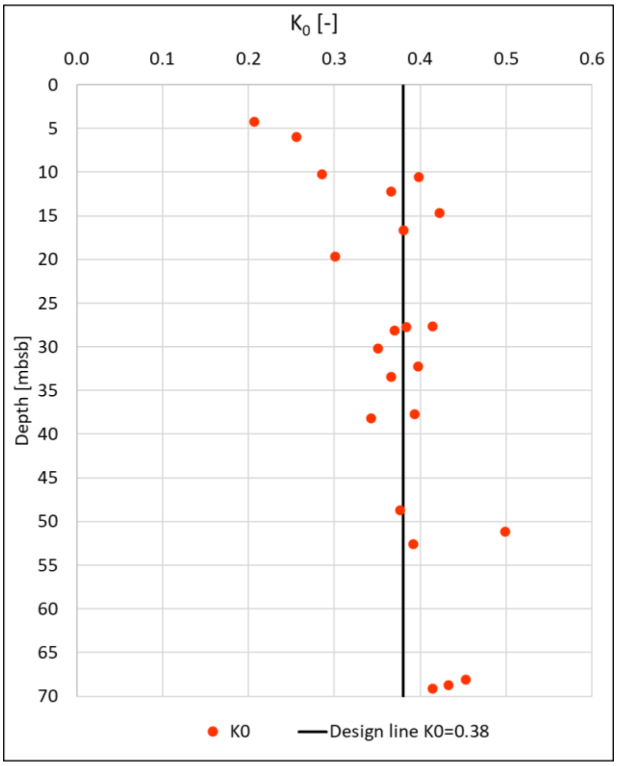


Figure 8-24 K_0 values.

8.5.9 Shear strength properties

8.5.9.1 Undrained Shear Strength

Undrained shear strengths are derived from the laboratory tests at the criteria's listed below:

- CAUc/CIUc tests: Maximum deviator stress or 10 % axial strain, whichever comes first.
- DSS tests: Maximum shear stress or 15 % shear strain, whichever comes first.
- UU tests: Maximum deviator stress or 10 % axial strain, whichever comes first.

In Table 8.17 and Figure 8-25-Figure 8-28, the laboratory strength tests on the cohesive soil units are presented.

Table 8.17 Number of laboratory strength tests on fine-grained soils.

Soil unit	CAUc/CIUc [-]	UU [-]	DSS [-]
Ib	11	45	2
II	3	8	0
III	13	18	4
IVb	22	23	10

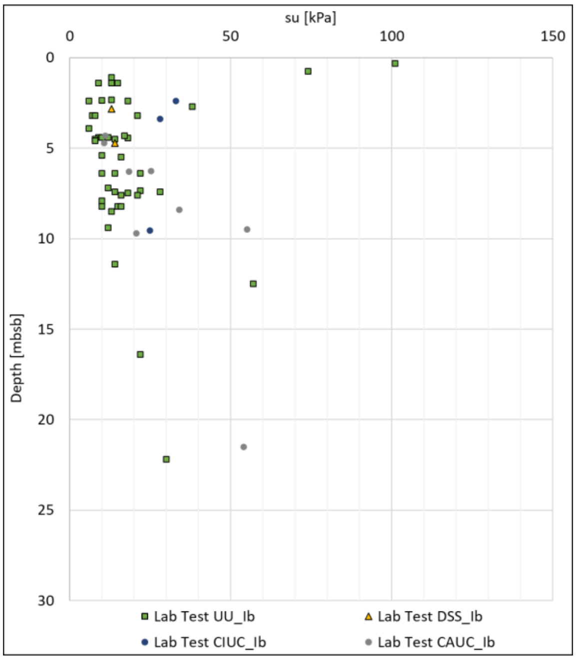


Figure 8-25 Undrained shear strength tests for unit Ib.

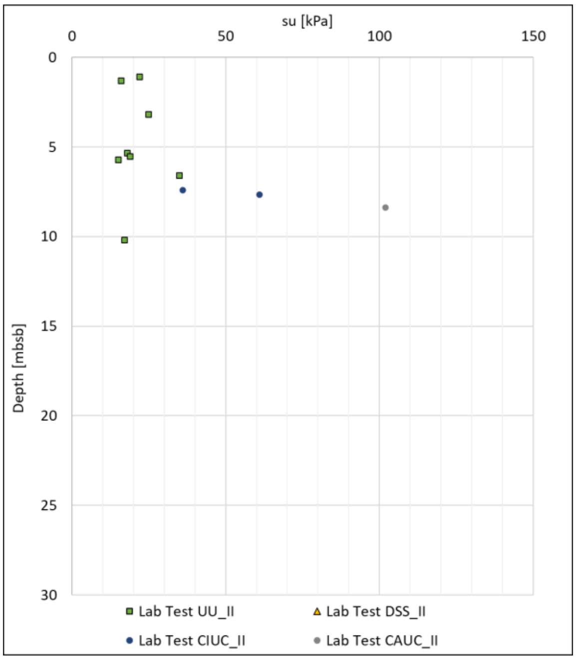


Figure 8-26 Undrained shear strength tests for unit II.

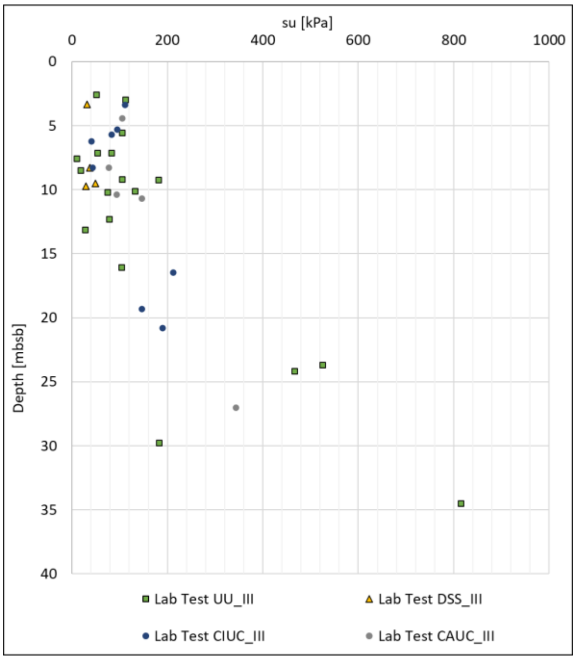


Figure 8-27 Undrained shear strength tests for unit III.

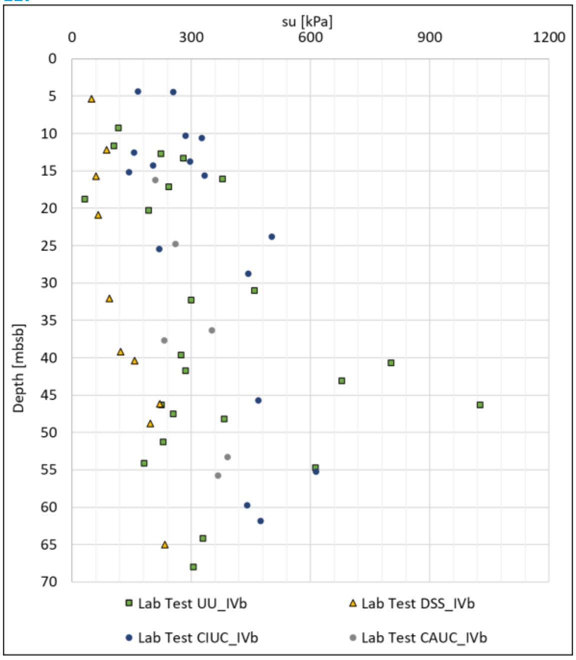


Figure 8-28 Undrained shear strength tests for unit IVb.

8.5.9.2 Evaluation of Cone Factors

In addition to the laboratory determined undrained shear strengths, the parameter may also be interpreted through the net cone resistance obtained from CPT tests. The empirical correlation between the cone resistance and the compressive undrained shear strength is found as (Lunne, Robertson, & Powell, 1997):

$$s_u = \frac{q_t - \sigma_{v0}}{N_{kt}} = \frac{q_{net}}{N_{kt}} \qquad (8.3)$$

q_t is the corrected cone tip resistance corrected for pore pressure, u_2
σ_{v0} is the total vertical in-situ stress
q_{net} is the net cone resistance
N_{kt} is a cone factor determined by comparing laboratory measurements of s_u with corresponding q_{net}.

For the N_{kt} assessment, the conventional laboratory strength tests (Unconsolidated Undrained [UU] triaxial tests) and advanced laboratory tests (Direct Simple Shear, DSS), Isotropically Consolidated Undrained triaxial (CIU) and Anisotropically Undrained (CAU) triaxial tests) have been used. For soil unit Ib, that comprises soft clay, the Pocket Penetrometer (PP) and the Vane (VAN) laboratory tests have been used. For the determination all values below 10 and above 35 have been omitted; these values are judged, from an engineering perspective, to be out of range. Furthermore, the methodology as described in Section 8.4 is used to find the cautious best estimate, BE.

The main results are shown in Table 8.18 where the N_{kt} range is two standard deviations across the cautious best estimate, so LB and UB are one standard deviation above and below the BE.

Table 8.18 Cone factor ranges.

Soil unit	N_{kt}, BE [-]	N_{kt}, LB [-]	N_{kt}, UB [-]	Test number
Ib	19	25	14	355
II	22	30	14	5
III	20	25	15	19
IVb	22	27	17	12

In Figure 8-29-Figure 8-32 the chosen values are shown together with the laboratory values. In the figures the outliers illustrates both values below 10 and above 35 together with the actual outliers defined as data that are located more than two standard deviations from the mean value.

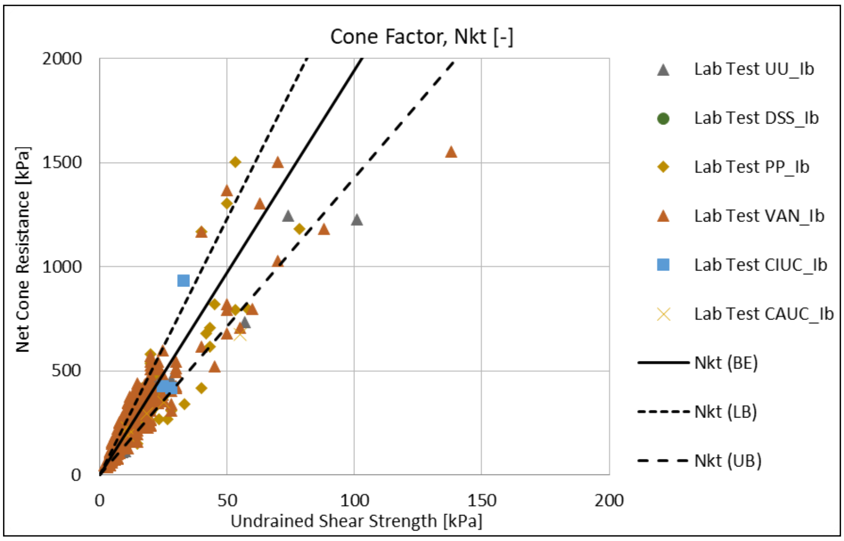


Figure 8-29 Cone factor estimation for soil unit Ib.

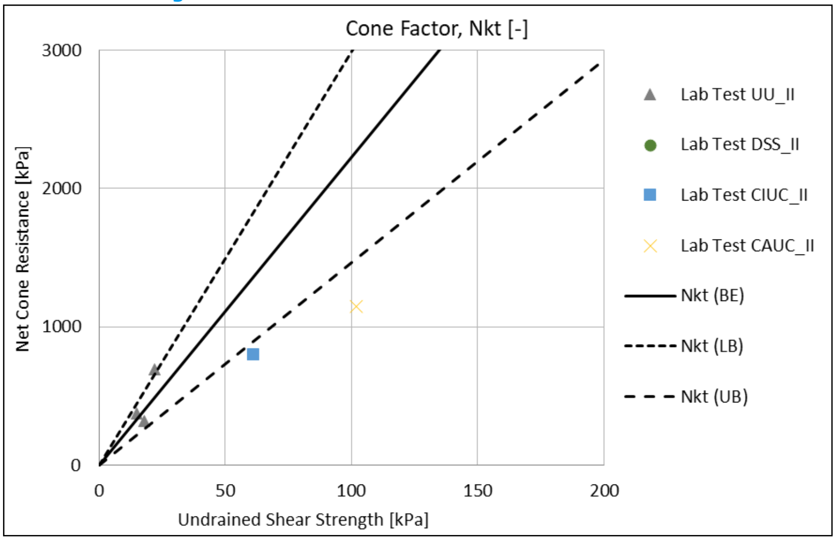


Figure 8-30 Cone factor estimation for soil unit II.

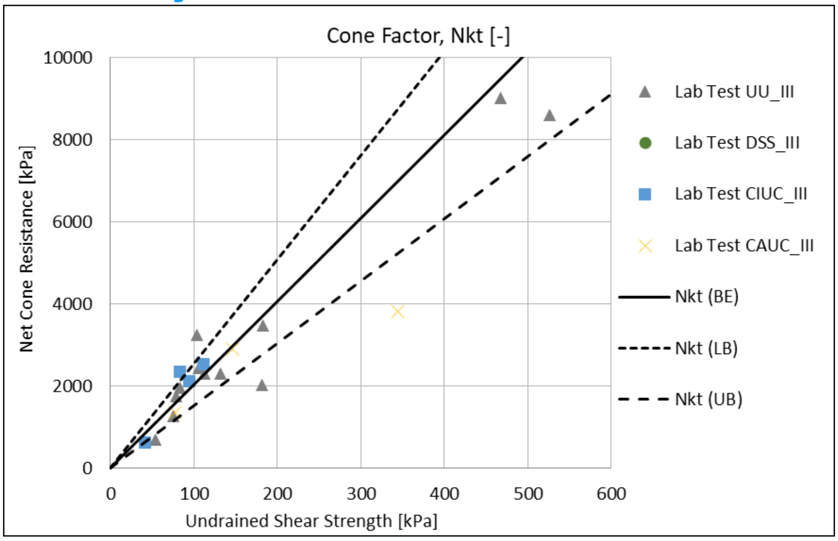


Figure 8-31 Cone factor estimation for soil unit III.

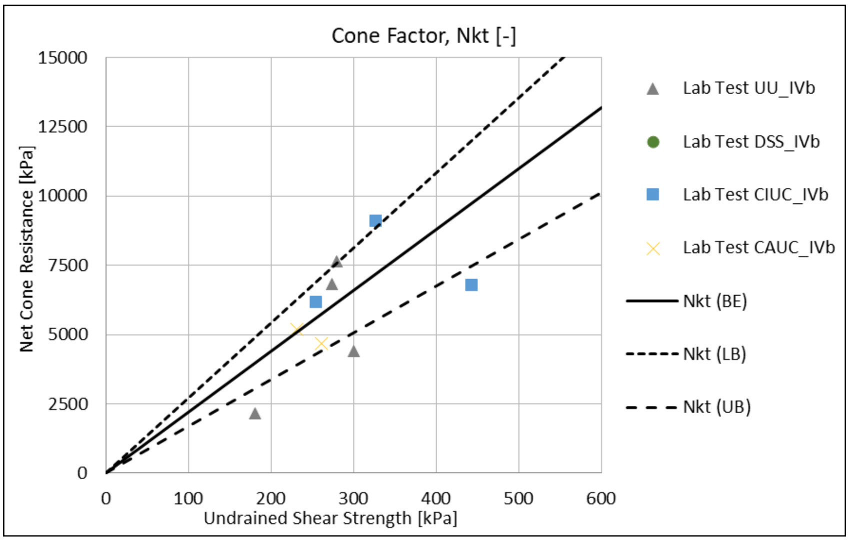


Figure 8-32 Cone factor estimation for soil unit IVb.

8.5.9.3 Effective Strength Properties

For coarse-grained soil, the Consolidated Isotropic Drained (CID) tests are available and therefore are these tests only used for information in the following.

Table 8.19 CID tests.

Soil unit	CID [No of test]
IVa	22

For CID tests the results are used directly. This means that there will also be effective cohesion included in the results. For the soil unit Ia, there are not available CID tests.

The relative density, D_r, can be determined from the laboratory test based on the below equation:

$$D_r = \frac{\gamma_{d,max}(\gamma_d - \gamma_{d,min})100}{\gamma_d(\gamma_{d,max} - \gamma_{d,min})} \tag{8.4}$$

where $\gamma_{d,max}$ and $\gamma_{d,min}$ are as the minimum and maximum value available for the present unit.

The in situ relative density of the non-cohesive soil formations is determined based on the CPT data according to the method proposed by Jamiolkowski (Jamiolkowksi, Presti, DCF., & Manaseero, 2001), where the dry relative density is expressed as:

$$D_r = \frac{1}{2.96} ln\left[\frac{q_c/98.1}{24.94 \cdot (\sigma'_m/98.1)^{0.46}}\right] \tag{8.5}$$

q_c is the measured cone tip resistance
σ'_m is the mean triaxial effective stress:

$$\sigma'_m = \frac{\sigma'_{v0} + 2K_0\sigma'_{v0}}{3} \tag{8.6}$$

σ'_{v0} is the in-situ vertical stress in kPa
σ'_{h0} is the in-situ horizontal stress in kPa
K_0 is the coefficient of lateral earth pressure.

The laboratory data of minimum and maximum dry density were carried out on bag (disturbed) samples, providing maximum/minimum densities for reconstitution of e.g. CID tests. As the in-situ density cannot be determined on these bags, the relative density cannot be derived from this data Therefore, the determination of the relative density is based on the CPT only. It must however be emphasized that the CPT correlations shall ideally be benchmarked using results from testing of soil specimens under controlled laboratory conditions.

The best estimate of the relative density is calculated for K_0 equal to 0.5, according to literature instead of the calculated K_0=0.38 (Section 8.5.8.2). In general, in-situ K_0 values are limited to the range of 0.5 to 1.0. The CPT correlation of relative density for the BE values from all the location is shown in Figure 8-33. The LB and UB for the soil profiles are based on half standard deviation from the BE value.

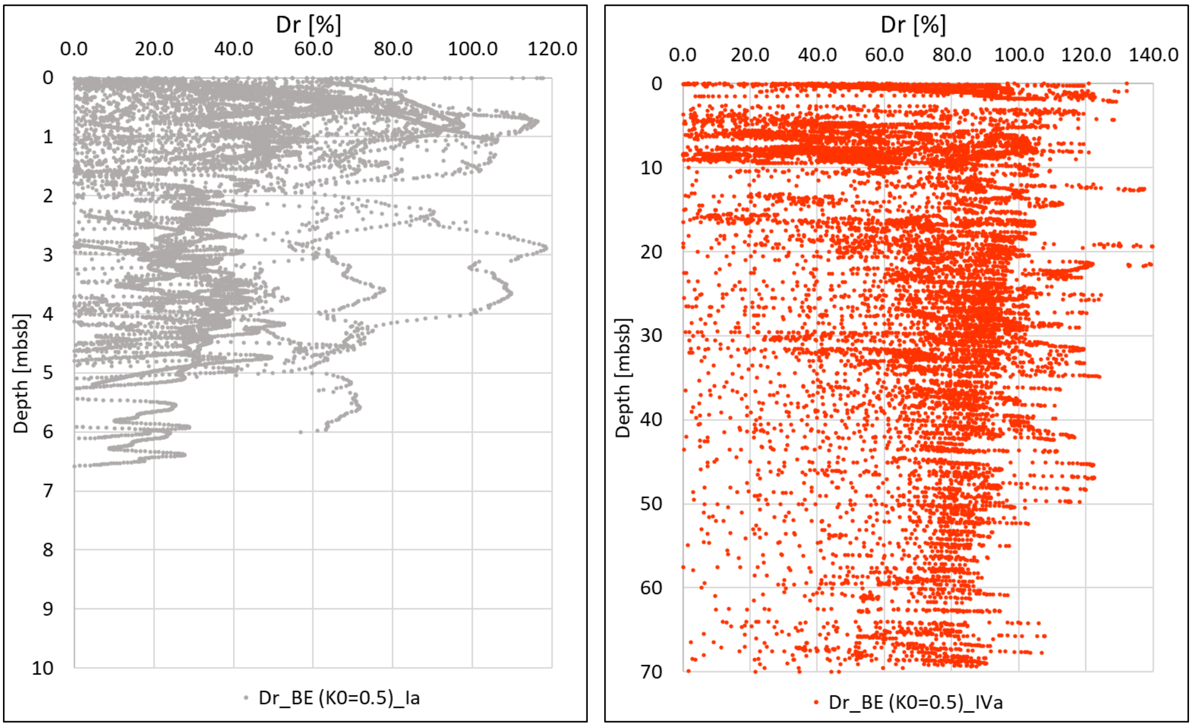


Figure 8-33 CPT correlation of Relative density for the non-cohesive soil units.

The laboratory friction angle data from the consolidated isotropic drained (CID) triaxial tests, and the relative density calculated from the laboratory tests can be used to format a site-specific CPT correlation for the friction angle in the non-cohesive units based on reference of (Schmertmann, 1978). However, for soil unit Ia, there are not available CID tests and for soil unit IVa, there are not adequate laboratory data. Therefore, no relationship between relative density (D_r) and friction angle (φ) can be found due to the limited amount of data. For this reason, the well-known equation for calculation of the angle of internal friction from CPT, Schmertmann for fine sand, Equation (8.7) is used for the estimation of the friction angle for soil unit Ia.

$$\varphi = 0.14D_r + 28 \tag{8.7}$$

In Figure 8-34, the calculated BE friction angles from the Equation (8.7) for all the locations is presented and supported by the CID tests.

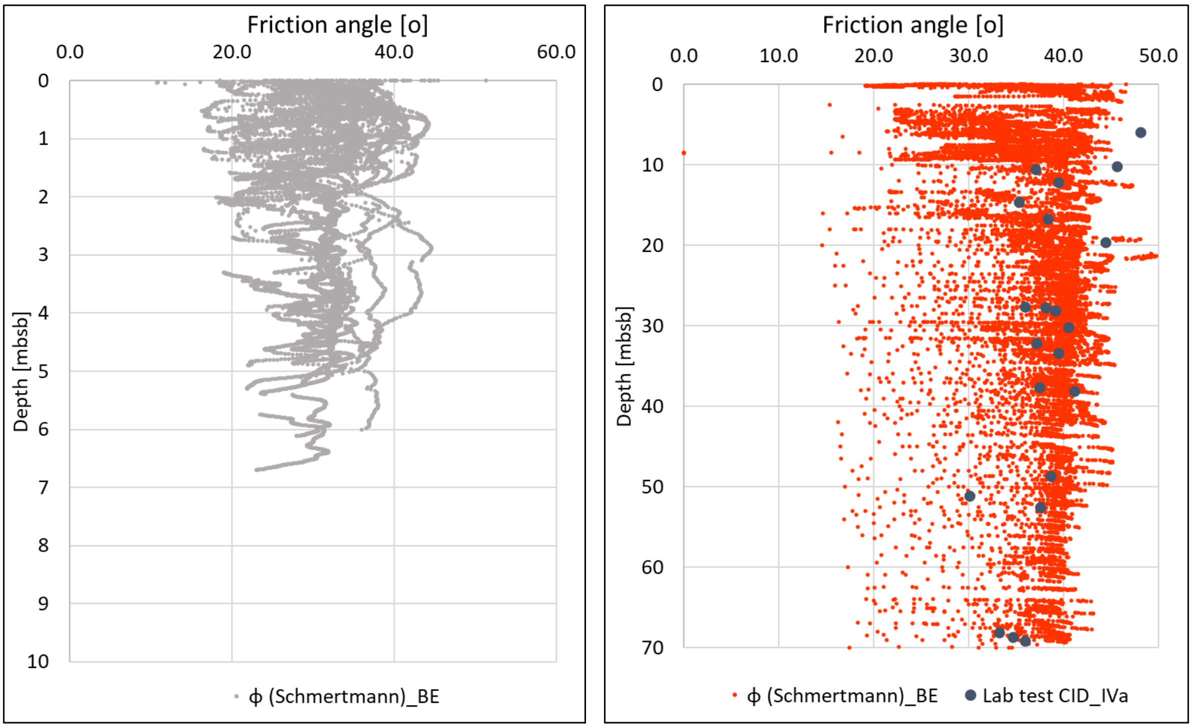


Figure 8-34 Angle of internal friction and CID tests for the non-cohesive soil units.

