Bright ideas.
Sustainable change.

Intended for
Energinet

Document type
Report

Date
February 2024

Document no.
RDK2022N01215-RAM-RP-00003

Version
5

Energy Island Bornholm I

Integrated Ground Model Report

Energy Island Bornholm I

Integrated Ground Model Report

Project name	**Energiøen Bornholm**
Project no.	**1100053029**
Document no.	**RDK2022N01215-RAM-RP-00003**
Recipient	**Energinet**
Document type	**Final Report**
Version	**5**
Date	**2024/02/22**
Prepared by	**NLPDSE/AKTI**
Checked by	**CMME**
Approved by	**UTN**
Description	**Ground Model Report for Bornholm I offshore wind farm site**

Ramboll
Hannemanns Allé 53
DK-2300 Copenhagen S
Denmark

T +45 5161 1000
https://dk.ramboll.com

Rambøll Danmark A/S
CVR NR. 35128417

Medlem af FRI

Revision	Date	Prepared by	Checked by	Approved by	Description
1.0	2023-08-21	NLPDSE AKTI HFCH	JKAMM CMME	NLPDSE	Draft Report
2.0	2023-11-17	NLPDSE AKTI HFCH	CMME NATC	UTN	Report
3.0	2023-12-12	NLPDSE AKTI	CMME	UTN	Report
4.0	2024-01-24	NLPDSE AKTI	CMME	UTN	Report
5.0	2024-02-22	NLPDSE	CMME	UTN	Final Report

Ramboll
Hannemanns Allé 53
DK-2300 Copenhagen S
Denmark

T +45 5161 1000
https://dk.ramboll.com

Rambøll Danmark A/S
CVR NR. 35128417

Medlem af FRI

Contents

1.	Executive Summary	1
2.	Introduction	6
2.1	Project Summary	6
2.2	Scope of Work	6
3.	Bornholm I – site location and data gathering campaigns	8
3.1	Introduction	8
3.2	Existing infrastructure and exclusion areas	9
4.	Databases and data quality	11
4.1	Applied geodetic systems	11
4.2	Data Bases	11
4.2.1	Geophysical Data Base	12
4.2.2	Geotechnical Data Base	12
4.3	Data Quality	13
4.3.1	Sub-bottom Profiler	13
4.3.2	2D UHR Seismic	13
4.3.3	Bathymetry vs. Seabed Depth	14
4.3.4	Lateral squeezing of the depth seismic data	15
5.	Bornholm I – site setting	16
5.1	Site topography and seabed morphology	16
5.2	Seabed – substrate type	21
5.3	Regional Geology: context for Bornholm I	22
5.3.1	Structural setting	22
5.3.2	Palaeozoic – Mesozoic Geology	23
5.3.3	Quaternary Geology of the Bornholm region	26
6.	Methodology	30
6.1	Seismic mapping	30
6.2	Velocity model workflow	30
6.3	Integration of Seismic Units with the Geotechnical Soil Units – the Ground Model	31
7.	Seismic Units and Sedimentology	32
7.1	Introduction	32
7.2	Terminology	32
7.3	Seismic Unit 1 – Holocene Sediments	35
7.3.1	Seismic definition – H00 Seabed	35
7.3.2	Internal Seismic Characteristics	35
7.3.3	Sedimentology and Geotechnical Characteristics	35
7.4	Seismic Unit 2	36
7.4.1	Seismic Unit 2a Mounds – Seismic definition	37
7.4.2	Seismic Unit 2a Mounds – Internal seismic characteristics	37
7.4.3	Seismic Unit 2a Mounds – Sedimentology and geotechnical characteristics	37
7.4.4	Seismic Unit 2b Channel features – seismic definition	39
7.4.5	Seismic Unit 2b Channel features – internal seismic geometry	39
7.4.6	Seismic Unit 2b Channel features – sedimentology and geotechnical characteristics	40
7.5	Seismic Unit 3 – Baltic Lake succession	40
7.5.1	Seismic Unit 3 definition – H05, H15, H20	40
7.5.2	Seismic Unit 3 - Internal seismic character	42
7.5.3	Seismic Unit 3 – Sedimentology and Geotechnical Characteristics	42