8.5.10 Soil Stiffness properties

8.5.10.1 Evaluation of Small Strain Shear Modulus

The small strain modulus, G_0 have been determined from in-situ testing, advanced laboratory testing or from correlations with geotechnical parameters from conventional in-situ and laboratory tests.

The small strain shear modulus G_0 have been derived from the logging results by means of the measured shear wave velocity v_s [m/sec] and the calculated mass density of the soil ρ [kg/m^3] based on the relation:

$$G_0 = \rho {v_s}^2 \tag{8.8}$$

Estimations of v_s can be obtained through the following CPT correlations. For cohesive material, (Mayne, 2017) formula is implemented:

$$v_s = 1.75(q_c)^{0.627} \tag{8.9}$$

where q_c is the measured cone tip resistance.

For non-cohesive material, two formulas are implemented:

Baldi et al. (1989) (Baldi, et al., 1989)

$$v_s = 277(q_c)^{0.13}\sigma'^{\,0,27}_{v0} \tag{8.10}$$

Rix and Stokoe (1991) (Rix & Stokoe, 1991)

$$\frac{G_0}{q_c} = 1634\left(\frac{q_c}{\sqrt{\sigma'_{v0}}}\right)^{-0.75} \tag{8.11}$$

where q_c is the measured cone tip resistance

σ'_{v0} is the effective total vertical in-situ stress.

The soil behaviour type index I_c-based approach can also be used to estimate shear wave velocity for all material types:

$$v_s = \left[\frac{a_{vs}(q_t-\sigma_v)}{pa}\right]^{0.5} \tag{8.12}$$

Where

$$a_{vs} = 10^{(0.55I_c+1.68)} \tag{8.13}$$

Where qt is the corrected cone resistance

σ_v is the total vertical in-situ stress

I_c is the soil behaviour type index.

These correlations are 73tillwat to establish the range of G_0 derived from CPT methods. The suitability of the resulting range was verified through PS logging data. However, for some soil units, for example unit Ib, the PS logging results do not give realistic values of the G_0 and they have not taken into account in the assessment. The chosen values for G_0 for all six soil units can be seen in Figure 8-35 to Figure 8-40 and Table 8.20. The values are taken as conservative values based on engineering judgement and the BE is taken equal to average of the LB and the UB. For detail design phase, further laboratory data is recommended to be acquired regarding G_0, for example resonant column or bender element tests. If further in situ testing is acquired, seismic CPT is recommended.

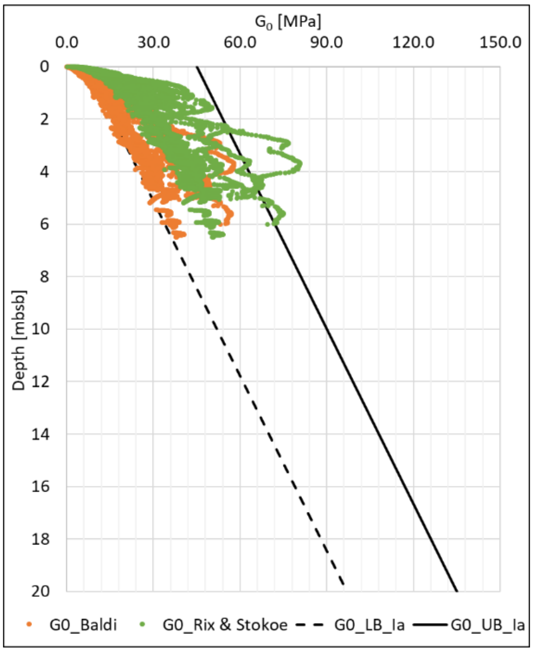


Figure 8-35 G_0 for soil unit Ia.

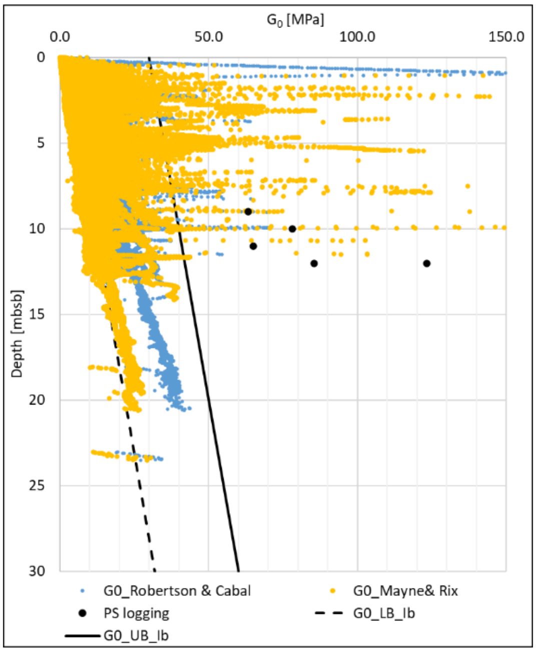


Figure 8-36 G_0 for soil unit Ib.

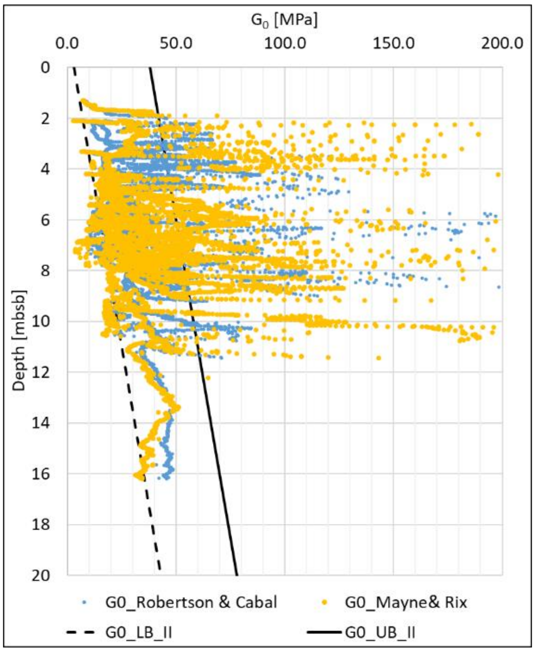


Figure 8-37 G_0 for soil unit II.

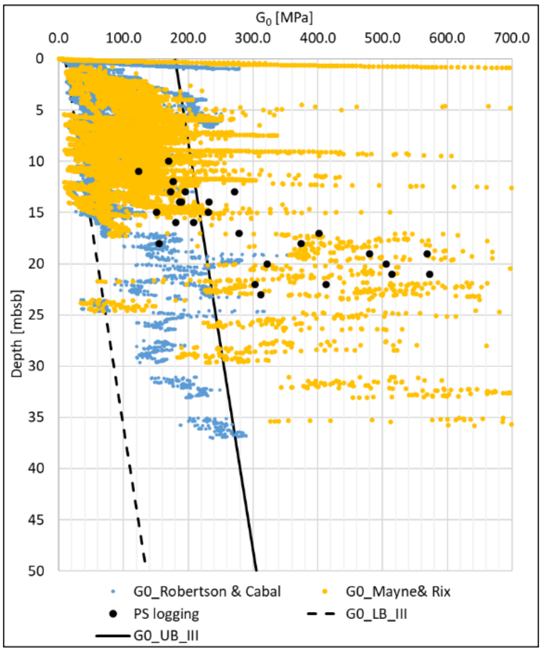


Figure 8-38 G_0 for soil unit III.

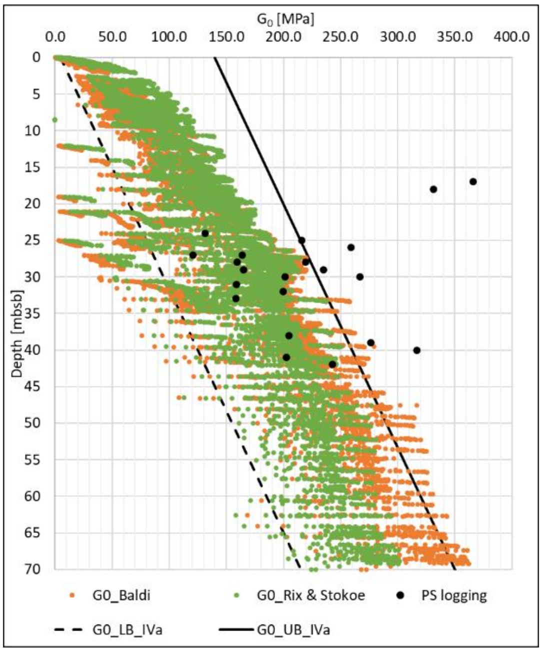


Figure 8-39 G_0 for soil unit IVa.

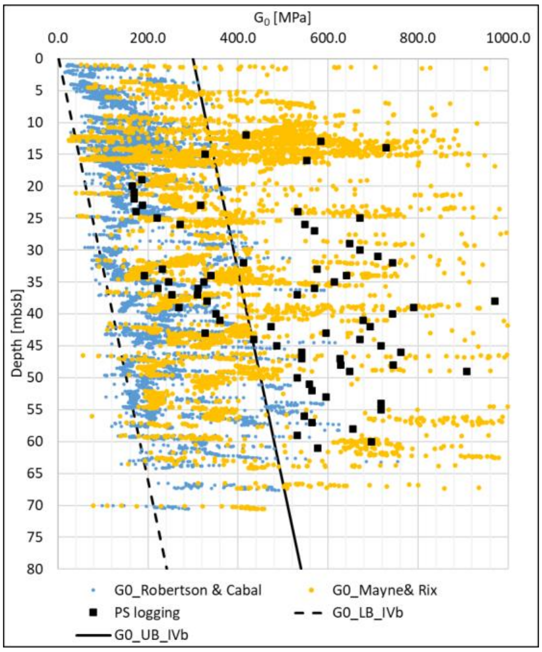


Figure 8-40 G_0 for soil unit IVb.

Table 8.20 G_0 values for design.

Soil unit	G_0_LB [MPa]	G_0_UB [MPa]
Ia	4.5z+7	4.5z+45
Ib	1.0z+2	1.0z+30
II	2.0z+3	2.0z+38
III	2.5z+10	2.5z+180
IVa	3.0z+5	3.0z+140
IVb	3.0z+2	3.0z+300

z is the depth calculated from seabed

8.5.10.2 Evaluation of Epsilon50

The strain of soil sample at 50% of the maximum deviatoric stress at failure, ε50, has been determined from the result of Uncosolidated Undrained (UU), Consolidated Isotropic Undrained compression (CIUc) and Consolidated Anisotropic Undrained compression (CAUc) tests. In Table 8.21, the results are shown.

Figure 8-41-Figure 8-44 present the ε50 values with the laboratory tests for the different cohesive soil units.

Table 8.21 Epsilon50 for the cohesive soil units.

Soil unit	Mean [%]	Max [%]	Min [%]	75% Confidence [%]	Test number
Ib	1.2	2.5	0.1	1.3	54
II	2.1	4	0.5	2.4	11
III	2	4.9	0.1	2.2	30
IVb	2.9	6.2	0.8	3	43

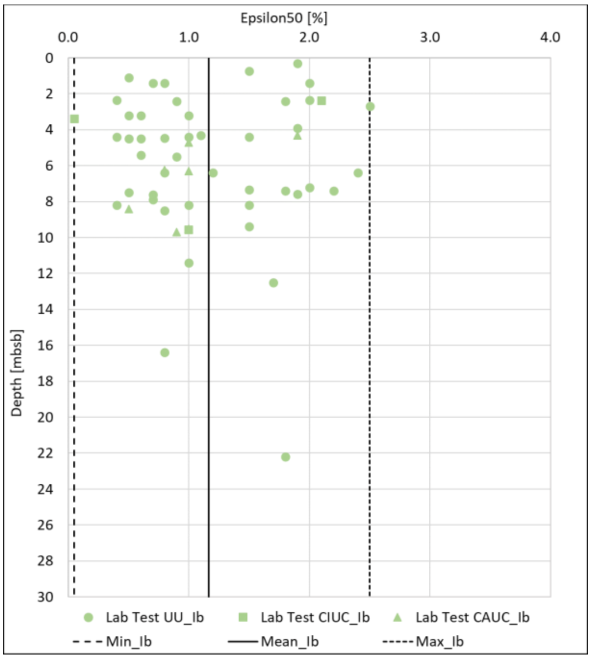


Figure 8-41 Epsilon50 values for unit Ib.

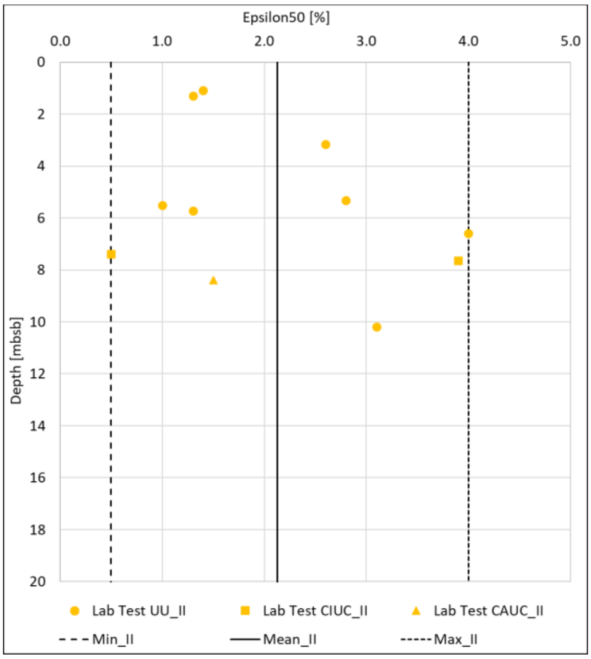


Figure 8-42 Epsilon50 values for unit II.

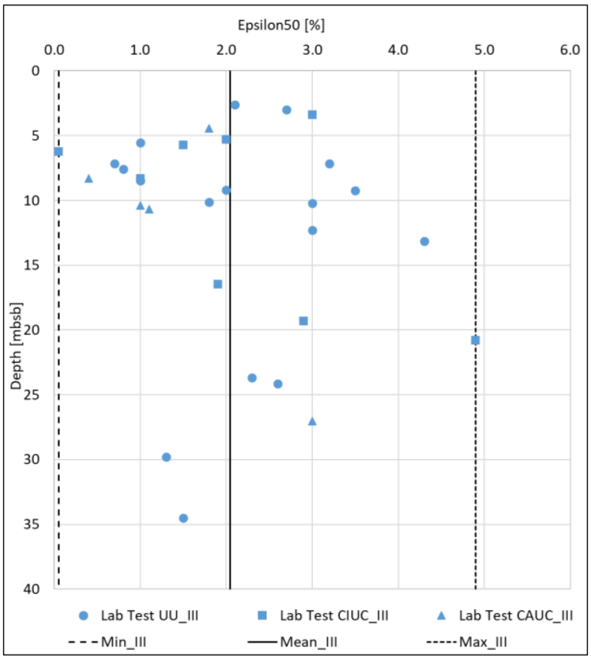


Figure 8-43 Epsilon50 values for unit III.

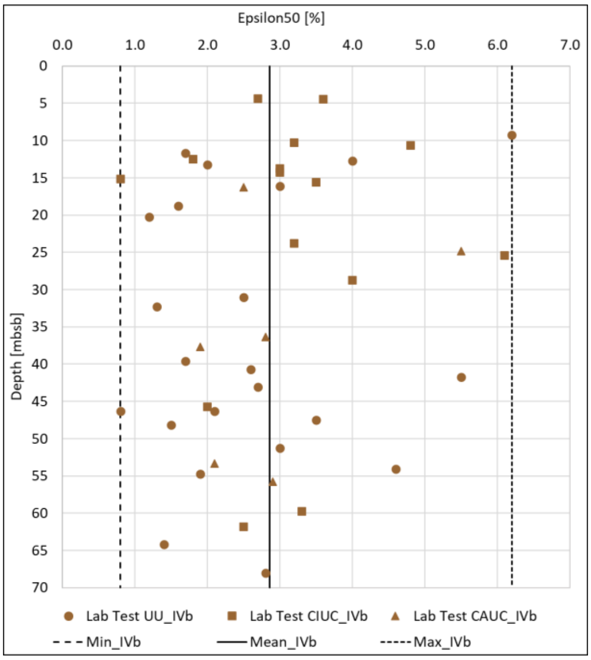


Figure 8-44 Epsilon50 values for unit IVb.

8.6 Rock Units – detailed Geotechnical Interpretation

Ramboll has subdivided the Rocks encountered in the Bornholm boreholes into six separate units that are shown in Table 8.22 below with the geotechnical behaviour of the rocks described below.

Table 8.22 Subdivision of Rocks in the Bornholm Sites

Unit	Rock Type	Description	Age and Seismic unit
Va1	Limestone/Mudstone	Soft, very weak to medium weak	Cretaceous – SU 3
Va2	Limestone/Mudstone	Hard, weak to extremely strong	Cretaceous – SU 3
Vb1	Chalk	Soft Chalk	Cretaceous – SU 3
Vb2	Chalk	Hard Chalk	Cretaceous – SU 3
Vc1	Sandstone	Soft, extremely weak to weak	Jurassic – SU 3
Vc2	Sandstone	Hard, medium strong to strong	Jurassic – SU 3

8.6.1 Available data

The available data for the rocks includes:

- Total core recovery TOC [%]
- Rock Quality designation RQD
- Unconfined compression tests UCS
- Point load tests PL
- Bulk density measurements of rock lumps
- Recorded induration H1-H5
- Rock type description (sandstone, mudstone, limestone etc.)
- Rock strength as recorded on the borehole logs (weak, strong, etc.)

8.6.2 Assessment of the available data

Due to the layered and fragile nature of many of the present rocks, the rock quality designation RQD tends to underestimate the rock quality due to drilling induced fracturing. The RQD value is calculated as the percentage of a core section being more than 10 cm in length. Examples of possible drilling induced fractures are seen in Figure 8-45.

Figure 8-45 Example of drilling induced fractures causing the RQD value to be low.

The corresponding values of total core recovery and RQD are seen in Figure 8-46. Even though core material has been recovered (TCR =60-80%), the RQD value is 20-40 %, and zero in some sections. No UCS tests have been carried out in the chalk.

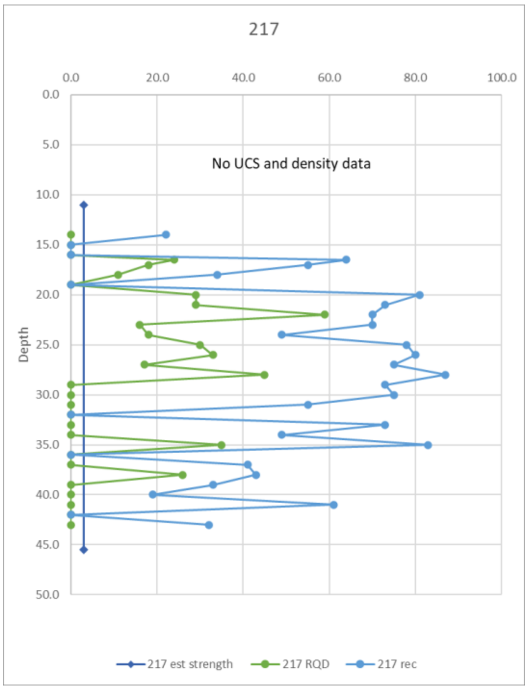


Figure 8-46 BH-217 TCR and RQD values in H2 chalk.

On the other hand, the sampling bias for the UCS tests (testing the remaining hardest pieces of the rock that survived the drilling process) can also lead to significantly overestimating the rock strength, Figure 8-47.

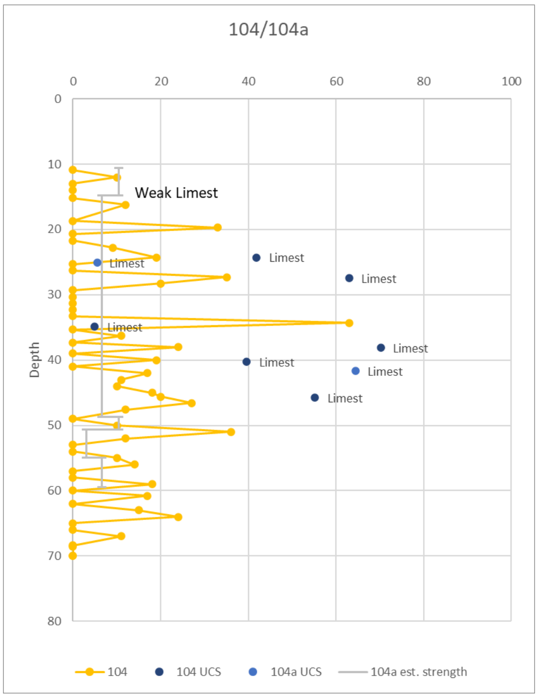


Figure 8-47 Example of weak limestone with very low RQD but showing high UCS strength.

In the following, the description of the rock core material on the borehole logs is used as the main guidance for the rock mass assessment, as it describes all the recovered material and not just the pieces longer than 10 m as the UCS. However, the other available data is also considered. For all rocks except chalk, the ISO 14689 strength assessment is used as per Table 8.23. Further, the induration is given, Table 8.24. For chalk, it is indicated whether it is high, medium or low-density chalk. The term DM (damaged) is also used. These terms come from the CIRIA description method, but the method is not used consistently.

Table 8.23 Rock strength assessment according to ISO 14689 (BS EN ISO 14689:2018. Geotechnical investigation and testing-Identification, description and classification of rock.).

Unconfined Compressive Strength of Rocks	Unconfined Compressive Strength (MPa)	Qualitative Interpretation of UCS (Geological Hammer)
Extremely Weak	0.6-1.0	Gravel size lumps crush between finger and thumb. Indented by thumbnail.
Very Weak	1-5	Crumbles under firm hammer blows. Can be peeled by knife.
Weak	5-25	Can be peeled with knife, fractures with single blow of hammer.
Medium Strong	25-50	Cannot be peeled with knife, fractures with single blow of hammer.
Strong	50-100	Rock broken by more than one hammer blow.
Very Strong	100-250	Requires many hammer blows to break specimen.
Extremely Strong	>250	Rings on hammer blows. Only chipped with geological hammer.

Table 8.24 Degree of induration.

Symbol	Term	Description
H1	Unlithified	The material can easily be formed by hand. Grainy material will fall apart when dry.
H2	Slightly Indurated	The material can easily be cut with a knife and can be scratched with a fingernail. Individual grains can be picked out with the fingers when the material is grainy. Ex: Chalk.
H3	Indurated	The material can be cut with a knife but cannot be scratched with a fingernail. Individual grains can be picked out with a knife when the material is grainy. Ex: Most Danish Danian limestone rocks.
H4	Strongly Indurated	The material can be scratched with a knife. Individual grains do not come out with a knife. Fractures will follow grain surfaces. Danish ex: Salthomkalk, Skelbrokalk, Neksl't sandsten.
H5	Very Strongly Indurated	The material cannot be scratched with a knife. Cracks and fracture surfaces will go through individual grains in grainy material. Danish ex: Balka sandsten, flint.