7.5.4	Seismic Unit 3a	42
7.5.5	Seismic Unit 3b	42
7.5.6	Seismic Unit 3c	44
7.5.7	Seismic Unit 3d	45
7.5.8	Discussion	45
7.6	Seismic Unit 4 – Glacial influenced strata	47
7.6.1	Seismic Unit 4a – glacial drift sediments (Tills and Moraines)	51
7.6.2	Seismic Subunit 4b – fine grained sediment fans	56
7.6.3	Seismic Subunit 4c – sand fan systems and palaeovalley fills	58
7.6.4	Seismic Unit 4 – bedrock valley fills	62
7.6.5	Seismic Unit 4 ridges	63
7.7	Seismic Unit 5 Bedrock	68
7.7.1	Bedrock seismic pick	68
7.7.2	Bedrock character	70
7.7.3	Bedrock structure	70
7.7.4	Bedrock geomorphology	70
8.	Geotechnical Interpretation	74
8.1	Geotechnical data	74
8.2	Geotechnical units	76
8.3	Geotechnical cross sections	77
8.4	Geotechnical derivation of soil parameters	78
8.5	Detailed Geotechnical Interpretation of the soil units	78
8.5.1	Particle Size Distribution	78
8.5.2	Maximum and Minimum Dry Unit Weight	80
8.5.3	Specific Gravity, d_s	80
8.5.4	Unit Weight	82
8.5.5	Moisture content	84
8.5.6	Plasticity Index and Atterberg Limits	86
8.5.7	Organic content and chemical composition content	87
8.5.8	In-Situ Stress State	88
8.5.9	Shear strength properties	90
8.5.10	Soil Stiffness properties	96
8.6	Rock Units - detailed Geotechnical Interpretation	100
8.6.1	Available data	101
8.6.2	Assessment of the available data	101
8.6.3	Unit weight	104
8.6.4	Specific gravity	105
8.6.5	Compressive strength	107
8.6.6	Stiffness	111
8.6.7	Bedrock overview and correlation with geophysical logs	114
8.7	Design soil profiles	115
9.	Leg Penetration analysis	116
9.1	Introduction	116
9.2	Seabed and Soil Conditions	116
9.2.1	Geotechnical	116
9.3	Methodology	116
9.4	Analysis input	117
9.4.1	Jack-up vessel information	117
9.4.2	Geotechnical parameters	118
9.5	Results	118
9.6	Group 1	122

9.7	Group 2	122
9.8	Group 3	123
9.9	Discussion and Potential Hazards	125
9.9.1	Spudcan-footprint/seabed interaction	125
9.9.2	Scour	126
9.9.3	Leg extraction	126
10.	Integrated Ground Model	127
10.1	Introduction	127
10.2	GMU1 – Geotechnical Soil Unit Ia (loose to medium dense sand)	128
10.3	GMU2 – Geotechnical Soil Unit Ib (soft, organic-rich clays)	129
10.4	GMU3 – Geotechnical Soil Unit III (firm to stiff, sandy clay)	131
10.5	GMU4 – Geotechnical Soil Unit IVb (very stiff to very hard clay till)	133
10.6	GMU5 – Geotechnical Soil Unit IVa (medium dense to dense sand)	135
10.7	GMU6 – Geotechnical Unit V (bedrock)	136
11.	Potential issues and hazards	137
11.1	Seismic to Soil Unit mismatches	137
11.1.1	Soil Unit II	137
11.1.2	The base of GMU3 (Soil Unit III)	137
11.1.3	Stratigraphically shallow Soil Unit IVa	138
11.2	Geological hazards highlighted by the model	138
11.2.1	Very soft sediments at shallow depths	138
11.2.2	Pockets of Soft Soils (Soil Unit Ib) in the eastern part of the site.	139
11.2.3	Sand overlying soft sediment	140
11.2.4	Irregular topography above very stiff sediments	146
11.2.5	Potential Boulders and Block fields	147
11.2.6	Faults and folding introducing very variable bedrock conditions at a very short lateral distance combined with shallow bedrock depths.	150
12.	Soil Zonation and Soil Provinces	151
12.1	Introduction	151
12.2	Soil zonation	151
12.3	Soil provinces	154
12.4	Examples of representative soil profiles for each soil zone/province	155
12.4.1	Soil zone/province A1	155
12.4.2	Soil zone/province A2	157
12.4.3	Soil zone/province A3	158
12.4.4	Soil zone/province B1	160
12.4.5	Soil zone/province B2	162
12.4.6	Soil zone/province B3	164
12.4.7	Soil zone/province C1	166
12.4.8	Soil zone/province C2	168
12.4.9	Soil zone/province C3	168
13.	Summary	170
14.	References	172

Appendices
Appendix 1 - Robertson Charts
Appendix 2 - Classification logs
Appendix 3 - Geotechnical sections
Appendix 4 - Design profiles-Tables
Appendix 5 - Design profiles
Appendix 6 - Bedrock strength profiles
Appendix 7 - Velocity Modelling Workflow

Appendix 8 - Charts
Appendix 9 - Charts – Geotechnical Soil Unit thickness
Appendix 10 - Cross Sections
Appendix 11 – Geotechnical Soil Zonation Map