8.6.3 Unit weight

The total unit weights are computed based on the bulk density laboratory test results. The unit weight for each rock unit is taken as the average value, and the submerged unit weight is presented Figure 8-48-Figure 8-53 and Table 8-25 for each rock unit.

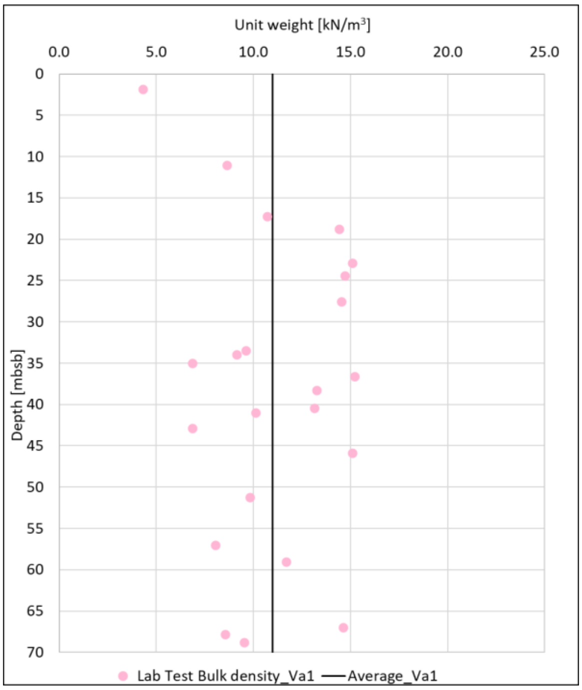


Figure 8-48 Submerged unit weight for unit Va1.

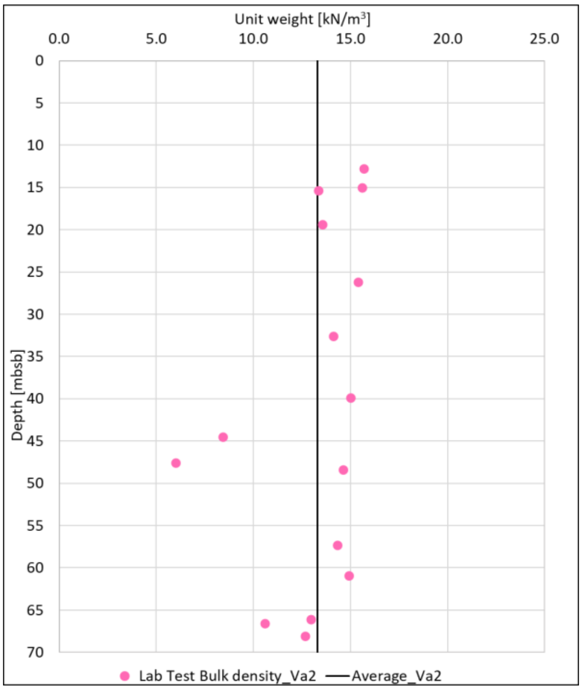


Figure 8-49 Submerged unit weight for unit Va2.

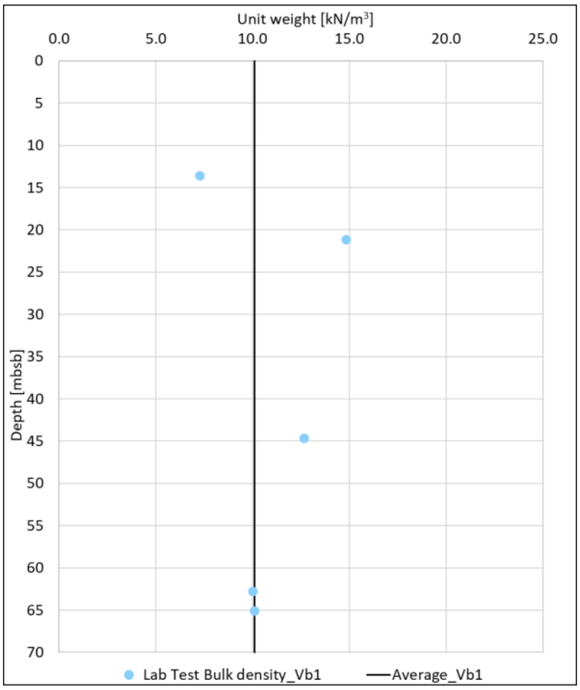


Figure 8-50 Submerged unit weight for unit Vb1.

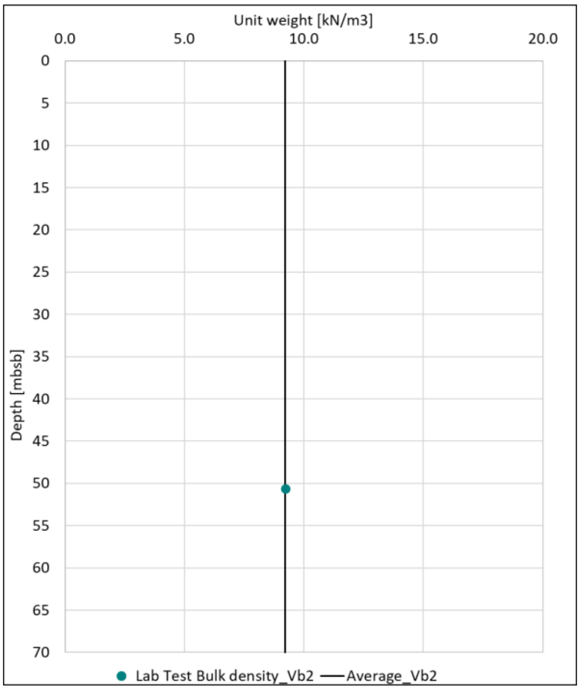


Figure 8-51 Submerged unit weight for unit Vb2.

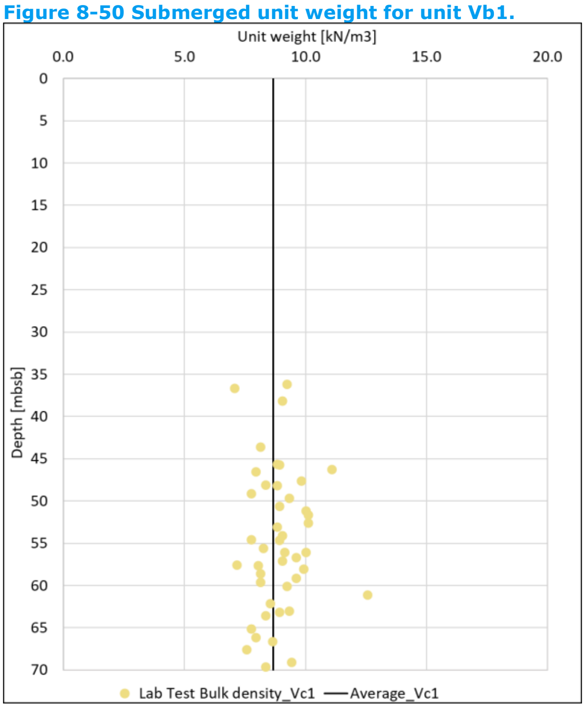


Figure 8-52 Submerged unit weight for unit Vc1.

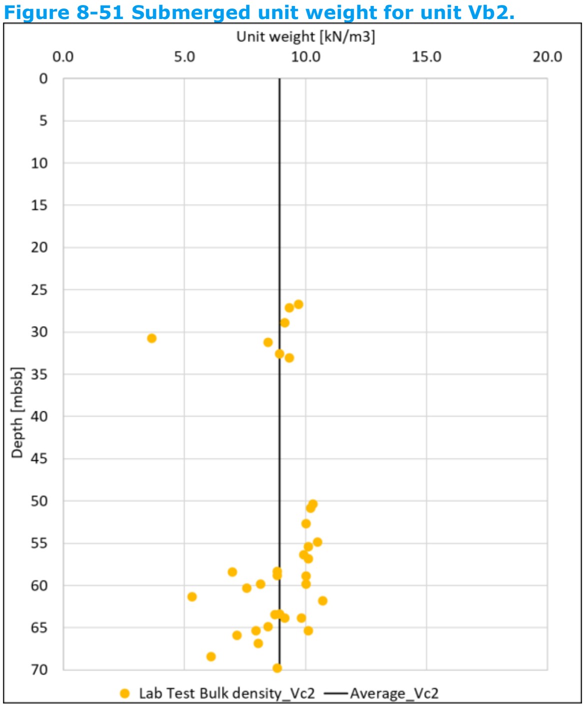


Figure 8-53 Submerged unit weight for unit Vc2.

Table 8.25 Submerged unit weight for each rock unit.

Rock Unit	γ_{sub} [kN/m³]
Va1	11
Va2	13.3
Vb1	10.1
Vb2	9.2
Vc1	8.7
Vc2	8.9

8.6.4 Specific gravity

The specific gravity has been determined from a total of 18 tests that have been performed (including outliers). For the rock units Va1 and Va2, there are not available laboratory tests for the specific gravity. The results for the rock units with available laboratory test are depicted in Figure 8-54-Figure 8-57.

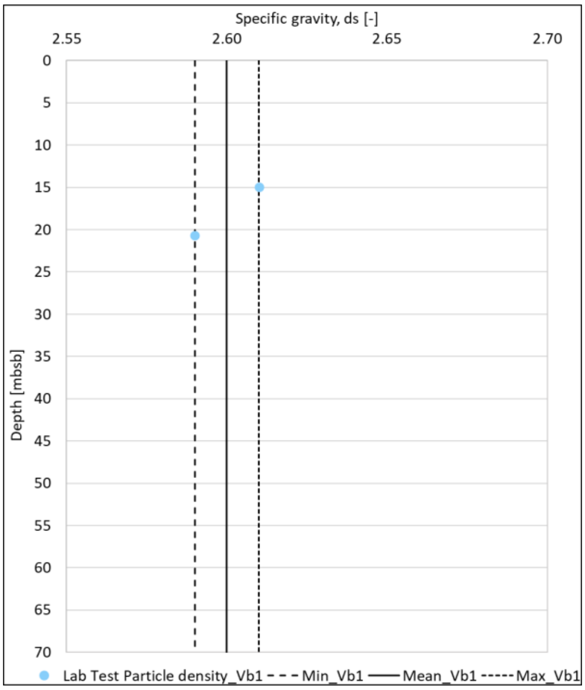


Figure 8-54 Specific gravity for unit Vb1.

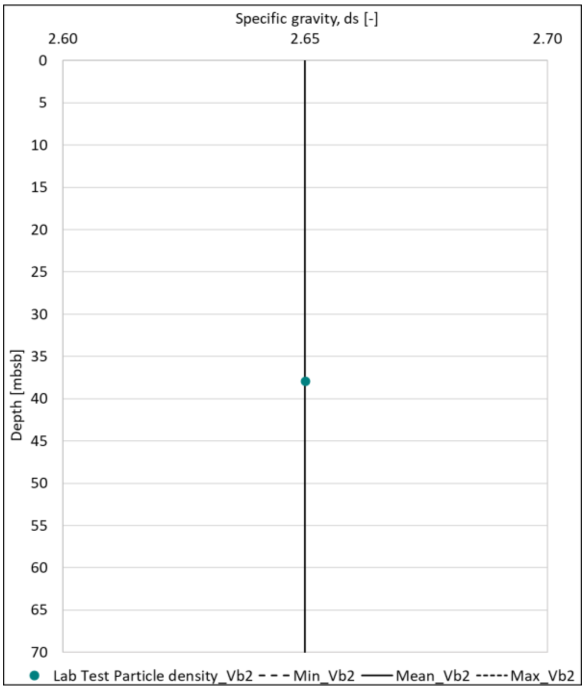


Figure 8-55 Specific gravity for unit Vb2.

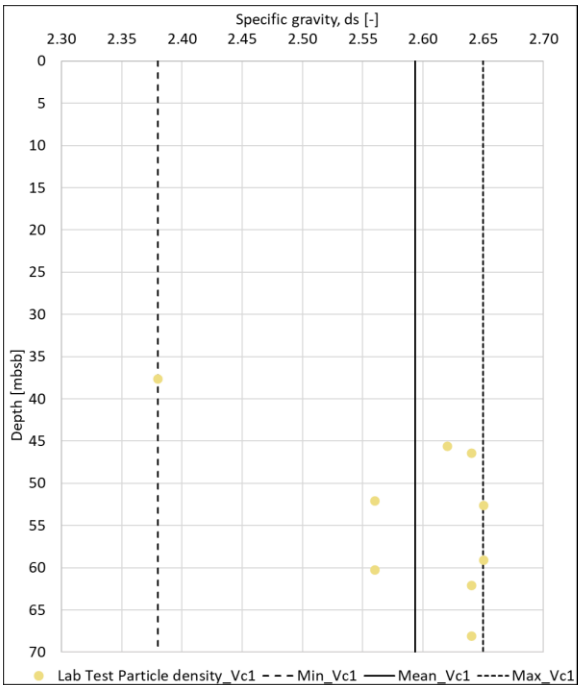


Figure 8-56 Specific gravity for unit Vc1.

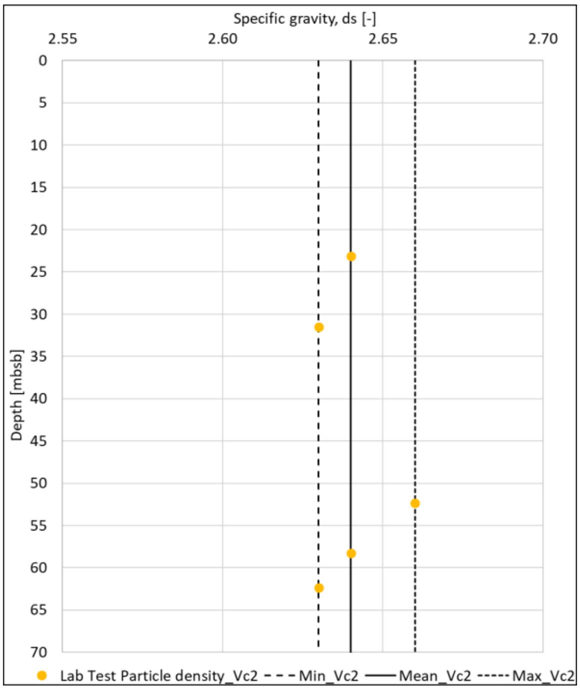


Figure 8-57 Specific gravity for unit Vc2.

As seen in the figures, the specific gravity varies between 2.38 to 2.66. The results are summarised in Table 8.26.

Table 8.26 Specific gravity for each rock unit.

Rock Unit	Mean [-]	Max [-]	Min [-]	75% Confidence [-]	Test number
Va1	-	-	-	-	0
Va2	-	-	-	-	0
Vb1	2.6	2.61	2.59	2.59	2
Vb2	2.65	2.65	2.65	2.65	1
Vc1	2.59	2.65	2.38	2.57	9
Vc2	2.64	2.66	2.63	2.64	5

8.6.5 Compressive strength

Compressive strength has been measured directly by the UCS tests and indirectly (on rock lumps) by Point load tests, giving the I_{50} index strength.

8.6.5.1 Point load index strength

The point load data has been sorted based on rock type (as described for the sample). Unfortunately, no corresponding density measurements are available, so it is not possible to link the PL data to the UCS data and thus convert the I50 index value to strength. The number of tests on each rock type is listed in Table 8.27.

Table 8.27 Point load data, number of tests on each rock type.

Rock Type	No of tests
Calcarenite	1
Chalk	13
Limestone	76
Marlstone	6
Metamorphic rock (granite)	6
Mudstone	21
Sandstone	3
Siltstone	11
Total	137

The I_{50} index is plotted versus depth per rock type in Figure 8-58 and Figure 8-59. The text added to each plotted represent the following: EW (Extremely Weak), VW (Very Weak), W (Weak), MW (Medium Weak), ES (Extremely Strong), VS (Very Strong), S (Strong) and MS (Medium Strong). The plots clearly illustrates that the top 30-40 m are dominated by limestone with very variable strength weak to very strong, while weak and very weak mudstone and siltstone seems to be present below 40-50 m.

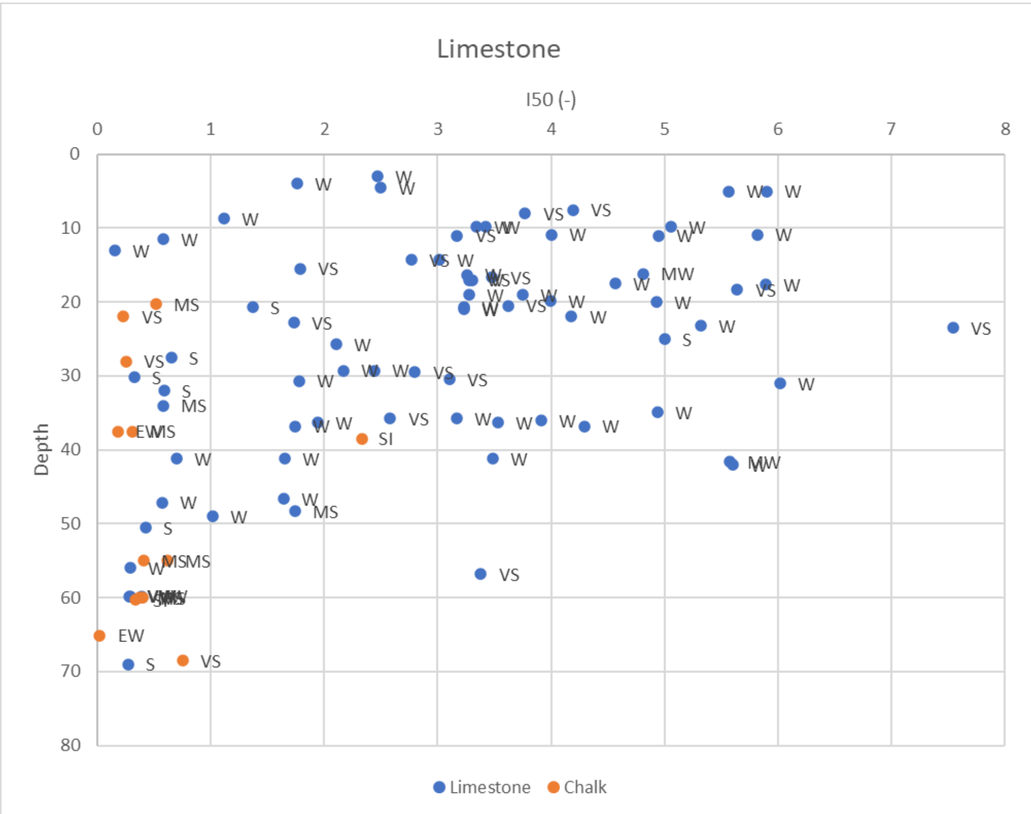


Figure 8-58 I_{50} index strength versus depth, limestone and chalk.

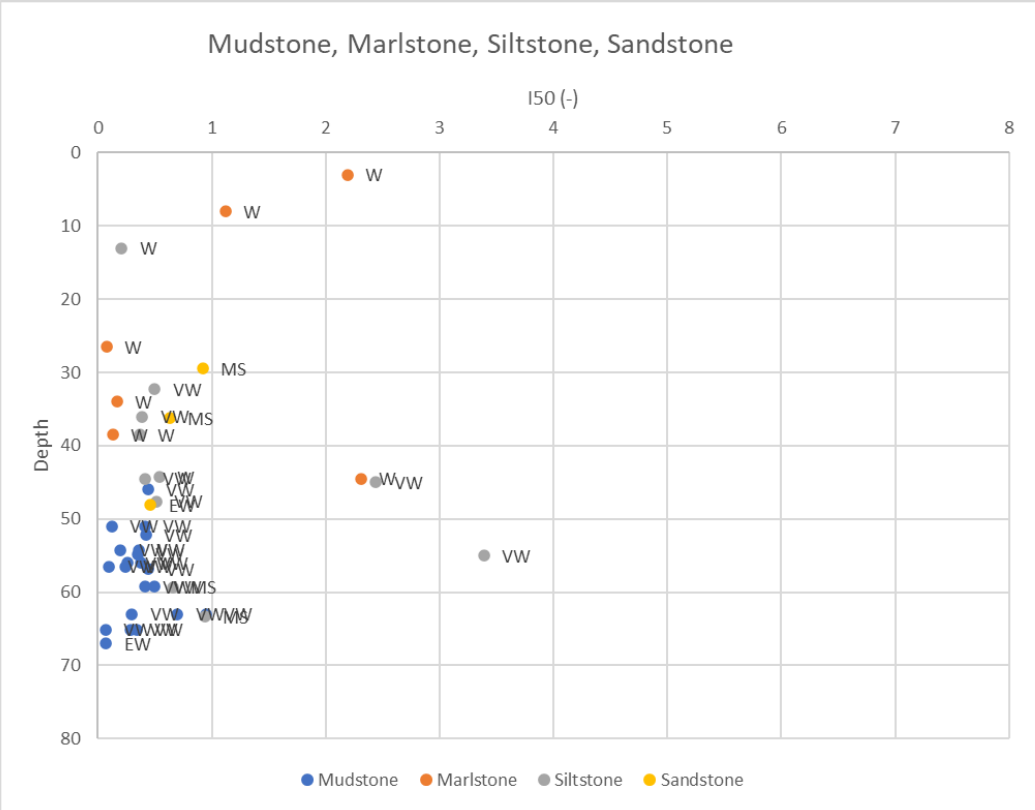


Figure 8-59 I_{50} index strength versus depth, mudstone, marlstone siltstone and sandstone.

8.6.5.2 Unconfined compressive strength

The unconfined compressive strength data has been sorted based on rock type (as described for the sample). The number of tests on each rock type is listed in Table 8.27. It should be noted that no UCS tests are available on the chalk, marlstone and mudstone. As mentioned above, it should be expected that the stronger units are more predominant for the UCS compared to the PL, as the UCS requires either a 20 cm unfractured core section or a 10 cm piece firm enough to sustain re-coring to a smaller diameter, whereas the PL test just requires a lump of the rock.

Table 8.28 Unconfined compressive strength data, number of tests on each rock type.

Rock Type	No of tests
Igneous rock	1
Chalk	0
Limestone	56
Marlstone	0
Mudstone	0
Sandstone	1
Siltstone	13
Total	71

However, the bulk density for the tested specimens and the unconfined compressive strength correlates well with strength description (weak, strong etc.) given for each test specimen, Figure 8-60. It should also be noted that the majority of the UCS tests have been done on limestone. Based on the limestone data a correlation is established between the unconfined compression strength and the bulk density of the limestone. It is assumed that the other units (apart from the chalk) also follow this correlation. The correlation allows for estimating the strength at locations where bulk density has been determined, supplementing the UCS tests.

Based on the rock strength description from the borehole logs and the available UCS tests, estimated strength for all rock sections can be established, as per Table 8.29 to Table 8.31.