List of Abbreviations

BH	Borehole
BHI	Bornholm I
BHII	Bornholm II
BP	Before Present
CPT	Cone Penetration Test
Energinet	Energinet Eltransmission A/S
ETRS89	European Terrestrial Reference System 1989
fs	Sleeve friction
IGM	Integrated Ground Model
IGMU	Integrated Ground Model Unit
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
TWT	Two-Way-Time
UTM	Universal Transverse Mercator
u_2	Pore pressure
2D UHR	2D Ultra High Resolution

1. Executive Summary

Ramboll has prepared this Integrated Ground Model Report for the Bornholm I (BHI) Offshore Wind Farm (OWF) project for Energinet Eltransmission A/S on behalf of the Danish Energy Agency. Denmark has committed to build the first Energy islands following the Climate agreement from June 2020. One of those associated wind farm areas will be in the Baltic Sea, near the island Bornholm. The energy complex will be constructed with an installation capacity of up to 3 GW offshore wind 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.

This report characterises the geological conditions across the Bornholm I Site and illustrates how the geology has been subdivided into Seismic and geotechnical soil units. Integration of the Geophysical and Geotechnical Units led to the creation of 6 Ground Model Units (GMUs) that have been mapped in three-dimensions across the Bornholm I site (BHI). Site characterisation is based on preliminary geophysical and geotechnical site investigations that were undertaken respectively by GEOxyz (2022) and Gardline (2023). The geophysical data consisted of approximately 5800 line kilometres of ultra-high resolution seismic (2D-UHR) and ca. 17000 line kilometres of sub-bottom profiler (SBP), side-scan sonar (SSS) and magnetometer (MAG). The data was collected in respective grids of 250 m and 62.5 m by 1000 m. Geotechnical data at the Bornholm I area consists of 14 geotechnical boreholes (BH) that were spread over 14 separate locations, and these were supplemented by 75 seabed Cone Penetration Tests (CPTs) distributed across 39 separate sites.

The Bornholm I OWF site covers approximately 340 km^2 and is situated South and West of the island Bornholm. Water depth ranges from 27 m to 47 m with an average water depth of 40.6 m. In general, water depths increase towards the West and North and the seabed topography is relatively smooth. The one exception to this is in the Northeast part of the site where there is a distinct bathymetric high that possesses uneven seabed topography. The seafloor sediments are predominately sand and gravel in the eastern parts of the Bornholm I Site whereas the western and northern part is dominated by clay.

Seismic Units
Five Seismic Units have been defined and are mapped across the Bornholm I Site. Several of the Seismic Units have internal subunits that are described herein. Not all the subunits have mapped since some subunits turned out to not be distinctive from a geotechnical perspective.

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 (both marls and claystones).

The six Geotechnical Soil Units defined herein represent a transition from soft, largely unconsolidated near surface sands (Soil Unit Ia) and soft, organic-rich clays (Soil Unit Ib), through transitional and increasingly stiff clay-rich soils (Soil Units II and III) into clay till (Soil Unit IVb) and dense sands (Soil Unit IVa). Soil Units III and IV (a&b) are associated with glacial deposits in Bornholm I whereas Soil Units I (a&b) and II occur in the post-glacial Baltic Lake succession or as part of the Holocene transgressive sequence.

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.

Three distinct bedrock provinces have been distinguished in Bornholm I. The first province lies in the southern two-thirds of the site and is dominated gently dipping Cretaceous aged limestones that are dominated by chalk. Locally this succession is folded. Interbeds of marl and mudstone have been recorded in these Cretaceous strata. The second bedrock province is centred on the southern limb of a large monoclinal fold where the bedrock strata turn vertical. The limb strikes WNW to ESE across the entire Bornholm I Site and the monoclinal fold brings up older strata to subcrop beneath the Pleistocene and Holocene sediment cover. Tightly folded siliciclastic sediments (sandstone, mudstone and locally thin coals) dominate the sub-cropping bedrock beneath the Pleistocene and Holocene sediment cover in the northern part of the Bornholm I Site. This area has been assigned to Bedrock Province 3. These siliciclastic sediments are considered to be of Lower Jurassic age. An important observation in this succession of Jurassic siliciclastic sediments is that many of the sandstone beds are only very weakly cemented; boreholes record dense sand from depth intervals that place the cores below the mapped top bedrock.

Integrated Ground Model

The Bornholm I Integrated Ground Model presented herein is derived from the aforementioned Seismic and Geotechnical Units; it comprises six units, designated GMU1 through to 6, as well as three bedrock provinces. The bedrock provinces are defined by a combination of lithology, age and structure. All the GMUs 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. Table illustrating the relationships between the Ground Model Units (GMU) and the defined Seismic and Geotechnical Units. Also provided are the dominant lithologies and estimated age of the GMUs.