Table 8.29 Strength for Limestone

Description	No of tests	Average [MPa]	Max [MPa]	Min [MPa]
Extremely Strong (ES)	1	261	261	261
Very Strong (VS)	5	123.8	142	100
Strong (S)	15	61.3	82.9	9.4
Medium Strong (MS)	11	34.9	49.4	28.3
Weak (W)	20	10.5	24.4	1.51
Medium Weak (MW)	0	6.9*	-	-
Very Weak (VW)	4	3.3	5.0	1.9

*Estimated values

Table 8.30 Strength for Siltstone, Sandstone and Marlstone

Description	No of tests	Average [MPa]	Max [MPa]	Min [MPa]
Strong (S)	2	38.2	65.5	10.9
Medium Strong (MS)	0	19.1*	-	-
Weak (W)	7	6.6	9.9	5.2
Medium Weak (MW)	0	5.1*	-	-
Very Weak (VW)	4	3.5	4.6	2.2
Extremely weak (EW)	0	1*		

*Estimated values

As mentioned above, there is no UCS data for the chalk, however the indurations are given. Based on these and general experience, the following strengths are estimated:

Table 8.31 Strength for Chalk

Description	No of tests	Average [MPa]
Chalk DM	0	1*
Chalk H2	0	3*
Chalk H3	0	15*
Chalk H4	0	40*
Chalk H5	0	70*

*Estimated values

On the basis of this strength evaluation, the bedrocks have been divided according to main rock type and strength (the UCS strength being lower or higher than 10 MPa):

Table 8.32 Rock units on the basis of this strength evaluation

Unit name	Rock type	Correlation to strength description on BH logs
Va1	Limestone, soft	Very weak to Medium weak
Va2	Limestone, hard	Weak to extremely strong
Vb1	Chalk, soft	Dm (H1) to H2
Vb2	Chalk, hard	H3 to H5
Vc1	Sandstone, soft	Extremely weak to weak
Vc2	Sandstone, hard	Medium strong to strong

Table 8.33 Strength for the rock units

Unit name	Description	Average [MPa]	Strength of units
Va2 Limestone, hard	ES	261	10-260 MPa
	VS	123.8	
	S	61.3	
	MS	34.9	
	W	10.5	
Va1 Limestone, soft	MW	6.9*	~3 to 7 MPa
	VW	3.3	

Unit name	Description	Average [MPa]	Strength of units
Vb1 Chalk, soft	Chalk DM	1*	~1-3 MPa
	Chalk H2	3*	
Vb2 Chalk, hard	Chalk H3	15*	15-70
	Chalk H4	40*	
	Chalk H5	70*	

Unit name	Description	Average [MPa]	Strength of units
Vc2 other, hard	S	38.2	19-38
	MS	19.1*	
Vc1 other, soft	W	6.6	~3-7 MPa
	MW	5.1*	
	VW	3.5	
	EW	1*	

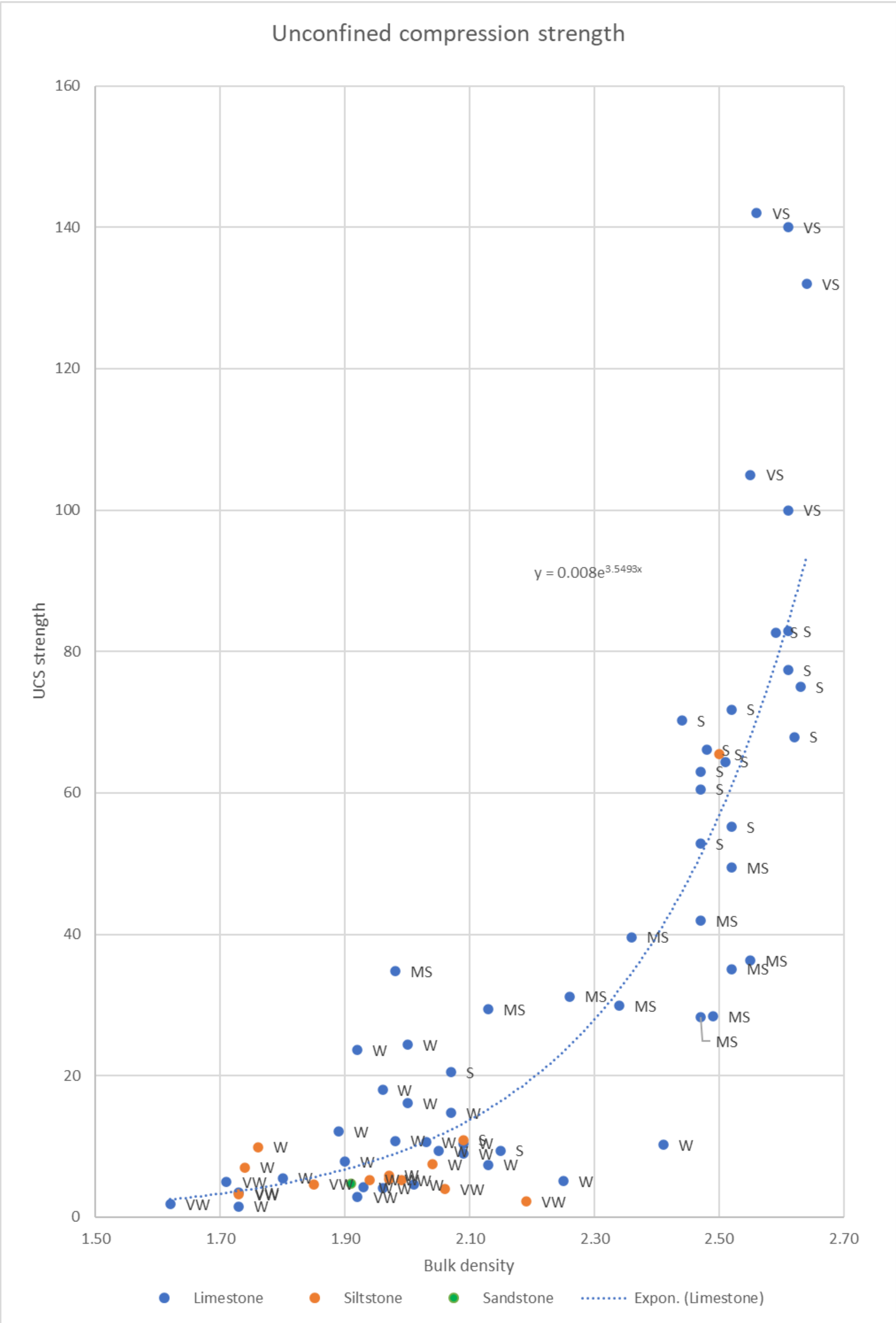


Figure 8-60 Unconfined compressive strength versus bulk density.

8.6.6 Stiffness

The stiffness data E_{50} from UCS tests has been sorted based on rock type (as described for the sample). However, not all UCS tests have a corresponding E_{50}, only the failure strength is given. The number of tests on each rock type is listed in Table 8.34. It should be noted that no stiffness data are available on the chalk, marlstone and mudstone. As mentioned above, it should be expected that the stronger units are more predominant for the UCS testing, as the UCS requires either a 20 cm unfractured core section or a 10 cm piece firm enough to sustain re-coring to a smaller diameter.

Table 8.34 E_{50} stiffness data, number of tests on each rock type.

Rock Type	No of tests
Igneous rock	1
Chalk	0
Limestone	46
Marlstone	0
Mudstone	0
Sandstone	1
Siltstone	1
Total	49

However, the bulk density for the tested specimens and the E_{50} stiffness correlates well with strength description (weak, strong etc.) given for each test specimen, Table 8.35. It should also be noted that the majority of the UCS tests (and thus stiffness determinations) have been done on limestone.

Based on the rock strength description from the borehole logs and the available E50 data, the stiffness can be estimated for the limestone:

Table 8.35 E_{50} for Limestone.

Description	No of tests	Average [MPa]	Max [MPa]	Min [MPa]
Extremely Strong (ES)	1	61300	-	-
Very Strong (VS)	4	27600	39900	18700
Strong (S)	10	19500	40500	11200
Medium Strong (MS)	9	11400	14300	5090
Weak (W)	16	2500	4500	230
Medium Weak (MW)	-	-	-	-
Very Weak (VW)	4	890	1200	282

Unit name	Description	Average [MPa]	Stiffness of units
Va2 Limestone, hard	ES	61300	2500-61300
	VS	27600	
	S	19500	
	MS	11400	
	W	2500	
Va1 Limestone, soft	MW	-	280* to 890
	VW	890	

*min value

Table 8.36 E_{50} for Siltstone, Sandstone and Marlstone.

Unit name	Description	Single value [MPa]	Stiffness of units
Vc2 other, hard	S	-	
	MS	-	
Vc1 other, soft	W	916 (siltstone)	
	MW	-	
	VW	1790 (sandstone)	
	EW	-	

For the VC1 and Vc2 units, it is suggested to use the same stiffness as for limestone units Va1 and Va2.

For the rock units of Vc1 and Vc2, the stiffness values are based on the experience.

Table 8.37 Estimated E_{50} for Chalk.

Unit name	Description	Estimated E_{50} [MPa]
Vb1 Chalk, soft	Chalk DM	300
	Chalk H2	1500
Vb2 Chalk, hard	Chalk H3	3000
	Chalk H4	12000
	Chalk H5	20000

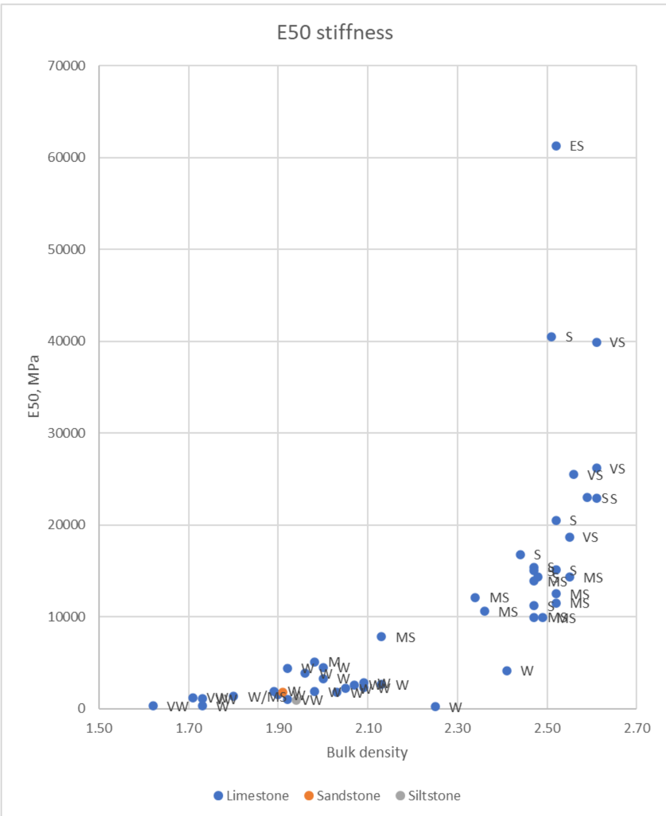


Figure 8-61 E50 stiffness from UCS tests, versus bulk density

8.6.7 Bedrock overview and correlation with geophysical logs

An overview of the bedrock types encountered in each borehole and the depth of the bedrock picked on the geophysical logs are given in
Table 8.38.

In the following sections, the strength profiles for the boreholes containing bedrock are presented, showing the estimated strength as well as the UCS test data, as these may indicate thin layers or lumps of harder material. Further, the UCS strength estimate based on bulk density (UCS, calc) and the top bedrock from geophysics are also indicated.

Table 8.38 Bedrock overview, Bornholm II.

Borehole	Picked "bedrock"	Rock type
BH-202	65.5	Very weak limestone (deep) Bedrock picked in this deep layer
BH-203	14.4	Weak marlstone
BH-205	19.0	Very weak and weak limestone/siltstone
BH-207	10.5	Chalk to 52 m, then limestone
BH-209	10.0	Weak limestone and very weak mudstone
BH-210	40.3	Sandstone followed by variable (strong) limestone layers. Sandstone may start at 16 m but no rock data Bedrock picked in limestone
BH-212	15.5	Limestone (very strong) w. siltstone/mudstone layers
BH213	1.0	Weak limestone/marlstone layers Bedrock picked in very weak siltstone consistent w. BH log but no rock data
BH-216	7	Weak limestone/siltstone to 31 m, then chalk. Bedrock picked top of in weak siltstone
BH-217	11.0	Chalk H2, 1 m strong limestone layer at 34-35 m
BH-218	35.0	Very and medium strong limestone to 60 m followed by chalk.
BH-219	7.5	Chalk to 44.5 m, then medium strong siltstone

8.7 Design soil profiles

For each Borehole performed in the soil investigation combined with the CPT, an individual profile has been made based on the findings presenting in this Chapter.

The individual profiles can be seen in Appendix 4 as tables. Appendix 5 presents the measured and derived values from the CPT for each of the individual profiles. Finally, Appendix 6 presents the bedrock strength profiles for each individual location of borehole with CPT.

9. Leg Penetration analysis

9.1 Introduction

Spudcan leg penetration analysis is an important process in the installation of jack-up vessels for WTG installation. The analysis involves evaluating the bearing capacity of a spudcan footing, which is a type of foundation used on jack-up vessels, to predict the penetration depth of the spudcan in different soil layers and to assess potential risks, such as punch-through and rapid leg penetration. An accurate prediction of the spudcan penetration depth is necessary to determine the minimum leg length of a jack-up and to predict any hazards that could destabilise the vessel and lead to an imbalance between the spudcan legs, which leads the vessel to tilt. This information is useful in evaluating the adequacy of the leg length and thus the suitability of the proposed vessel for a particular location. The analysis also helps to identify precautionary measures that an installation contractor can adopt to facilitate a safe installation of the spudcan.

This section of the report will take the different risks into account during installation and provide estimated leg penetration depths.

9.2 Seabed and Soil Conditions

9.2.1 Geotechnical

The geotechnical interpretation of the ground information recovered from the Bornholm Sites is provided in Section 8 with the Geotechnical Soil Profiles provided as tables in Appendix 4. Appendix 5 presents the measured and derived values calculated from the CPTs for each of the individual profiles. The site is generally underlain by clay units, though one borehole location showed a layer of approximately 9 m below seabed of sand on top of clay. A few locations have a very loose sand layer at the seabed which can be present to depths of up to 0.5 m below the seabed.

9.3 Methodology

Spudcan penetration predictions are typically made using standard formulas for calculating the bearing capacity of shallow, circular, flat foundations. However, the methods used to analyse these foundations and predict spudcan penetration can differ as shown in Figure 9-1. For a circular footing at depth D, the conventional analysis involves determining the ultimate bearing capacity, Q_v, at that depth and then calculating the vertical displacement, z_u, required to mobilise this resistance. This process includes both a strength analysis and a deformation analysis.

In contrast, a spudcan penetration analysis uses the deformation at ultimate resistance (i.e., the spudcan penetration D) as an input to directly compute the associated soil resistance. This analysis involves only one step and uses the same bearing capacity criteria as for shallow foundation analysis. To account for the differences between these approaches, empirical corrections are often applied to classical bearing capacity formulas.

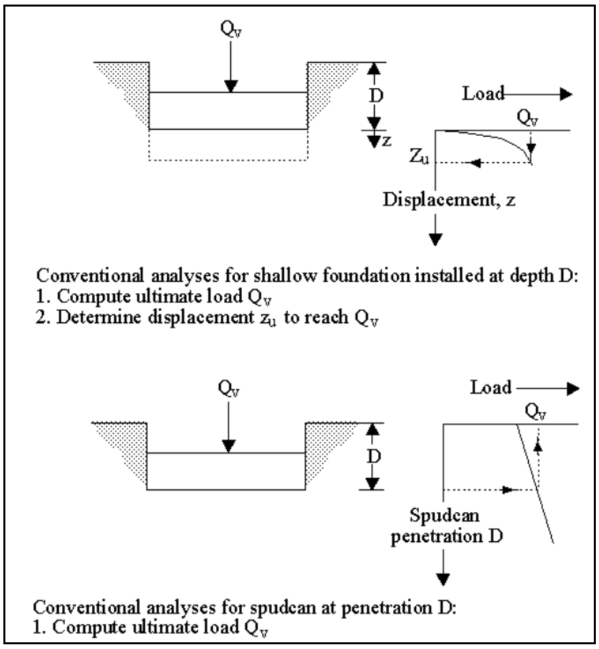


Figure 9-1 Conventional bearing capacity vs spudcan leg penetration (The Society of Naval Architects and Marine Engineers (SNAME)., August 2008)

In soils with multiple layers, it is important to consider two key phenomena when analysing bearing capacity: punch-through and squeezing.

- Squeezing happens when a thin layer of clay is compressed between two harder or stiffer layers of soil, resulting in a higher bearing capacity than what the general formula predicts.
- Punch-through occurs when the soil layer below the one supporting the spudcan has a lower bearing capacity. Where the soil layer supporting the spudcan will behave as a soil plug, penetrating the soil layer below it.

This report will not include the different formulas used. The derived bearing capacity of the locations is done according to standards (The Society of Naval Architects and Marine Engineers (SNAME)., August 2008) (International Standards Organisation, ISO 19905-1:2016(E) Petroleum and natural gas industries-Site-specific assessment of mobile offshore units-Part 1:Jack ups), where a full detailed description can be found.

9.4 Analysis input

9.4.1 Jack-up vessel information

The project is in a preliminary state and no vessel has been selected. As a result the analysis presented in this Chapter will use the 'standard' dimensions of a installation vessel; a typical design is presented in Figure 9-2.

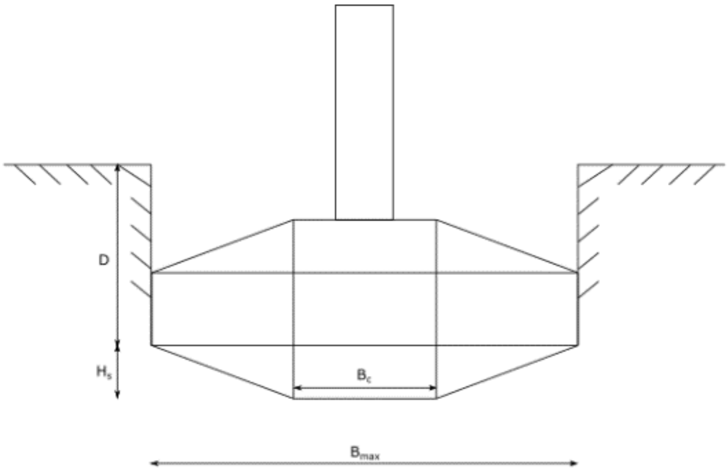


Figure 9-2 A common design of a spudcan.

The geometric and mechanical properties are given below:

Base area at D	95.4 m^2
Base diameter, B_{max}	11.02 m
Volume of the spudcan	266.7 m^3
Tip to base distance, H_s	1.0 m
Base of tip, B_c [m]	3.2 m
Preload bearing pressure	89.5 t/m^2

The preload footing reaction is set to 8,538.3 tonnes and the 93tillwater footing reaction as 5,466.2 tonnes.

9.4.2 Geotechnical parameters

The main soil parameters and terminology used in the spudcan penetration analysis are:

SAND:	design internal friction angle, φ'_{des}
	submerged unit weight, γ'
CLAY:	Undrained shear strength, s_u
	submerged unit weight, γ'
SILT:	Calculated as either cohesive (CLAY) or cohesionless soil (SAND), based on the classification data.

The interpreted soil stratigraphy for each location has been conducted based on in situ data of Cone Penetration Tests (CPT) and soil samples from boreholes; the evaluation of these data is presented in this report and in the Appendix 4 and 5. The detailed analysis of the unit weight, the undrained shear strength and the internal friction angle can be found in Section 8.5.

9.5 Results

The predicted spudcan resistance curves for the used rig are based on three different risks groups, where a specific borehole location will be representative for each group. The risks for each group can be seen in Table 9.1.

Table 9.1 Groupings of analysis based on risks.

Group	Circumstance	Risk
1	Hard soil conditions typically sand or clay with undrained shear strength above 100 kPa.	Small risk as the penetration rate is controllable and the penetration depth is usually small (< than 5 m below seabed).
2	Seabed consisting of soft clay[1].	Medium to high risk which can result in squeezed soil layer and/or rapid penetration due to punch through.
3	Seabed consisting of sand over clay.	High risk of rapid penetration due to punch through.

Locations consisting of a very loose sand layer thinner than 0.5 m from seabed are included.

The groupings of the different boreholes combined with the CPTs can be seen in Figure 9-3 and are described below:

- Group 1 consists of location CPT/BH-213 and CPT/BH-220
- Group 2 consists of location CPT/BH-201, CPT/BH-207, CPT/BH-208 and CPT/BH-214
- Group 3 consists of location CPT/BH-202, CPT/BH-203, CPT/BH-204, CPT/BH-205, CPT/BH-206, CPT/BH-209, CPT/BH-210, CPT/BH-211, CPT/BH-212, CPT/BH-215, CPT/BH-216, CPT/BH-217, CPT/BH-218 and CPT/BH-219.

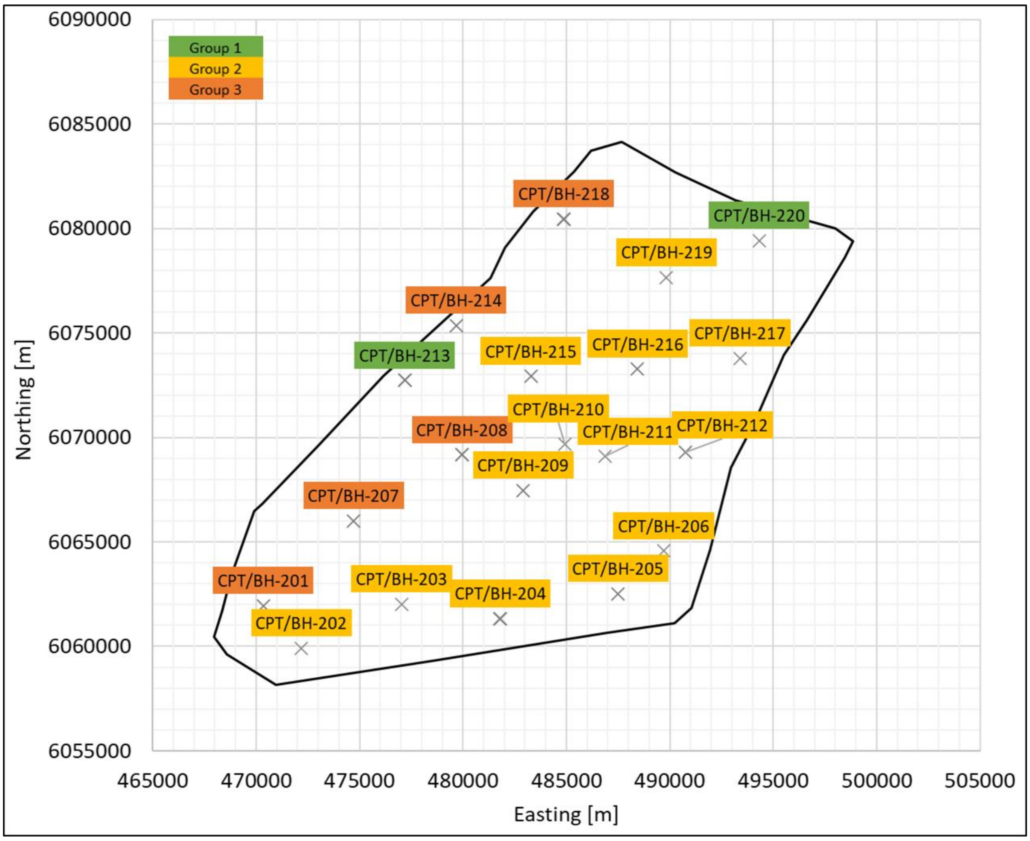


Figure 9-3 Group divided borehole with combined CPT locations.

For a better overview of the area, polygons have been created for the three groups of risks for all CPT and borehole locations and are shown in Figure 9-4.

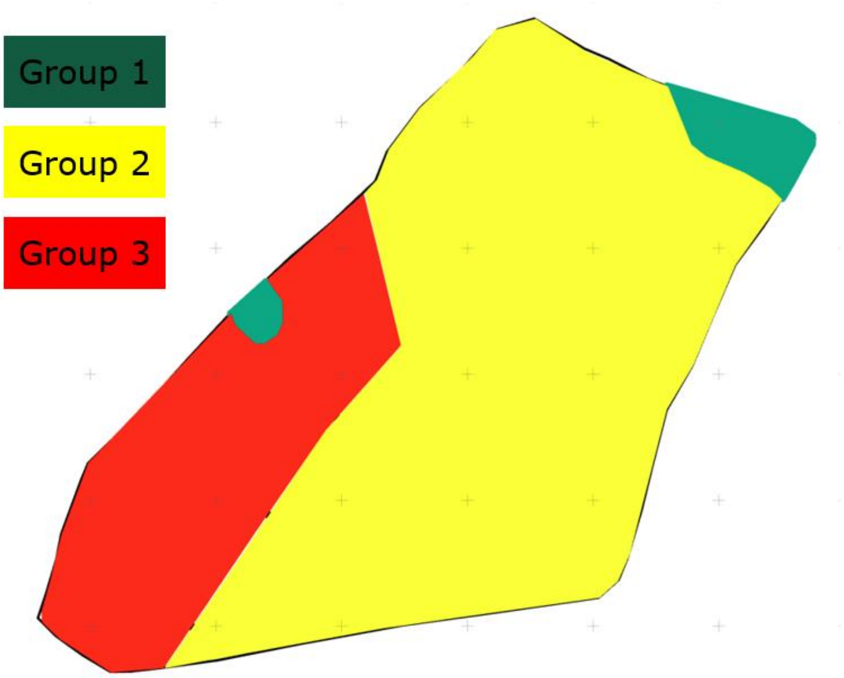


Figure 9-4 Group divided map showing polygons of the 3 areas.

For the leg penetration analysis, the geotechnical characteristics of the representative soil profiles selected from Figure 9-3 are shown in Appendix 4.

9.6 Group 1

Group 1 is solely based on location CPT/BH-220, which will be the representative soil profile of the group. The predicted spudcan resistance of Group 1 can be seen in Figure 9-5.

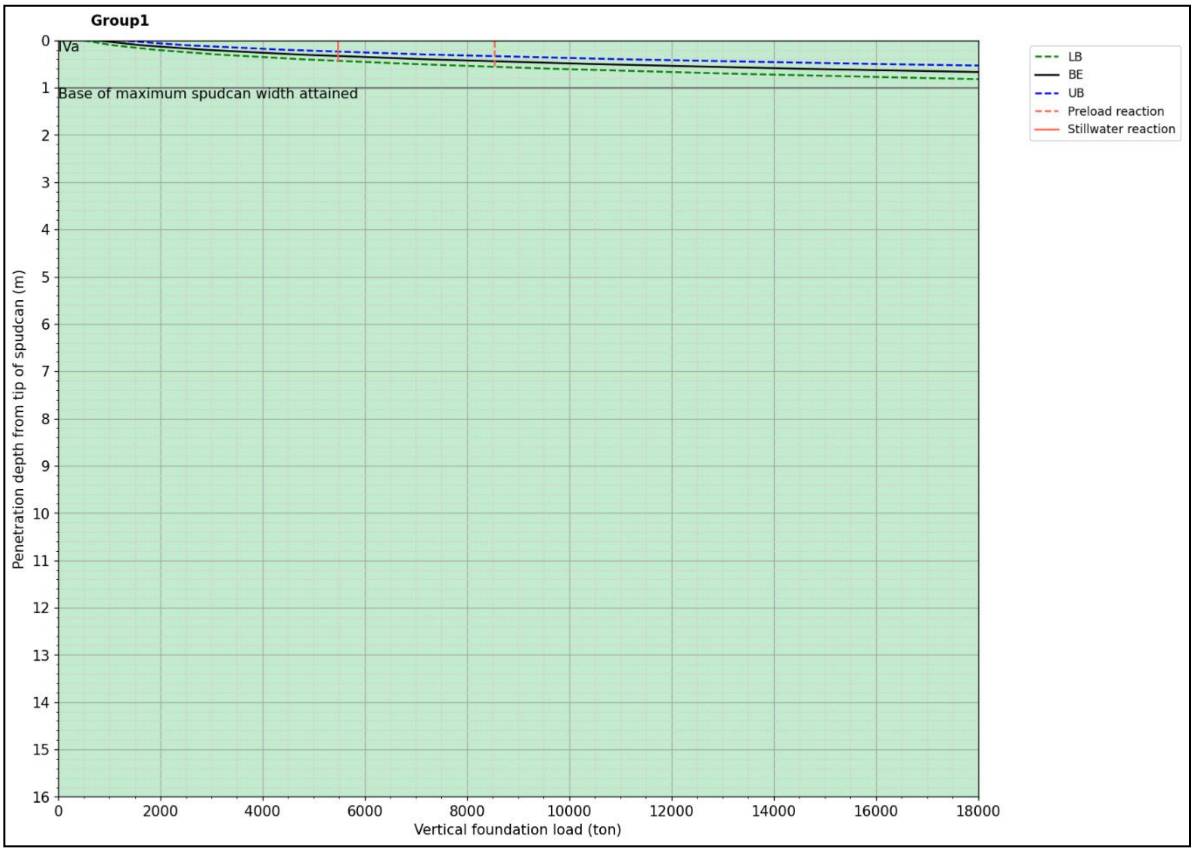


Figure 9-5 Predicted spudcan resistance of Group 1.

Table 9.2 gives the predicted penetration depths for stillwater and preload reaction. It can be observed the predicted penetration depths are less than 1m below seabed, which is considered as low risk.

Table 9.2 Predicted penetration depth for Group 1.

Boundary	Depth for stillwater reaction [m]	Depth for preload reaction [m]
LB	0.43	0.56
BE	0.33	0.44
UB	0.24	0.33

9.7 Group 2

The representative location of Group 2 is CPT/BH-204, where the soil profile consists of 13 m soft clay, underlain by a stiffer clay down to 15.3 m below seabed. This is then followed by interchanging hard and stiff sand and clay layers. The predicted spudcan resistance of Group 2 can be seen in Figure 9-6.

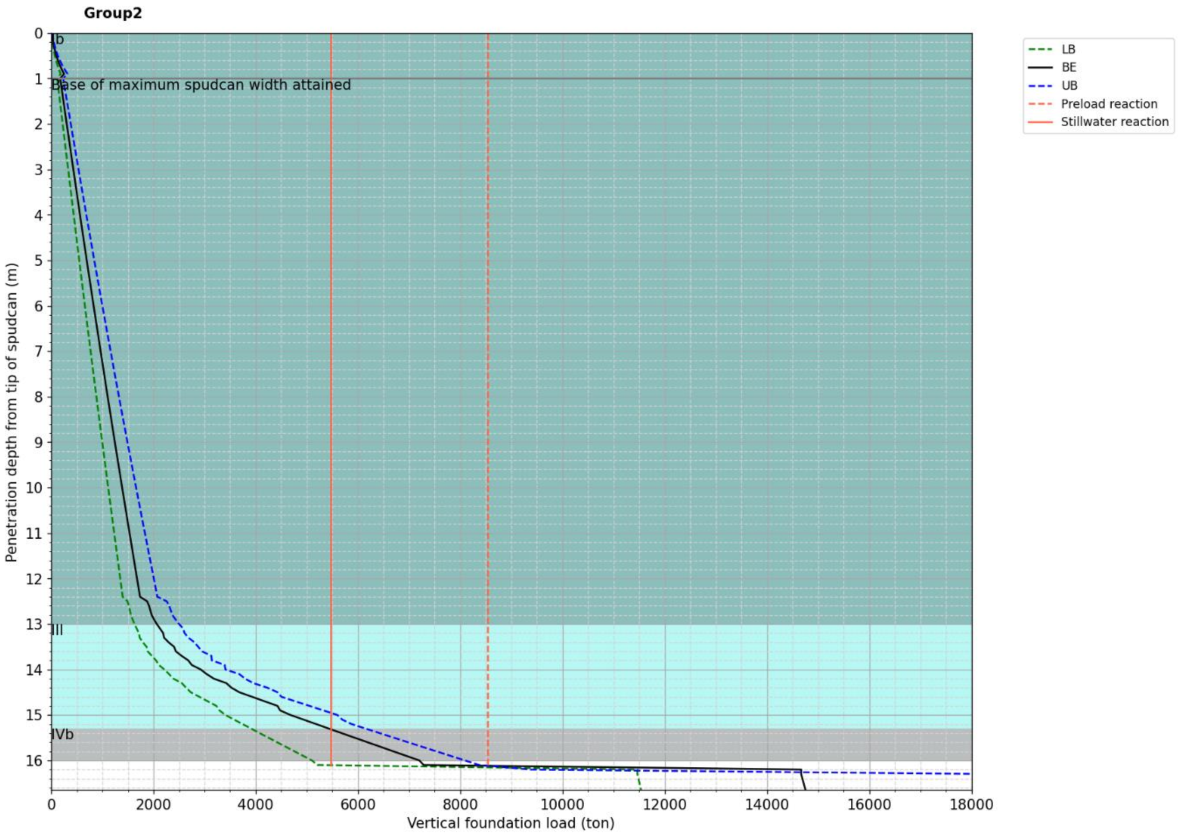


Figure 9-6 Predicted spudcan resistance of Group 2.

Table 9.3 gives the predicted penetration depths for stillwater and preload reaction. It can be observed the predicted penetration depths are around 15.0 m below seabed to 16.2 m below seabed. From 0 m to 12.4 m the penetration happens in the soft clay layer, where from 12.4 m to 16.2 m the penetration method is punch-through clay over clay interchanged with squeezed clay, depending on the boundary (LB, BE or UB) the ranges changes.

Table 9.3 Predicted penetration depth for Group 2.

Boundary	Depth for stillwater reaction [m]	Depth for preload reaction [m]
LB	16.1	16.2
BE	15.3	16.1
UB	15.0	16.1

9.8 Group 3

The representative location of Group 3 is CPT/BH-201, where the soil profile consists of 2.0 m loose sand, underlying by soft clay down to 14.2 m below seabed. Subsequently followed by soft to medium stiff clay down to 37 m below seabed. This is then followed by interchanging hard and stiff sand and clay below seabed. The predicted spudcan resistance of Group 3 can be seen in Figure 9-7.

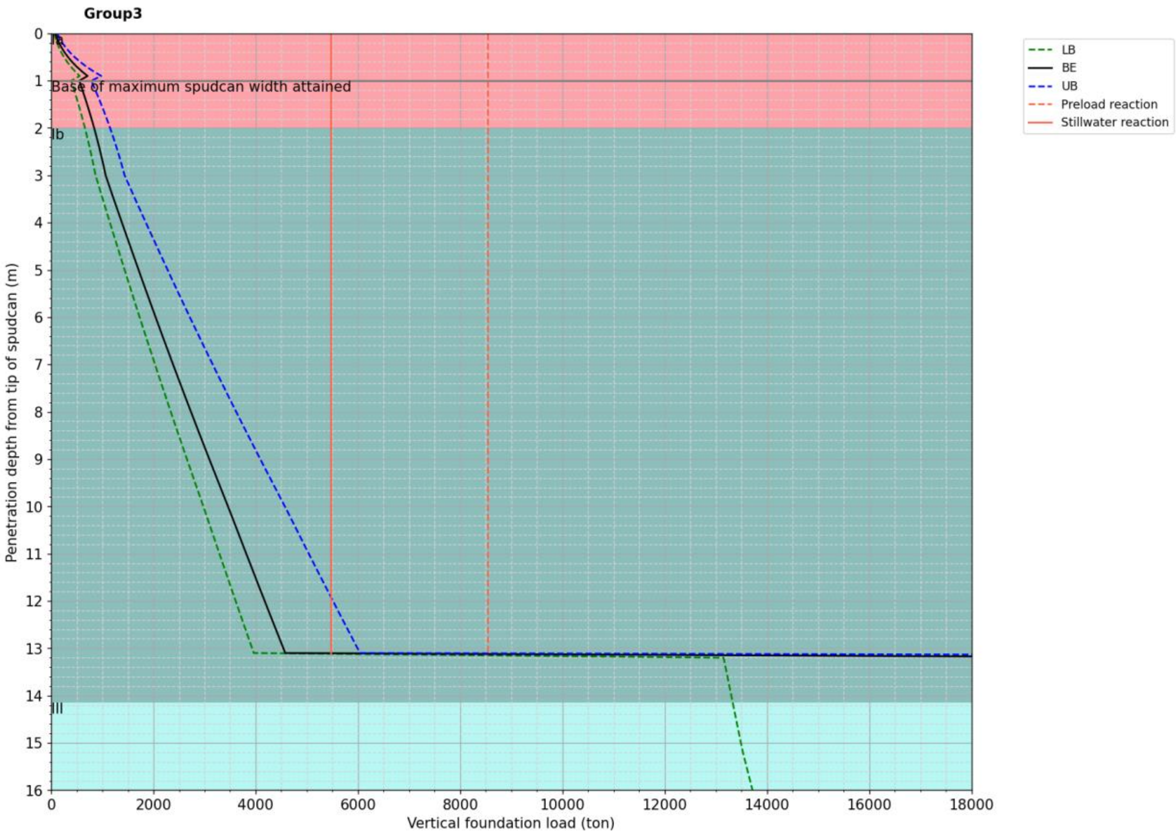


Figure 9-7 Predicted spudcan resistance of Group 3.

Table 9.4 gives the predicted penetration depths for stillwater and preload reaction. It can be observed the predicted penetration depths are from 11.9 m to 13.1 m below seabed. The 2.0 m of sand results in continuously punch-through of the underlying clay layers. The risk of rapid penetration is high at this location.

Table 9.4 Predicted penetration depth for Group 3

Boundary	Depth for stillwater reaction [m]	Depth for preload reaction [m]
LB	13.1	13.1
BE	13.1	13.1
UB	11.9	13.1

9.9 Discussion and Potential Hazards

9.9.1 Spudcan-footprint/seabed interaction

The creation of a spudcan-footprint will occur during leg extraction where leg jetting has been involved. The risk of the footprint and seabed interaction is highly related to the diameter of the spudcan, that is, the distance between the footprint and the soil profile at the investigated location. Moreover, the influence of the footprint cavity left by the spudcan will also influence the diameter of the footprint.

The risk of spudcan-footprint/seabed interaction cannot be ruled out, as the top layer of the stratification for Group 2 is mainly soft clay, where the footprint will potentially disturb the nearby seabed. Subsequently, Group 3 has around 12 m of soft clay below the top sand layer, which might result in the same risks. Therefore, it is recommended to do a site-specific analysis.

9.9.2 Scour

The risk of scour is mainly driven by the seabed mobility due to the current and waves at the seabed, which is reliant on the bathymetry and environment of the site. Moreover, scour occurs for cohesionless soils at the seabed, which have a shallow leg penetration. In this case the most likely group with the potential of scour is Group 1 and Group 3. For mitigating the risk of scour it is recommended to look at the current velocities before operation and/or apply scour protection such as gravel beds or prefabricated mattresses.

9.9.3 Leg extraction

The potential risk of leg extraction is enhanced by deep leg penetrations, which is predicted for Group 2 and Group 3. The difficulties of leg extraction typically occur when there is a potential for large suction effects below the spudcan that can be exacerbated by potential backfill on top of the spudcan. The risk of leg extraction cannot be ruled out and a specific site-by-site analysis is therefore recommended for locations that fall into the Group 2 and Group 3 categories.

10. Integrated Ground Model Units (IGMU)

This section describes the BHII Integrated Ground Model Units. Each section describes one of the key geotechnical soil units that were defined in section 8 above and details how the soil unis were mapped across the site. When possible, the geotechnical soil units were tied to the seismic units that are described in detail in section 7. It must be noted that not all Geotechnical soil units have been incorporated into the Integrated Ground Model. For example, a distinction between soil units Ia and Ib in the shallow subsurface was not possible due to a homogenous seismic appearance in the depth between the two soil units. Also, the fact that the soil units are interbedded throughout most of the site has posed difficulties for the distinction between the two to be done. Similarly, no distinction has been done between soil units IVa and IVb as it proved to be difficult to achieve in the seismic data. The BHII Ground Model is comprised of the following integrated ground model units from top to bottom:

1. IGMU 1 (comprising soil units Ia and Ib) – loose to medium dense sand and soft, organic rich clays and gyttja.
2. IGMU 2 (comprising soil units II and III) – transitional to stiff clays.
3. IGMU 3 (comprising soil units IVa and IVb) – medium dense to dense sand and very stiff to very hard clay till.
4. IGMU 4 (comprising soil units Va1, Va2, Vb1, Vb2, Vc1 and Vc2) – variable lithologies including limestone/mudstone, chalk and sandstone.

The relationship of these geotechnical soil units to the mapped seismic units is summarised in Table 7.1.

In some cases it was not possible to define a perfect match between the mapped seismic horizons and the geotechnical soil units that were defined in CPTs and Boreholes. Best efforts have been made in aligning the geotechnical information with the mapped seismic horizons.

Each Integrated Ground Model Unit is described below. Charts illustrating the depth below seabed to top of the soil units have been provided. An overview of the chart deliverables is seen in Appendix 8.

10.1 Integrated Ground Model Unit 1 (IGMU 1)

This unit is comprised of loose, low to medium strength sands (soil unit Ia) and soft, organic-rich clays along with gyttja formation (soil unit Ib). No distinction between the two soil units was possible due to a homogenous seismic appearance between the two definitions. Also, both soil units are present in large parts of the site with an alternating deposition between the two soil units throughout single boreholes, hence no distinct depositional pattern could be determined.

Transitional and stiff clays (soil unit II and III) can possibly be encountered at the base of IGMU 1. The uncertainty range in which soil unit II and III has been included within IGMU 1 was of maximum 3 m. The base of IGMU 1 was difficult to map consequently throughout the entire site and therefore several approaches had to be used. Where thicknesses of IGMU 2 (soil unit II and III) was less than 3 m within borehole and CPTs, the base for IGMU 1 was defined with H30 horizon which has been mapped throughout the entire site and is a clear seismic definition.

A polygon, shown in Figure 10-1 illustrates an isolated area of the site where no soil unit Ia is present in borehole and CPTs, only soil unit Ib, meanwhile both soil units are present in the remaining part of the site. Digital deliverables include charts, where Chart 2.1 illustrates the thickness of IGMU 1 (comprised of soil units Ia and Ib and occasionally soil unit II and III). Cross sections showing the distribution of the IGMU within the site are provided in the deliverables, defined as Chart 5.1 – 5.6.

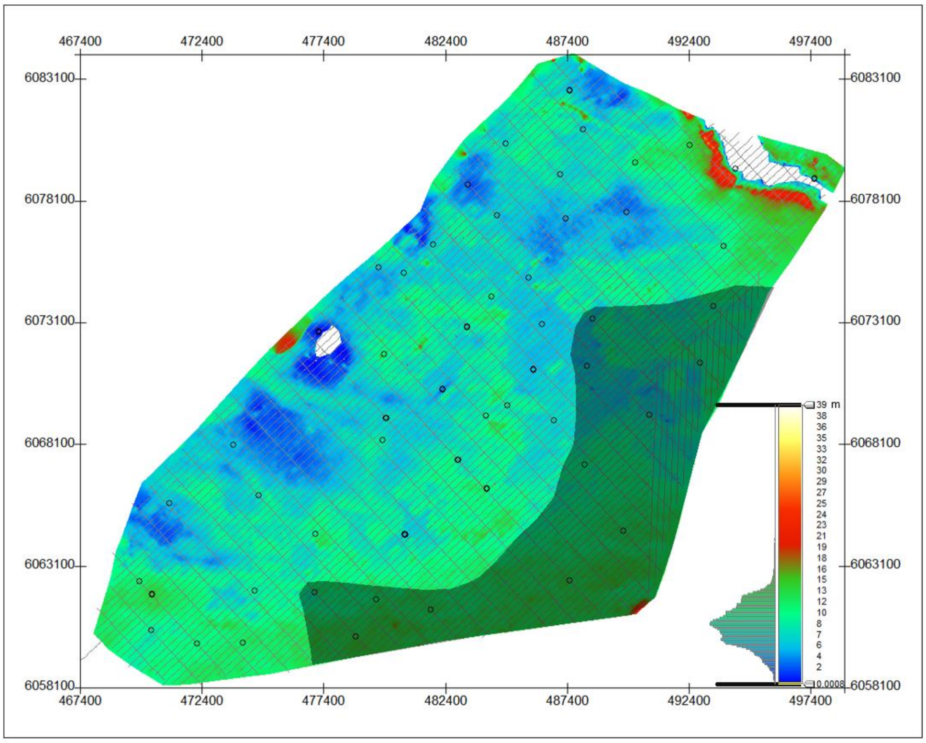


Figure 10-1 Isochore map of IGMU 1 (comprised of geotechnical soil units Ia and Ib; occasionally geotechnical soil unit II and III can be encountered), illustrating the distribution and the thickness of the unit across the site. The polygon in the south-western part of the site illustrates a section of the site where no soil unit Ia is present in the borehole and CPTs, only soil unit Ib. Remaining part of the site is comprised of both soil unit Ia and Ib. Grey lines represent the 2D UHRS survey lines. Black circles represent the location of the borehole and CPTs. Colorscale is thickness in meters (m).

The top of IGMU 1 corresponds to the top of SU 1 which is defined at the seabed reflector (H00). The base of IGMU 1 is marked by H25. Varying mapping approaches done for the base of this unit pose some degree of uncertainty for the thickness of the soft sediments, but these approaches were deemed less uncertain than an interpolated grid between the geotechnical formation tops would produce.

10.2 Integrated Ground Model Unit 2 (IGMU 2)

This unit is comprised comprised of transitional clay (soil unit II) and very stiff clays (soil unit III). No distinction between the two soil units was possible due to a homogeneous seismic appearance between the two definitions. Also, the thickness of these merged soil units is relatively thin, ranging generally between 0 – 5 m with local areas in the south-western part reaching up to 37 m. Soil unit III is the main soil detected, while soil unit II is occasionally also detected either above soil unit III or as single soil deposition with no soil unit III being present. This could potentially be due to erosion of soil unit III. Figure 7-10 illustrates the thickness of IGMU 2 throughout the site.

Chart 2.2 illustrates the thickness of IGMU 2 (comprised of soil unit II and III), meanwhile Chart 3.1 illustrates the depth below seabed for the top of IGMU 2. Cross sections showing the distribution of the IGMU within the site are provided in the deliverables, defined as Chart 5.1 – 5.6.

10.3 Integrated Ground Model Unit 3 (IGMU 3)

This unit is comprised of medium dense to dense sand (soil unit IVa) and very stiff clay till (soil unit IVb). The soil units IVa and IVb are confined to the seismic unit 3 within the site. The top of soil unit IV is defined by seismic horizon H30, meanwhile the base of soil unit IV is defined by seismic horizon H50.

No distinction between the two soil units was possible due to a shifting sediment deposition within the boreholes between the two geotechnical soil units. An internal horizon (H45_i) has been mapped, which represents a distinct sand succession detected in the central part of the site. Figure 7-12 illustrates the thickness variation of the IGMU 3 throughout the site.

Chart 2.3 illustrates the thickness of IGMU 3 (comprised of soil unit IVa and IVb), meanwhile Chart 3.2 illustrates the depth below seabed for the top of IGMU 3. Cross sections showing the distribution of the IGMU within the site are provided in the deliverables, defined as Chart 5.1 – 5.6.

10.4 Integrated Ground Model Unit 4 (IGMU 4)

The BHII site has a rather complicated bedrock composition and distribution which subcrops the Pleistocene and Holocene sediment succession. The bedrock is mainly composed of Cretaceous and Jurassic rocks. The most encountered type of bedrock is limestone/mudstone (soil units Va1 and Va2), but other typeS including sandstone (Vc1 and Vc2) and chalk (Vb1 and Vb2) are also encountered in the site. Figure 7-20 illustrates the depth below seabed for top of IGMU 4 throughout the site.

Chart 3.3 illustrates the depth below seabed for top of IGMU 4 (comprised of soil unit V). Cross sections showing the distribution of the IGMU within the site are provided in the deliverables, defined as Chart 5.1 – 5.6.

Two updated schematic illustrations of the final IGMU are shown in Figure 10-2 and Figure 10-3.

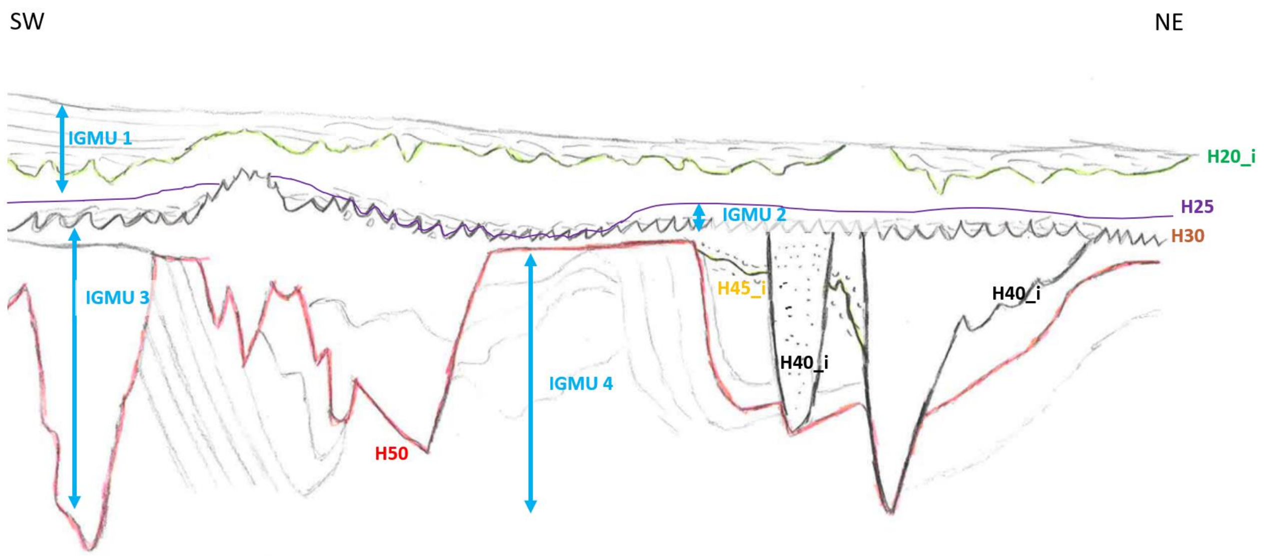


Figure 10-2 Schematic illustration of the final IGMU and horizon distribution throughout the site in a SW – NE orientation. The light green color represents H20_i which is an internal horizon mapped within IGMU 1. H25 (purple) represents the base of IGMU 1. H30 (brown) represents the base of IGMU 2. H40_i (black) is an internal horizon mapped within IGMU 3 which represents some of the base of paleovalley systems. H45_i (yellow) is an internal horizon mapped within IGMU 3 which represents the top of the sandy succession. H50 (red) represents the base of IGMU 3 / top of IGMU 4.

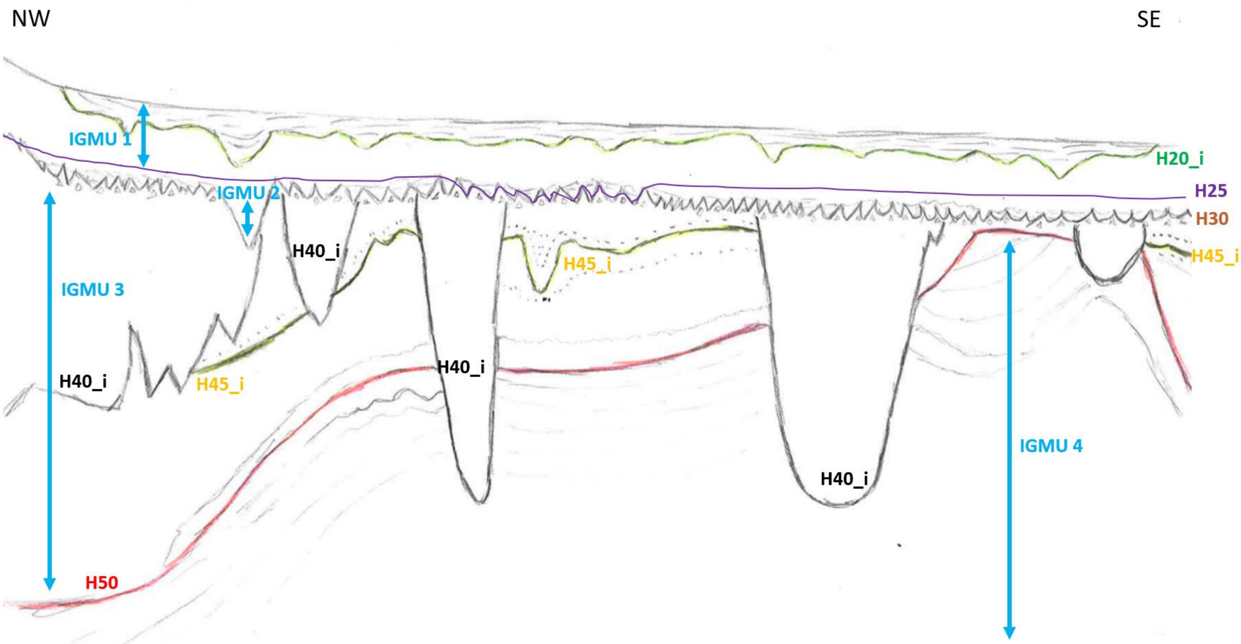


Figure 10-3 Schematic illustration of the IGMU and horizon distribution throughout the site in a NW – SE orientation. The light green color represents H20_i which is an internal horizon mapped within IGMU 1. H25 (purple) represents the base of IGMU 1. H30 (brown) represents the base of IGMU 2. H40_i (black) is an internal horizon mapped within IGMU 3 which represents some of the base of paleovalley systems. H45_i (yellow) is an internal horizon mapped within IGMU 3 which represents the top of the sandy succession. H50 (red) represents the base of IGMU 3 / top of IGMU 4.

11. The Ground Model – potential issues and hazards

This chapter highlights some of the potential issues within the current ground model and some of the potential geotechnical hazards that should be in focus. The hazards discussed in this section should be considered for further study.

11.1 Issues and potential geological hazards highlighted by the model

A review of the distribution of the seismic units compared to their inherent soil types, raises a set of issues or hazards that need to be noted. These are:

- Very soft sediments at shallow depths
- Irregular topography above very stiff sediments
- Sand overlying soft clays
- Potential Boulders and Block fields
- Faults and folding introducing very variable bedrock conditions at a very short lateral distance combined with shallow bedrock depths.

11.1.1 Very soft sediments at shallow depths

Soft sediments at the shallow subsurface are extremely common throughout BHII and are present throughout the entire site. These can reach a thickness of up to 20 m in the southern part of the site. Soft sediments comprise soil unit I.

Over a large part of the Bornholm II site these soft sediments could pose issues. hese soils do not provide sufficient strength for foundation design, resulting in risks during pile installation and inadequate bearing capacity, necessitating the use of longer piles. They correspond to Group 2 in Leg Penetration analysis that is presented in Section 9.

11.1.2 Irregular topography above very stiff sediments

The top of SU 3, marked by H30, is a very uneven surface that can locally have significant topography. Given that the uneven, hummocky surface at the top of SU 3 normally marks the change between the transitional clays from soft towards stiff and the very dense sandy clay-tills (soil unit IV) there is an obvious danger of tilt development, especially in the case of multiple-legged foundations.

11.1.3 Sand overlying soft clays

Sand areas are identified from analyzing CPT and BHs available at the site and they are summarized in the chapter 9. Sand aread alone were not able to be identified from the seismic data as the IGMU 1 includes both sands and clays.

11.1.4 Potential Boulders and Block fields

As is described in previous chapters (Section 7.3), the H30 Seismic Horizon marks a change in the depositional environment across the Bornholm II Site. The hummocky moraines were created during the retreat of the Last Glacial Maxima Ice Sheet from the Bornholm region. The depositional setting switched from one that was influenced by the direct action of ice and/or ice melt, to deposition in a standing water body. It is very likely that blocks, boulders and even rafts of semi-coherent rock were deposited as the ice sheet retreated. The soil unit III is therefore likely to be, not only a hazard due to its inherent topography (marked with H30), but also to the possible presence of blocks and boulders and the transition into the stiff clay tills of soil unit IVb. From the geotechnical data boulders were mentioned in locations BH-204, BH-205, BH-208 and BH-210. In general the possibility of finding boreholes can be a risk for foundations of driven piles or monopiles, as the steel can get damaged in the case of large size boulders.

11.1.5 Faults and folding introducing very variable bedrock conditions at a very short lateral distance combined with shallow bedrock depths.

A very variable depth of bedrock conditions is identified in the next chapter which can significate in the need of using a drilling method during installation of foundations or a driven method. Figure 12-2 can help identifying such a risk.

12. Soil Zonation and Soil Provinces

12.1 Introduction

The comprehensive geological model provides a understanding of the soil conditions for future offshore wind farms. In this section, it is outlined a review of the key geological units that could be useful to the foundation design. The water depth range in Bornholm II falls within the anticipated ranges for fixed foundations, such as gravity-based structures, monopiles, jacket foundations with piles, and suction bucket jackets. Alternative solutions, such as floating foundations, are not considered in this assessment. The conclusions in this section are orientated for an early phase development. This analysis is considering the current site investigation and could be further updated after additional soil investigations.

Building on the geotechnical interpretation of soil and rock parameters and the integrated geological model, a soil zonation has been developed. This soil zonation serves as the basis for grouping the primary geological formations relevant to the future wind turbine (WTG) foundation design. The soil zonation is simplified into a single map that divides the entire site into distinct soil provinces. For deriving foundation concept design, the varying depth in Bornholm II will need to be analysed in detail.

The most prevalent geological features are the presence of soft organic clays and gyttja soils (unit Ib) or loose sands (unit Ia) on the top layers combined with rock (unit V) at shallow depths. Other Soil Types are present across the site, such as tills and dense stiff sands, but these soils are not expected to play a significant role in deciding the type of foundation.

Soft soils, particularly organic clays and gyttja, pose several challenges for OWFs: they offer insufficient support wind turbines, are challenging for cable routing across the wind turbines, affect the jack-up installation vessel leg penetration as seen in section 9 and presented difficulties during the geotechnical investigation campaign.

The presence of rock, rock characteristics and its depth below seabed is one of the main drivers for selecting a foundation type. As described in the section 8, rocks formations (Unit V) are very complex in Bornholm area with cretaceous Limestones/Mudstones and Chalk and Jurassic Sandstone which vary across the windfarm.

12.2 Soil zonation

Two main soil zonations are derived to understand better the spatial distribution of both soft soils and rock depths.

The upper subsurface soft soils representing the low strength layers are presented in Figure 12-1 with a limit thickness of 5m. The limit is given to isolate positions with more favourable conditions and understand how extensive the presence of soft soils in the OWF is. Hence, the soft soil thickness was divided into:

- Soft soils < 5 m
- Soft soils > 5 m

Green colour represents the areas where the soft soils have a thickness below 5m, and red colour represents the areas where the soft soils have a thickness more than 5m. These layers include the Holocene units of Ia and Ib and have low strength which applies for gyttja and post glacial sand and clay. Additionally, these deposits are widespread throughout the area, are shallow, and are found close to the seabed. As a result, they could significantly affect the foundation design and the developed capacity of the structure. Furthermore, a solid knowledge of the properties of the shallow sediments is required over the cable routes.

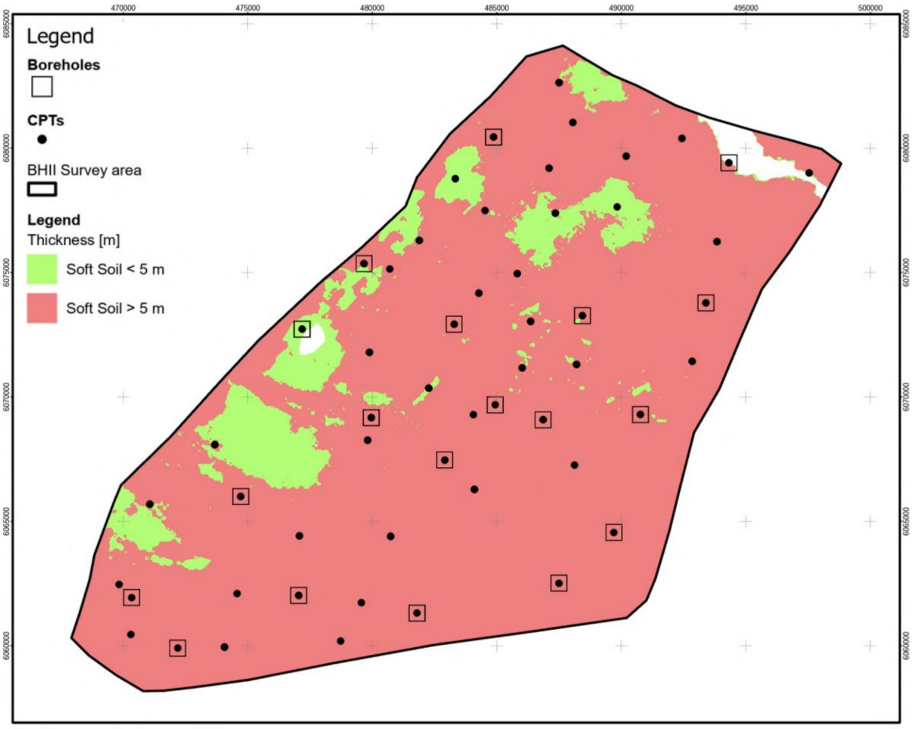


Figure 12-1 Overview map of the upper soft soils in the area. Green colour illustrates areas where soft soils have a thickness below 5 m, meanwhile red colour illustrates areas where soft soils have a thickness above 5 m. Black lines represent the 2D UHRS survey lines. Black circles represent the location of the borehole and CPTs. Colorscale is thickness in meters (m).

Figure 11-2 illustrates an overview map of the depth below seabed distribution of the top bedrock. The structure of the foundation can be defined based on the depth of the top bedrock and for this reason three zones of the bedrock depth have been selected in this report. Specifically, the depth below seabed of top bedrock was divided into:

- Top Bedrock < 15 m
- Top Bedrock 15 – 40 m
- Top Bedrock > 40 m

The first is the shallow bedrock where the depth below the seabed is above 15m and is represents with blue colour in Figure 12-2. The most used types of foundations on bedrock are the gravity-based foundations. To acquire the required bearing capacity of a gravity foundation, it needs to be supported by very strong soil layers or most frequently rock instead of soft soils for its stability. Since soft soils with low strength are present frequently, and the depth bedrock is varying, it is required to analyse both in the soil provinces. It is anticipated that soft soils will challenge this foundation type and a drilled solution needs to be studied in detail for this zone. The second zone represented with yellow colour in Figure 12-2 is the intermediate depth of the bedrock from 15m to 40m. In this case, suction caisson foundations will not reach the rock depth, while in some instances monopile foundations could be installed without the need of drilling depending on the pile penetration. Due to the complexity of the soft soils and the hard tills in the area, suction bucket foundation could be difficult to design and install depending on the permeability of the soil sitting over the bedrock. The third zone is the deep bedrock where the depth below the seabed of the top bedrock is below 40m and is represented with green colour in Figure 12-2. In this zone, multi-piled (jacket) or single pile (monopile) foundations can be installed. A significant component for the selection of the foundation structure is the installation method. The most commonly used installation methods for monopiles are either driving, drilling or a combination of drilling and driving. Drilling is required in the case of rock, depending on its strength, or very hard soil. For all three zones described above, a foundation structure of either drilled monopile or jacket pile can be used. However, it has to be noticed that the drilling method is complex, time consuming and hence more expensive than driving. Installation using a driving hydraulic hammer could be used in some areas, but a detailed drivability analysis needs to be carried out as well to analyse this issue.

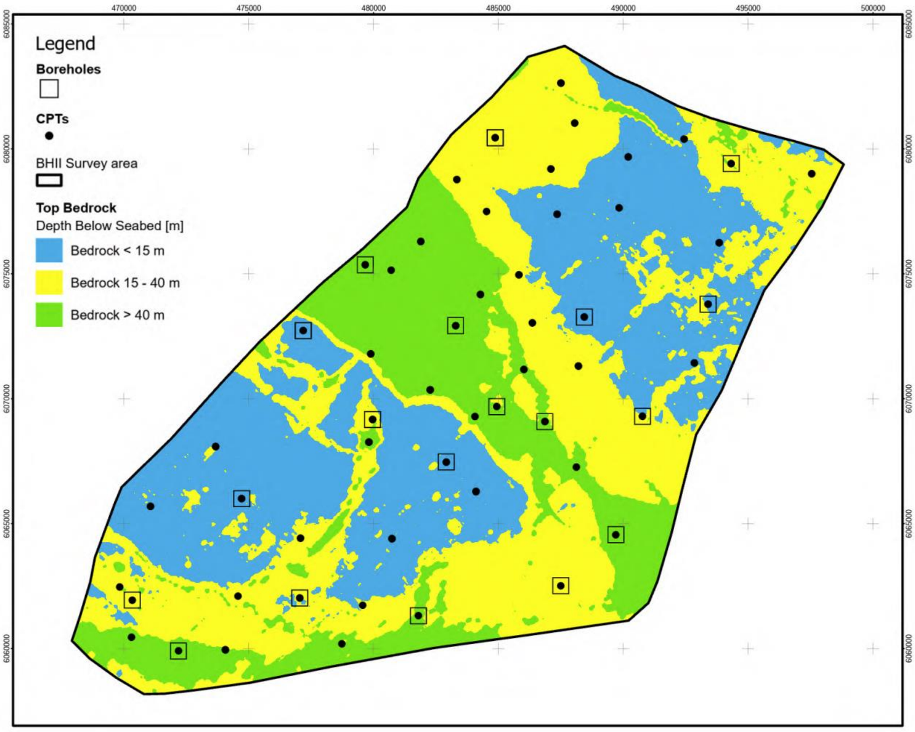


Figure 12-2 Overview map of the depth below seabed of top bedrock in the area. Blue colour illustrates areas where depth below seabed for top bedrock is below 15 m; Yellow colour illustrates areas where depth below seabed for top bedrock is between 15 – 40 m; and Green colour illustrates areas where depth below seabed for top bedrock is between.

12.3 Soil provinces

To provide a geological overview with respect to foundation conditions, the two maps of soft soils and bedrock have been simplified into one single map showing 9 soil provinces, see Figure 12-3. These provinces are based on the thickness of the Holocene soft soil layers (unit Ia and Ib) and the depth of the top bedrock (unit V) below the seabed. The same general colour scheme used for the Figure 12-2 was employed for Figure 12-3.

The 9 soil provinces that have been defined based on the soil zonation are summarized in Table 12.1. Examples for each soil province from the boreholes with the corresponding CPT are given in the table also, however there are soil provinces where there are not available examples from the geotechnical profiles. Therefore, omitting the upper 3.4m of soft soils, CPT-218/BH-218 would be considered a representative profile for the B3 soil province. Similarly, reducing the upper 14.2m of soft soils in less than 5m, CPT-201/BH-201 would be considered a representative profile for the C3 soil province.

Table 12.1 Soil provinces.

Bedrock Zone	Code related to soft organic clay/gyttja (Soil Unit Ib) thickness	Description	Corresponding examples from geotechnical data
A	1	Soft clay > 5m Top bedrock < 15m	CPT-203/BH-203 & CPT-207/BH-207 & CPT-217/BH-217
	2	Soft clay < 5m Top bedrock < 15m	CPT-209/BH-209 & CPT-216/BH-216 & CPT-219/BH-219
	3	No Soft clay Top bedrock < 15m	CPT-213/BH-213
B	1	Soft clay > 5m Top bedrock =15-40m	CPT-205/BH-205 & CPT-208/BH-208 & CPT-212/BH-212
	2	Soft clay < 5m Top bedrock =15-40m	CPT-218/BH-218
	3	No Soft clay Top bedrock =15-40m	*not available examples however omitting the upper 3.4m of soft soils, CPT-218/BH-218 would be considered a representative profile
C	1	Soft clay > 5m Top bedrock > 40m	CPT-201/BH-201 & CPT-202/BH-202 & CPT-204/BH-204 & CPT-206/BH-206 & CPT-210/BH-210 & CPT-211/BH-211 & CPT-214/BH-214 &CPT-215/BH-215
	2	Soft clay < 5m Top bedrock > 40m	* not available examples however reducing the upper 14.2m of soft soils in less than 5m, CPT-201/BH-201 would be considered a representative profile
	3	No Soft clay Top bedrock > 40m	CPT-220/BH-220

The overall results show contiguous areas with local changes. The south-western and north-eastern parts show relative shallow depths of the top bedrock. In the middle of the area, the top bedrock appears relatively at deep depths.

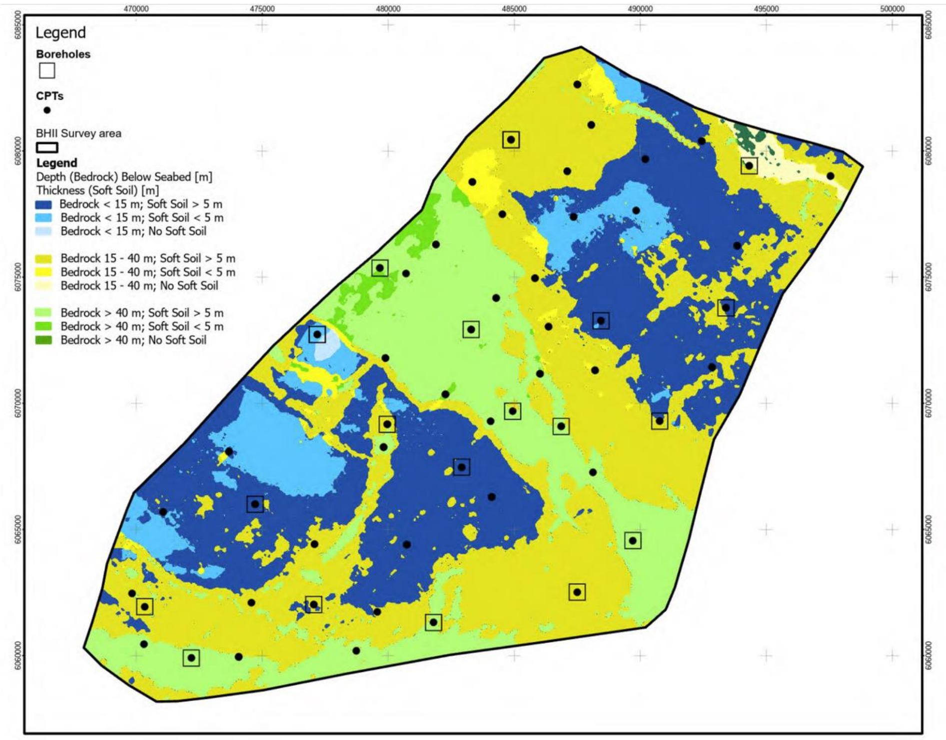


Figure 12-3 Overview map that was created by combining figures Figure 12-1 and Figure 12-2.

12.4 Examples of representative soil profile for each soil zone/province

The nine (9) soil provinces are described in the following subsections, and further representative soil profiles are also presented. The representative profiles are selected based on geotechnical location tests present within each zone. Detailed geotechnical parameters can be extracted in different appendices provided in the report.

12.4.1 Soil zone/province A1

This zone is characterized by having depth of Soil Unit Ib greater than 5 m and the top bedrock is found in depth above the 15 m. From the available geotechnical locations, three of them belong to this zone, namely CPT-203/BH-203, CPT-207/BH-207 and CPT-217/BH-217 and they represent mostly clay dominated positions with small sand layers. One representative profile is selected for this zone due to its deepest presence of soft Soil Unit Ib. The stratigraphy in table format is presented in. This profile is CPT-203/BH-203, where the CPT profile is presented in Figure 12-4, regardless the early CPT refusal, soft soil conditions are expected based on geotechnical and geophysical data.

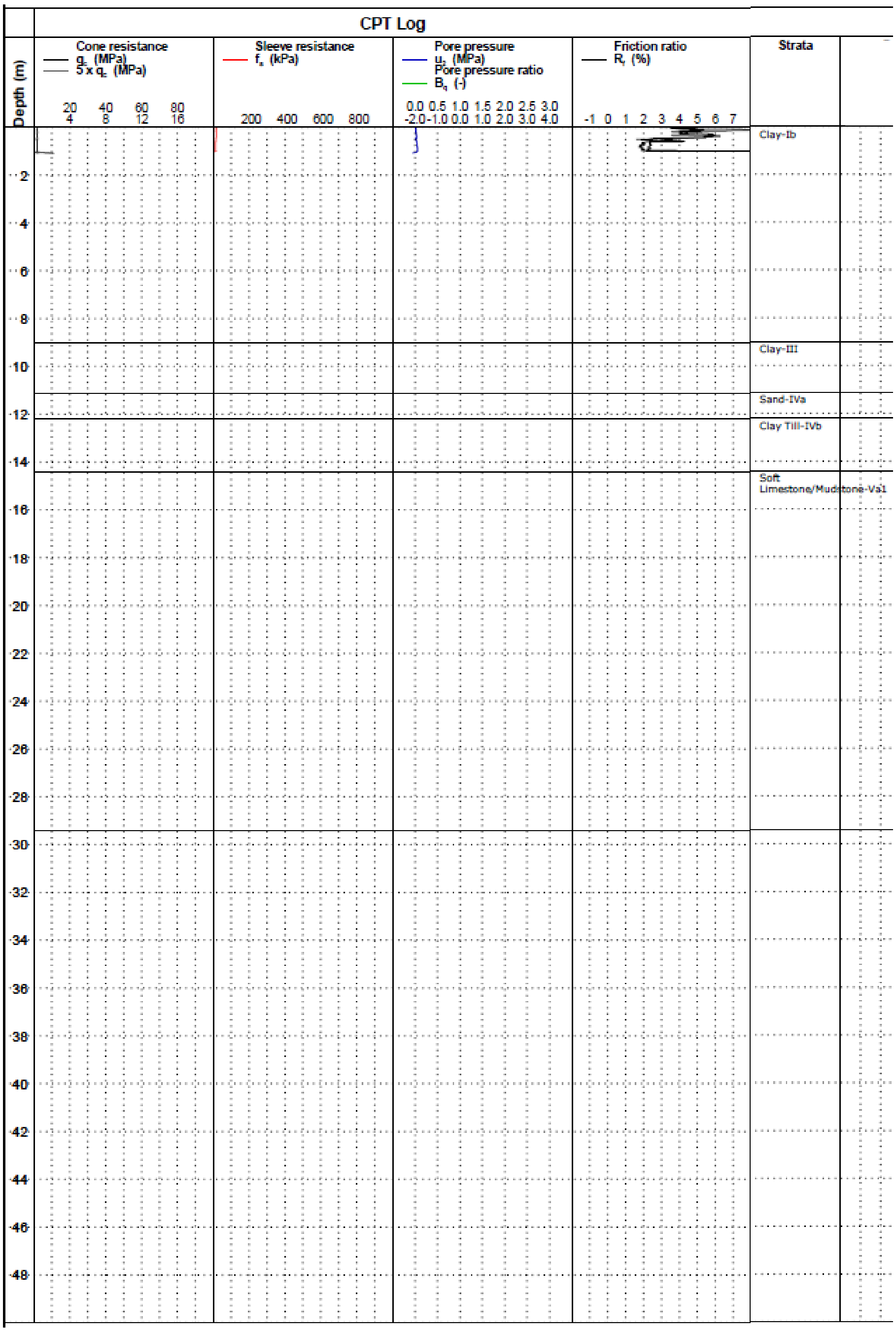


Figure 12-4 CPT measurements for CPT-203/BH-203 found as representative for zone A1.

Table 12.2 Soil stratigraphy for CPT-203/BH-203 found as representative for zone A1.

Top [mbsb]	Bottom [mbsb]	Integrated ground model unit	Soil Unit	Soil/Rock Type
0.0	9.0	IGMU1	Ib	Clay
9.0	11.1	IGMU2	III	Clay
11.1	12.2	IGMU3	IVa	Sand

Top [mbsb]	Bottom [mbsb]	Integrated ground model unit	Soil Unit	Soil/Rock Type
12.2	14.4	IGMU3	IVb	Clay Till
14.4	29.4	IGMU4	Va1	Marlstone

12.4.2 Soil zone/province A2

This zone is characterized to comprise limited, less than 5 m, presence of Soil Unit Ib. The top bedrock for this zone is met in depth above the 15 m. From the available geotechnical locations, three of them belong to this zone, namely CPT-209/BH-209, CPT-216/BH-216 and CPT-219/BH-219. One representative profile is selected for this zone due to its deepest measurements of CPT. This profile is CPT-209/BH-209, where the CPT profile is presented in Figure 12-5. The stratigraphy in table format is presented in Table 12.3.

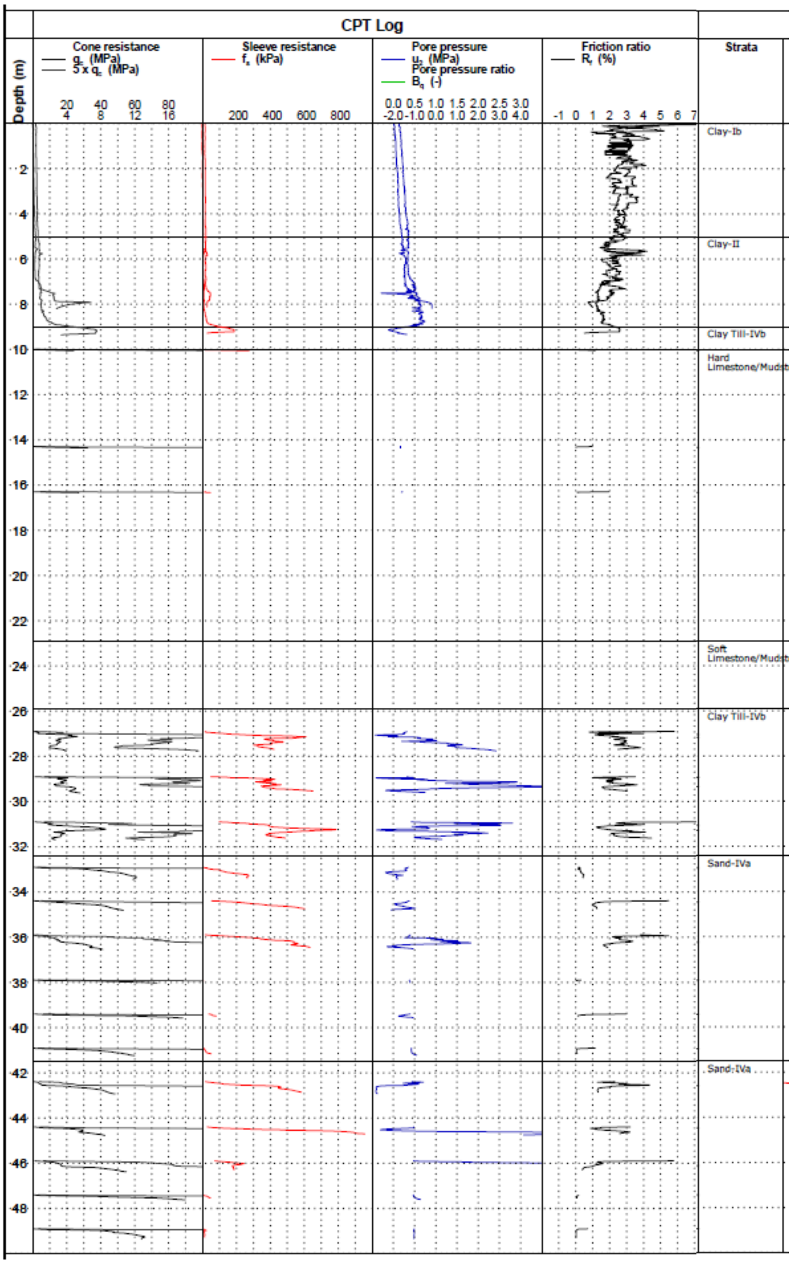


Figure 12-5 CPT measurements for CPT-209/BH-209 found as representative for zone A2.

Table 12.3 Soil stratigraphy for CPT-209/BH-209 found as representative for zone A2.

Top [mbsb]	Bottom [mbsb]	Integrated ground model unit	Soil Unit	Soil/Rock Type
0.0	5.0	IGMU1	Ib	Clay
5.0	9.0	IGMU2	II	Clay
9.0	10.0	IGMU3	IVb	Clay Till
10.0	22.9	IGMU4	Va2	Limestone
22.9	25.9	IGMU4	Va1	Mudstone
25.9	32.4	IGMU3	IVb	Clay Till
32.4	41.5	IGMU3	Iva	Sand
41.5	64.4	IGMU3	IVa	Sand
64.4	70.1	IGMU3	IVa	Sand

12.4.3 Soil zone/province A3

This zone is characterized to comprise no presence of the soft Soil Unit Ib. The top bedrock for this zone is found in depth above the 15 m. From the available geotechnical locations, one of them belong to this zone, namely CPT-213/BH-213 which is a sand dominated position. The CPT profile is presented in Figure 12-6. The stratigraphy in table format is presented in Table 12.4.

Table 12.4 Soil stratigraphy for CPT-213/BH-213 found as representative for zone A3.

Top [mbsb]	Bottom [mbsb]	Integrated ground model unit	Soil Unit	Soil/Rock Type
0.0	0.6	IGMU1	Ia	Sand
0.6	1.7	IGMU3	IVa	Sand
1.7	2.0	IGMU4	Va1	Siltstone
2.0	2.1	IGMU4	Va2	Granite
2.1	6.2	IGMU4	Va1	Marlstone
6.2	8.1	IGMU4	Va2	Limestone
8.1	14.3	IGMU4	Va1	Marlstone
14.3	16.2	IGMU4	Va2	Limestone
16.2	43.5	IGMU4	Va1	Marlstone
43.5	68.0	IGMU4	Va2	Limestone

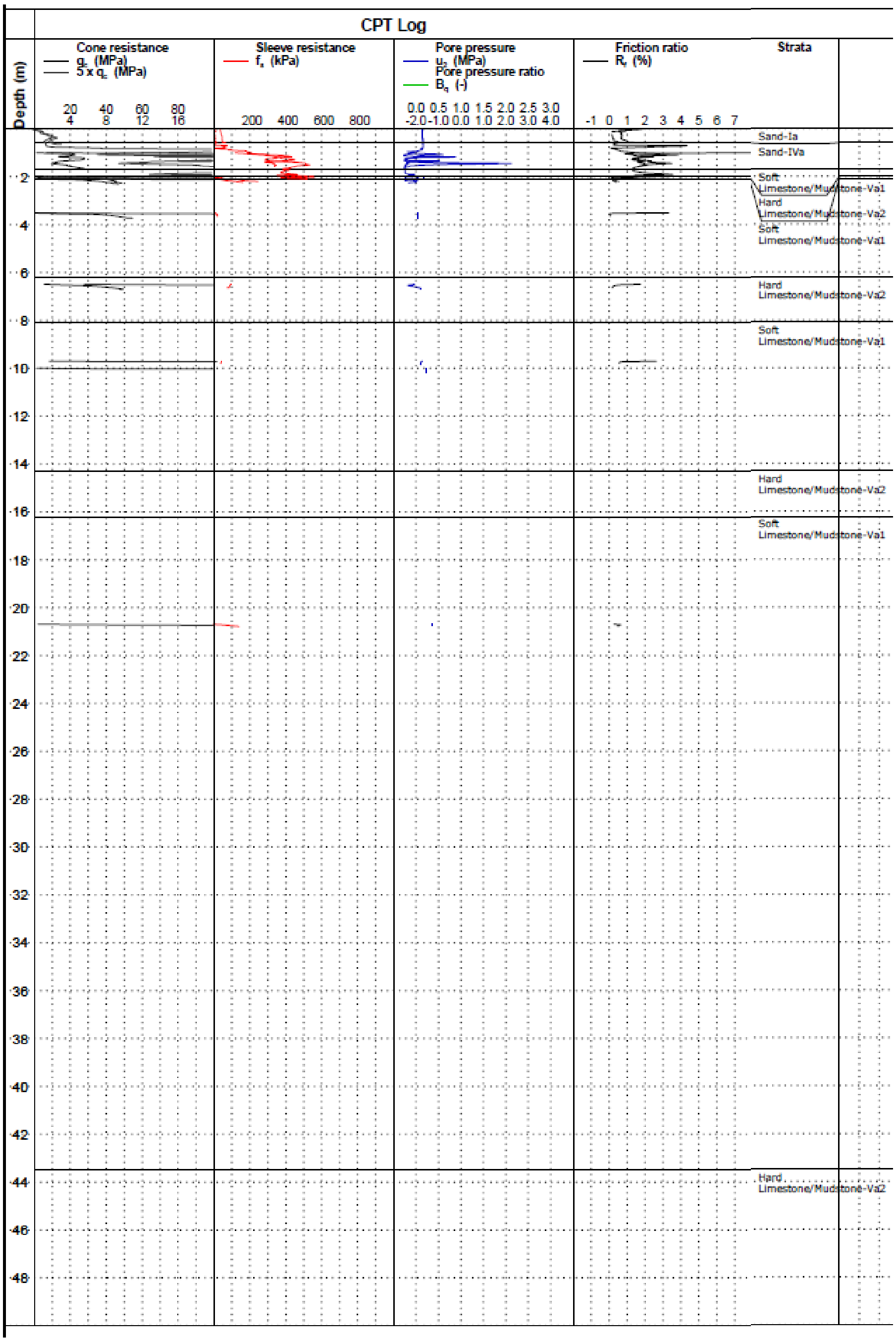


Figure 12-6 CPT measurements for CPT-213/BH-213 found as representative for zone A3.

12.4.4 Soil zone/province B1

This zone is characterized by having depth of Soil Unit Ib greater than 5 m and the top bedrock is met in depth between 15 and 40 m. From the available geotechnical locations, three of them belong to this zone, namely CPT-205/BH-205, CPT-208/BH-208 and CPT-212/BH-212. One representative profile is selected for this zone due to its deepest presence of soft Soil Unit Ib. This profile is CPT-205/BH-205, where the CPT profile is presented in Figure 12-7. The stratigraphy in table format is presented in Table 12.5.

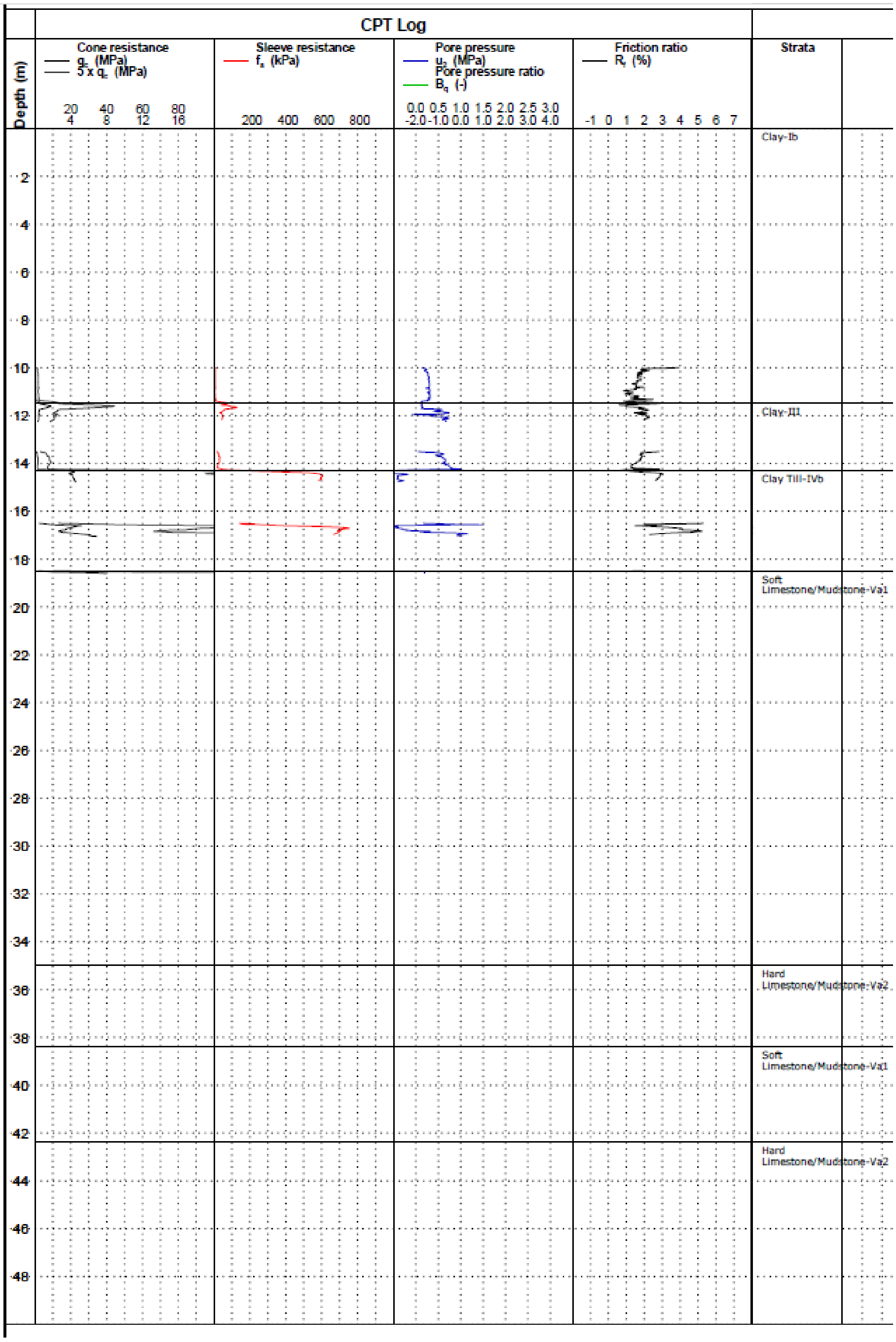


Figure 12-7 CPT measurements for CPT-205/BH-205 found as representative for zone B1.

Table 12.5 Soil stratigraphy for CPT-205/BH-205 found as representative for zone B1.

Top [mbsb]	Bottom [mbsb]	Integrated ground model unit	Soil Unit	Soil/Rock Type
0.0	11.5	IGMU1	Ib	Clay
11.5	14.3	IGMU3	III	Clay
14.3	18.5	IGMU3	IVb	Clay Till
18.5	35.0	IGMU4	Va1	Limestone
35.0	38.4	IGMU4	Va2	Limestone
38.4	42.4	IGMU4	Va1	Siltstone
42.4	50.0	IGMU4	Va2	Limestone
50.0	53.5	IGMU4	Va1	Mudstone
53.5	54.8	IGMU4	Va2	Limestone
54.8	58.7	IGMU4	Va1	Siltstone
58.7	62.5	IGMU4	Va2	Limestone
62.5	63.4	IGMU4	Va1	Siltstone
66.2	67.6	IGMU4	Va2	Limestone
67.6	68.2	IGMU4	Va1	Siltstone
68.2	69.1	IGMU4	Va2	Limestone
69.1	70.4	IGMU4	Va1	Siltstone

12.4.5 Soil zone/province B2

This zone is characterized to comprise limited, less than 5 m, presence of Soil Unit Ib. The top bedrock for this zone is met in depth between 15 and 40 m. From the available geotechnical locations, one of them belong to this zone, namely CPT-218/BH-218. The CPT profile is presented in Figure 12-8. The stratigraphy in table format is presented in Table 12.6.

Table 12.6 Soil stratigraphy for CPT-218/BH-218 found as representative for zone B2.

Top [mbsb]	Bottom [mbsb]	Integrated ground model unit	Soil Unit	Soil/Rock Type
0.0	3.4	IGMU1	Ib	Clay
3.4	7.0	IGMU2	II	Clay
7.0	7.7	IGMU2	III	Clay
7.7	19.5	IGMU3	IVa	Sand
19.5	35.0	IGMU3	IVa	Sand
35.0	37.5	IGMU4	Va2	Siltstone
37.5	38.0	IGMU4	Vc1	Sandstone
38	38.5	IGMU4	Va2	Limestone
38.5	39.5	IGMU4	Va1	Siltstone
39.5	59.7	IGMU4	Va2	Limestone
59.7	70.1	IGMU4	Vb1	Chalk

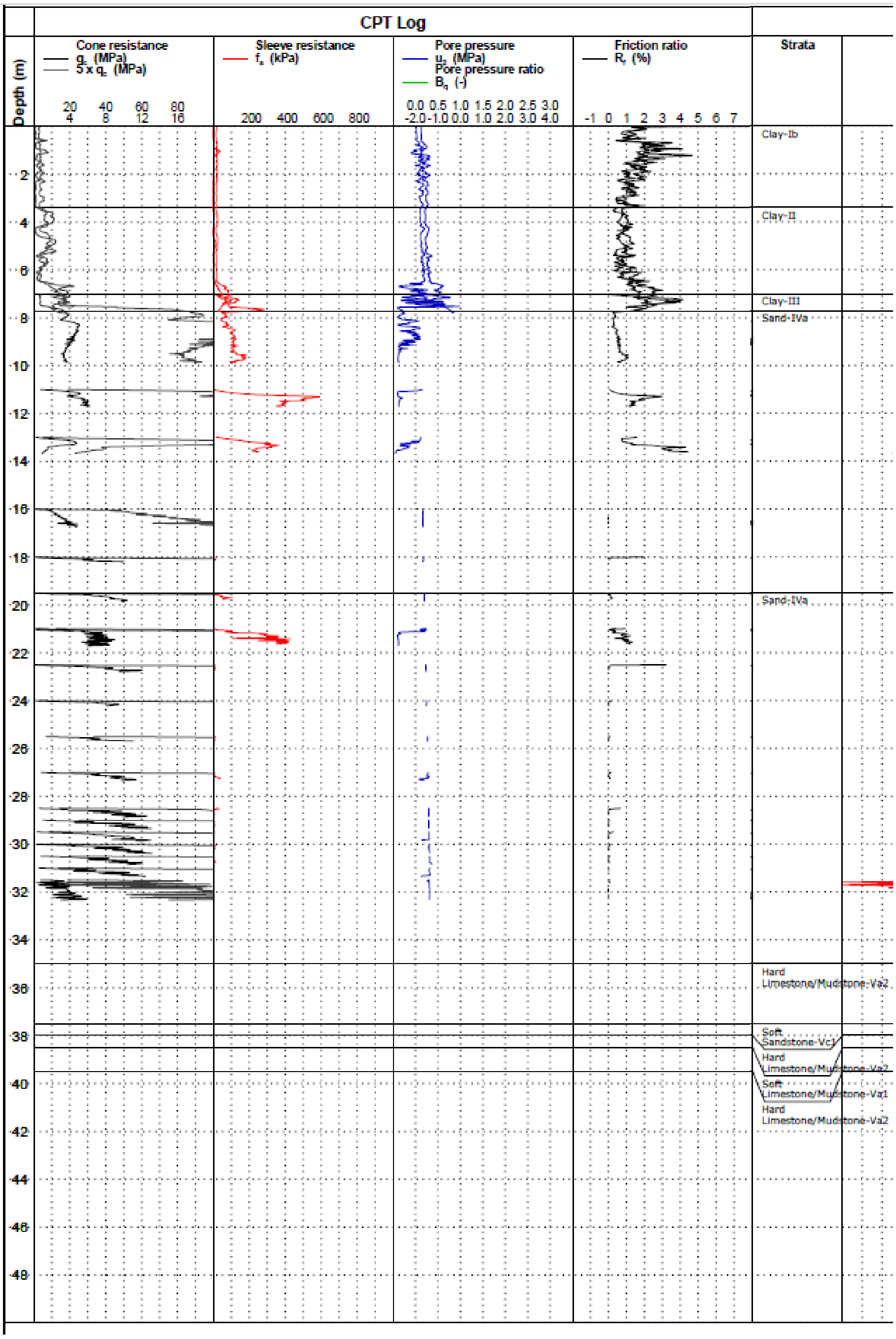


Figure 12-8 CPT measurements for CPT-218/BH-218 found as representative for zone B2.

12.4.6 Soil zone/province B3

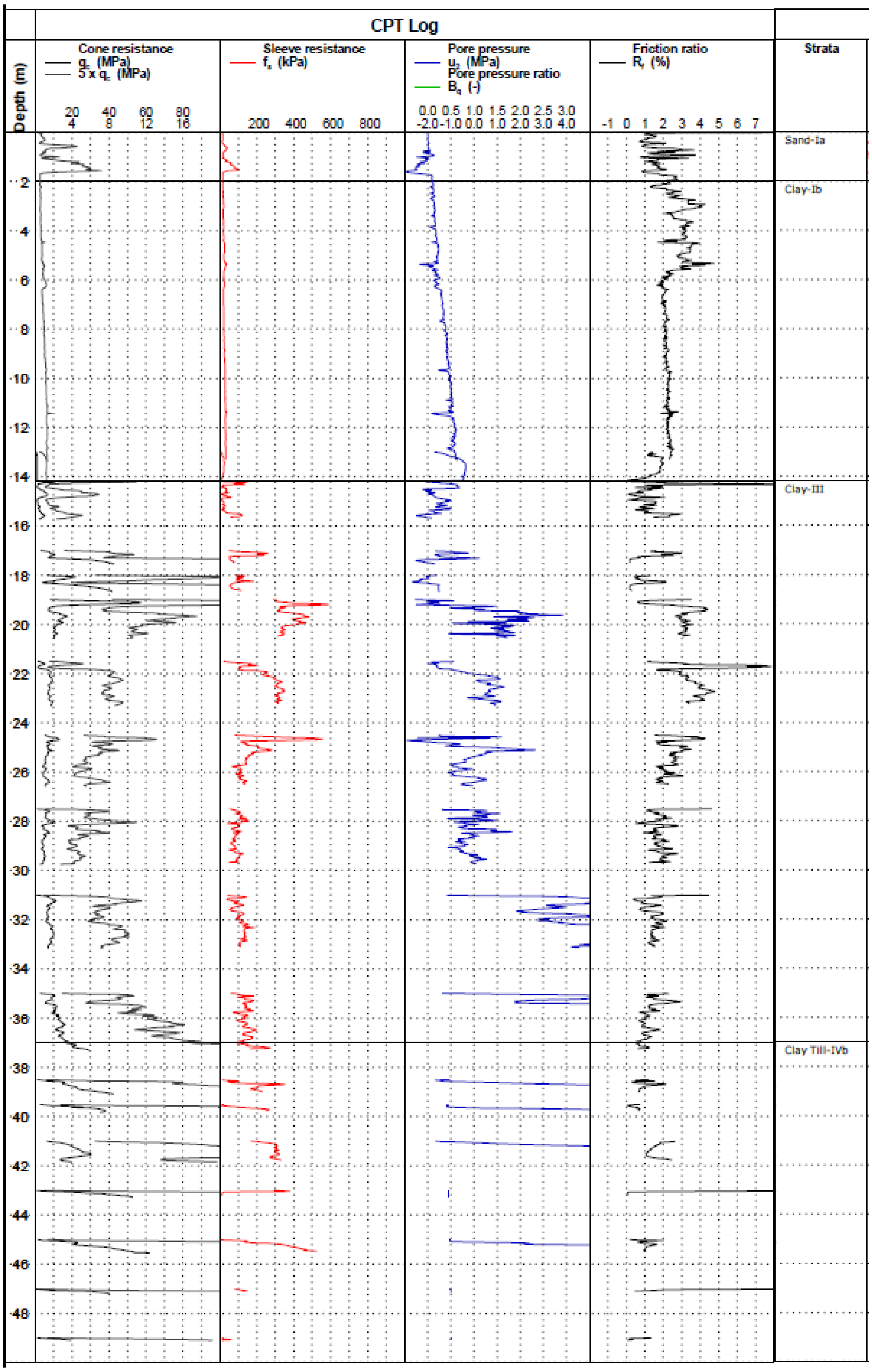
This zone is characterized to comprise no presence of the soft Soil Unit Ib. The top bedrock for this zone is met in depth between 15 and 40 m. From the available geotechnical locations, there is not available example however omitting the upper 3.4m of soft soils, CPT-218/BH-218 would be considered a representative profile. The stratigraphy in table format for an artificial profile representing soil zone B3 is presented Table 12.7.

Table 12.7 Soil stratigraphy as representative for zone B3.

Top [mbsb]	Bottom [mbsb]	Integrated ground model unit	Soil Unit	Soil/Rock Type
0.0	7.0	IGMU2	II	Clay
7.0	7.7	IGMU2	III	Clay
7.7	19.5	IGMU3	IVa	Sand
19.5	35.0	IGMU3	IVa	Sand
35.0	37.5	IGMU4	Va2	Siltstone
37.5	38.0	IGMU4	Vc1	Sandstone
38	38.5	IGMU4	Va2	Limestone
38.5	39.5	IGMU4	Va1	Siltstone
39.5	59.7	IGMU4	Va2	Limestone
59.7	70.1	IGMU4	Vb1	Chalk

12.4.7 Soil zone/province C1

This zone is characterized by having depth of Soil Unit Ib greater than 5 m and the top bedrock is met in depth more than 40 m. From the available geotechnical locations, many of them belong to this zone, namely CPT-201/BH-201, CPT-202/BH-202, CPT-204/BH-204, CPT-206/BH-206, CPT-210/BH-210, CPT-211/BH-211, CPT-214/BH-214 and CPT-215/BH-215. One representative profile is selected for this zone due to its deepest presence of soft Soil Unit Ib. This profile is CPT-201/BH-201, where the CPT profile is presented in Figure 12-9. The stratigraphy in table format is presented in Table 12.8.


CPT Log
Depth (m)
Cone resistance
q_c (MPa)
5 x q_c (MPa)
Sleeve resistance
f_s (kPa)
Pore pressure
u_2 (MPa)
Pore pressure ratio
B_q (-)
Friction ratio
R_f (%)
Strata
Sand-Ia
Clay-Ib
Clay-III
Clay Till-IVb

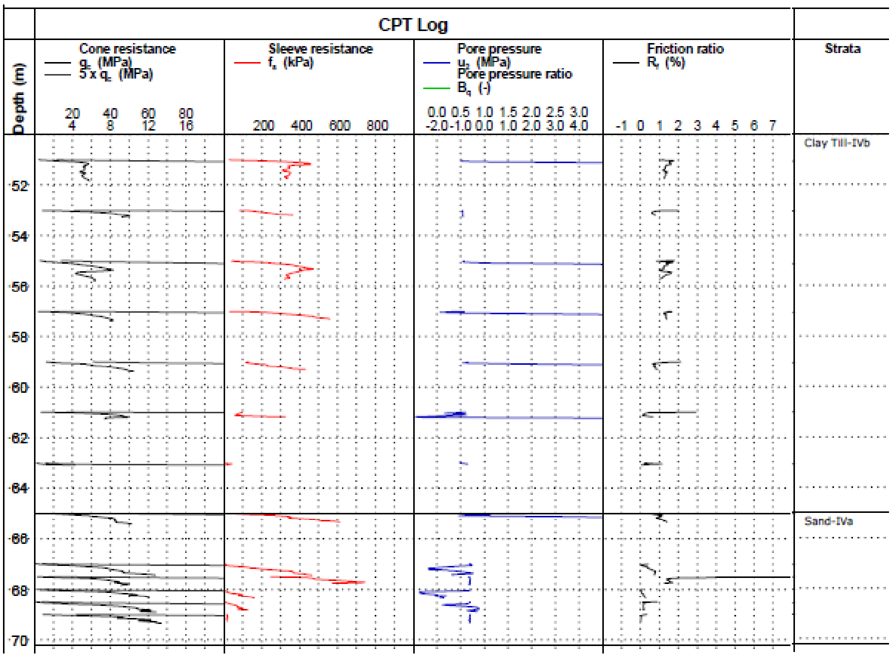


Figure 12-9 CPT measurements for CPT-201/BH-201 found as representative for zone C1.

Table 12.8 Soil stratigraphy for CPT-201/BH-201 found as representative for zone C1.

Top [mbsb]	Bottom [mbsb]	Integrated ground model unit	Soil Unit	Soil/Rock Type
0.0	2.0	IGMU1	Ia	Sand
2.0	14.2	IGMU1	Ib	Clay
14.2	17.2	IGMU2	III	Clay
17.2	37.0	IGMU3	IVb	Clay Till
37.0	65.0	IGMU3	IVb	Clay Till
65.0	70.2	IGMU3	IVa	Sand

12.4.8 Soil zone/province C2

This zone is characterized to comprise limited, less than 5 m, presence of Soil Unit Ib. The top bedrock for this zone is met below the depth of 40 m. From the available geotechnical locations, there is not available example however reducing the upper 14.2 m of soft soils in less than 5m, CPT-201/BH-201 would be considered a representative profile. The stratigraphy in table format for an artificial profile representing soil zone C2 is presented in Table 12.9.

Table 12.9 Soil stratigraphy as representative for zone C2.

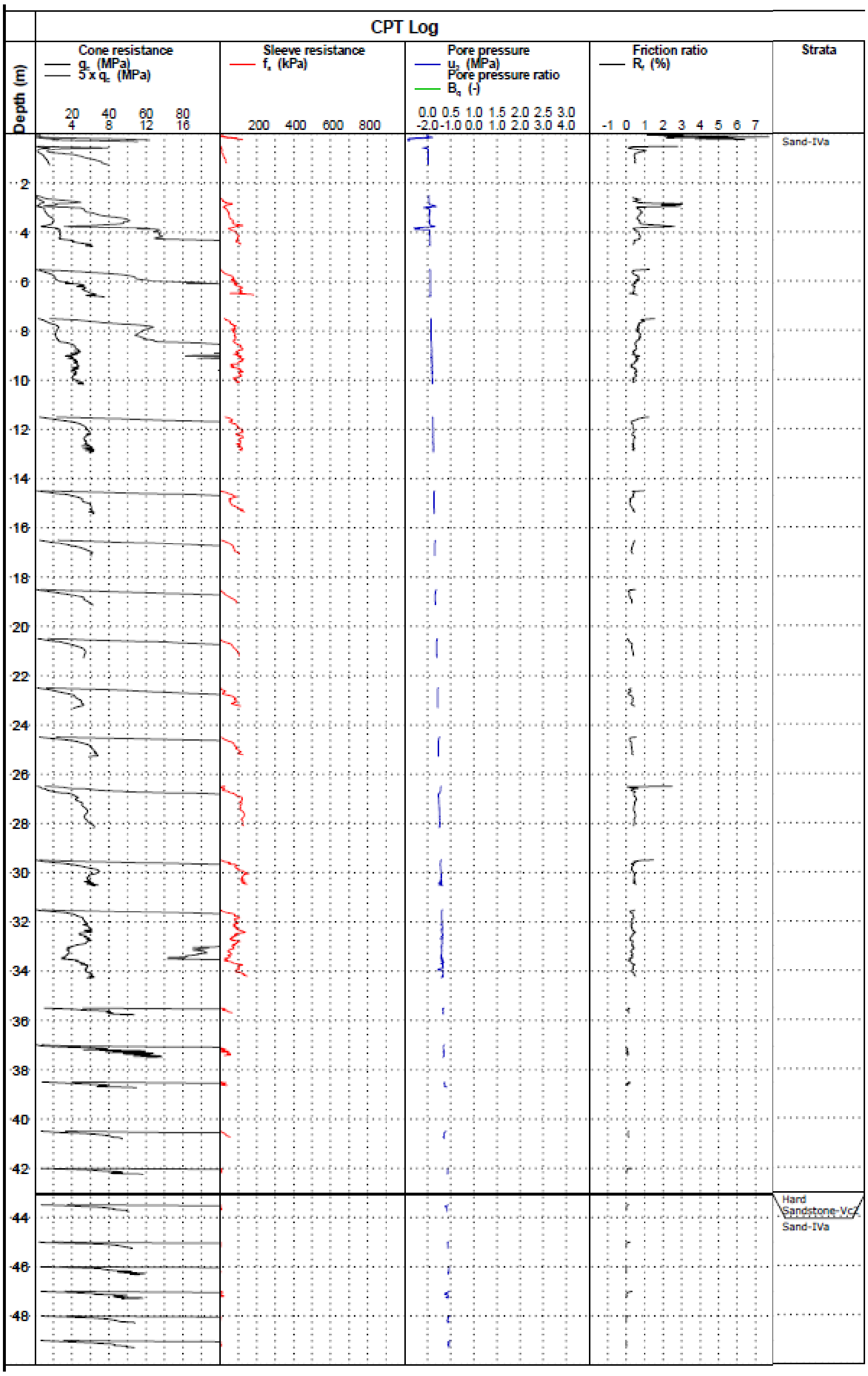
Top [mbsb]	Bottom [mbsb]	Integrated ground model unit	Soil Unit	Soil/Rock Type
0.0	5.0	IGMU1	Ib	Clay
5.0	17.2	IGMU2	III	Clay
17.2	37.0	IGMU3	IVb	Clay Till
37.0	65.0	IGMU3	IVb	Clay Till
65.0	70.2	IGMU3	IVa	Sand

12.4.9 Soil zone/province C3

This zone is characterized to comprise no presence of the soft Soil Unit Ib. The top bedrock for this zone is met in depth below the depth of 40 m. From the available geotechnical locations, one of them belong to this zone, namely CPT-220/BH-220 which is a sand dominated position. The CPT profile is presented in Figure 12-10. The stratigraphy in table format is presented in Table 12.10.

Table 12.10 Soil stratigraphy for CPT-220/BH-220 found as representative for zone C3.

Top [mbsb]	Bottom [mbsb]	Integrated ground model unit	Soil Unit	Soil/Rock Type
0.0	43.0	IGMU3	IVa	Sand
43.0	43.1	IGMU4	Vc2	Sandstone
43.1	62.9	IGMU4	IVa	Sand


CPT Log
Depth (m)
Cone resistance
q_c (MPa)
5 x q_c (MPa)
Sleeve resistance
f_s (kPa)
Pore pressure
u_2 (MPa)
Pore pressure ratio
B_q (-)
Friction ratio
R_f (%)
Strata
Sand-IVa
Hard Sandstone-Vc
Sand-IVa

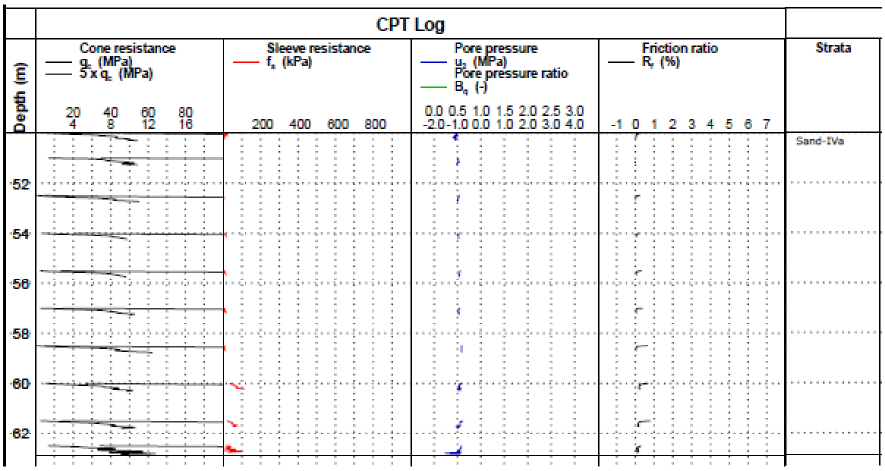


Figure 12-10 CPT measurements for CPT-220/BH-220 found as representative for zone C3.

13. Summary of results

Seabed levels across the survey site based on bathymetric data shows depths ranging between 15 and 57.6 m (MSL) with an increasing depth in a NW to SE orientation.

The presented Integrated Ground Model for BHII comprised of four major horizons (H00, H25, H30 and H50) along with four minor horizons (H10_i, H20_i, H40_i and H45_i). The three major horizons mark the shift between four major IGMU defined within the model. The horizon selection criteria were based on the site's stratigraphic framework of the site, geotechnical data, spatial reflector continuity, and the boundaries between seismic facies. The encountered subsurface material of BHII has been interpreted to comprise Holocene, Weichselian, Cretaceous and Jurassic sediments. No direct age dating methods were available and therefore the inferred ages are based on reports from previous studies along with the geotechnical investigations.

H25 horizon has been created using three separate approaches which were merged together into one. In the southern part of the area, the base of soft sediments could seismically be mapped above a laminated package. In large parts of the remaining area, the base of soft sediments, was determined with H30 as many parts of the site had thin thicknesses of IGMU 2 (below 3 m), meaning that transitional and stiff clays with thicknesses below 3 in borehole and CPTs were included in IGMU 1 instead of IGMU 2. This poses some degree uncertainty regarding the thickness map of both IGMU 1 (soft sediments) and IGMU 2 (transitional and stiff clays), but this approach was deemed to illustrate a clearer image than an interpolated grid between borehole and CPTs, solely based on geotechnical information would. In eight local areas (BH-217, BH-216, CPT-251, BH-214, CPT-239, CPT-233, CPT-221 and BH-201) an alignment between the seismic data and geotechnical information proved to be difficult and the thickness of the below lying unit (IGMU 2) was greater than 3 m. Therefore, an interpolation between the boreholes was used to guide the interpretation of H25.

First IGMU is comprised of soil unit I (soil unit Ia and Ib) of recent Holocene age that alternate between soft sand (soil unit Ia) and soft clay (soil unit Ib). Occasionally the transitional and stiff clays (soil unit II and III) can be encountered at the base of this unit. The sand (soil unit Ia) is believed to have been deposited during the Holocene transgression or the late Pleistocene regression in a set of shoreface deposits. Meanwhile, the clay (soil unit Ib) accounts for a large proportion of the Baltic Lake sediments. Generally, the unit represents the post-glacial transition clays and post-glacial marine sediments, deposited during the Yoldia Sea, the Ancylus Lake, Littorina Sea and last part of Baltic Ice Lake stages. Deposits are laminated with an increasing acoustic signal with depth followed by homogeneous seismic facies. The top of the unit is marked by the seabed reflector (H00) while the base is marked by H25. The thickness of this unit ranges between 0 – 39 m.

As soil unit Ia and Ib are well mixed together throughout the site, a separate distinction between the two within the model was not possible to accomplish. Generally, both soil units are present in all boreholes. An exception to this is the southern part of the site, where only soil unit Ib was encountered while soil unit Ia not being present. H10_i mapped by GEOxyz within the unit, potentially represents the base of organic rich formation known as gyttja formation. This assessment is solely based on borehole description with no support from the geotechnical information and therefore it was deemed too complicated to define a separate unit for this formation.

Second IGMU is comprised of transitional to stiff clays (soil unit II and III) which have not been included within the IGMU 1. These deposits are glaciolacustrine. These sediments mark a shift in the depositional environment from glacial to glaciolacustrine as the Weichselian glacier retreated and represent the Baltic

Ice Lake deposits. Occasionally sand laminae in parts of the site can occur with downwards increasing frequency which suggest that the ice front became more distal to the Bornholm Basin with time. The top of the unit is marked by H25 while the base is marked by the H30 horizon. Thickness of this unit range between 0 – 37 m.

Third IGMU is mainly comprised of very dense sand (soil unit IVa) in the northern part of the site and clay till (soil unit IVb) with a sand succession in the south-western part of the site. The origin of the unit is glacial and was deposited and reworked several times during the last glacial event. Soil unit IVa is often seen as infill of paleovalleys that have been carved into the bedrock in the central-northern part of the site. Sand deposits could possibly be a result of deltas that were built into a standing body of water, possibly by an ice dammed lake, or have been deposited by streams exiting from below an ice sheet into a standing water body. The top of the unit is marked by the H30 horizon while the base is marked by the H50 horizon. Thickness of this unit ranges between 0 – 104 m. Additional internal mapping (H40_i and H45_i) within the seismic unit was carried out. H40_i represents the base of paleovalley systems. H45_i represents the top of a sand succession within the unit.

The geotechnical characteristics are outlined, beginning with soil unit Ia which represents loose to medium-dense silty sand located in the upper layers. Meanwhile soil unit Ib, encountered also in the uppermost layers, comprises very soft clay, along with organic silty material. Notably, soil unit Ib also denotes the presence of gyttja formation in the vicinity. Below soil units Ia and Ib appears either soil unit II or III. Soil unit II is distinguished by the prevalence of soft to firm clay material, whereas soil unit III is defined by firm to stiff clay material. Deposits below the stiff clays include soil units IVa and IVb, composed of very stiff to extremely hard sandy clay till.

Last IGMU has a diverse succession of bedrock subcrops below the Pleistocene sedimentary succession. Three bedrock types have been defined from Cretaceous and Jurassic periods. The most encountered type of bedrock is limestone/mudstone (soil unit Va) but other type including sandstone (Vc) and chalk (Vb) are also encountered in the site. Based on the variation in geotechnical properties, each bedrock type has been subdivided into two segments, aiming to capture the distinct strength characteristics of each rock type. Therefore, a total of six bedrock units have been identified. Va1 and Va2 represent limestone/mudstone. Va1 categorises the limestone/mudstone as soft with characteristics ranging from very weak to medium weak, meanwhile Va2 categorises the limestone/mudstone as hard with characteristics ranging from weak to extremely strong. Vb1 and Vb2 represent the chalk. Vb1 categorises the chalk as soft, whereas Vb2 categorises the chalk as hard. Vc1 and Vc2 represent the sandstone. Vc1 categorises the sandstone as soft with properties ranging from extremely weak to weak, meanwhile Vc2 categorises the sandstone as hard with characteristics ranging from medium-strong to strong. Depth below seabed for top bedrock ranges between 0 – 110 m.

The kingdom project received by Ramboll had offsets between the time and depth domain. After a discussion with the client, it was decided that a velocity model should be created to solve the issue. All interpretation for the model were done within the time domain but with the Dynamic Depth Conversion (DDC) module the interpretations were transformed into depth domain as well. Also, during the first phase of the project issues arose with the correlation between the geophysical and geotechnical data. This was solved by an iterative process which ensured an alignment between the two datasets. Therefore, the presented interpretation of H30 and H50 which are the two most important interpretations within the model are of high degree of confidence.

The integrated Geological Model, coupled with the geotechnical analysis of rock and soil parameters, resulted in the establishment of Soil Design Zonation and a Soil Province style map. The two geotechnical criteria used to create the Soil Zone map were (i) depth of the bedrock below the seabed, and (ii) the thickness of the very soft sediments. The interaction of these two geological and geotechnical elements has the greatest impact on foundation design and feasibility, considering the site likely to be feasible for either drilled or driven jacket piles or monopiles depending on those soil zones. However, due to the difficulty to drill large diameter monopiles, a jacket structure with piles seems to be the most feasible option after this study. Further conclusions could be updated after new site investigations.

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