Integrated Ground Model Units	Top Seismic Horizon	Bottom Seismic Horizon	Geotechnical Soil Unit	Seismic Unit(s)	Lithology	Depositional Environment	Age
GMU1	H00 Seabed	H15	Soil Unit Ia	Seismic Unit 2a	Loose Sand	Shoreface, shallow marine	Latest Pleistocene to Holocene
GMU2	H00 Seabed/H15	H30	Soil Unit Ib	Seismic Unit 1 Seismic Unit 2b Seismic Unit 3	Soft, Organic-rich Clay	Marine and lacustrine clays	Late Pleistocene (Baltic-Lake/Sea)
GMU3	H30 (H35)	H40 or interpolated from CPT/BH picks	Soil Unit III	Seismic Unit 4	Transitional to Stiff Clay (Silty Clay)	Glacial Till and/or Moraine	Pleistocene
GMU4	H40 or interpolated from CPT/BH picks	H50 (Bedrock) or H45	Soil Unit IVb	Seismic Unit 4	Clay Till	Glacial Till and ice-front distal subaqueous fan or distal delta front	Pleistocene
GMU5	H45	H50 (Bedrock)	Soil Unit IVa	Seismic Subunit 4c	Dense sand	Sandy delta or ice-front subaqueous plume fan	Pleistocene
GMU6	H50 (Bedrock)		Soil Unit V	Bedrock	Limestones, chalk, sandstone, marls and locally coal	Deltaic to marine	Jurassic & Cretaceous

Ground Model Unit 1 (GMU1) is comprised of Soil Unit Ia that is characterised by shallow, loose sands. This Unit is associated with a set of shallow mounded features that are defined by Seismic

Unit 2a. The sands are believed to have been deposited during the Holocene transgression or the late Pleistocene regression as shoreface deposits. These sands are generally restricted to the Eastern part of the Bornholm I Site where they are locally associated with a series of benches orientated obliquely to the present-day bathymetry. Shallow sands are also encountered to the south of a distinct bathymetric high present in the NE part of the site and have also been included in GMU1.

Ground Model Unit 2 (GMU2) is defined by Geotechnical Soil Unit Ib which is composed of very soft, organic-rich clays that are of Holocene to latest Pleistocene age. This Ground Model unit encompasses several of the defined Seismic Units (1, 2b and 3). Whilst the Seismic Units are distinct, and can be mapped individually, the sediments that comprise these Seismic Units possess similar geotechnical properties and are thus grouped into a single Ground Model Unit. In the Eastern part of the site GMU2 is only sporadically developed. Soil Unit Ib clays are locally preserved in shallow discontinuous pockets that have been created by the very irregular top of the glacial deposits that characterise Seismic Unit 4 and GMUs 3 and 4. Further East and North GMU2 becomes a laterally continuous package with the soft organic-rich clays thickening both westwards and northwards. Here GMU2 can attain thicknesses in excess of 30 m. Soil Unit Ib soft, organic rich clays account for a large proportion of the Baltic Lake sediments, and they transition into stiffer transitional Soil Units (II & III) with depth. Soil Unit II as defined for the Bornholm Sites is not a common soil type in Bornholm I. This unit is defined in the geotechnical assessment, but it has not been incorporated into the Bornholm I Ground Model as a separate Ground Model Unit. Across the Bornholm I Site, Soil Unit Ib generally passes, with depth, into the stiffer soils of Soil Unit III. This contact normally occurs at the H30 Seismic Horizon that defines the top of Seismic Unit 4 and the base of GMU2, though it may occur just above the seismically defined base of GMU2.

Ground Model Unit 3 is characterised by Geotechnical Soil Unit III. This GMU has proved the most difficult to define accurately from a seismic perspective since its base often occurs within Seismic Unit 4 and it cannot always be tied directly to a Seismic event. In the current Ground Model, the base of GMU 3 is defined by the contact of Geotechnical Soil Unit III with Soil Unit IVb. Since this contact does not always align with a mappable Seismic Horizon the contact has been created using the Geotechnical Soil Unit picks in the CPTs and Boreholes, with the resulting surface being tied to seismic horizons, either the H30, H40 or the H45 seismic horizon depending on how deep Geotechnical Soil Unit III extends. Over parts of the Bornholm I the site the base of Soil Unit III should be viewed as a "best estimate" and it remains uncertain; more data, in the form of CPTs and Boreholes, is required to refine the base of this GMU.

In the eastern areas GMU3 is normally underlain by very stiff silty to sandy Clays. These till-like sediments are assigned to GMU4 with the stiff silty clays having been assigned to Geotechnical Soil Unit IVb. GMU4 in the integrated Ground Model is confined to Seismic Unit 4 and it plugs tunnel valleys carved into the bedrock, particularly in the southwestern part of the site. At such locations Soil Unit IVb and GMU4 can be in excess of 50 m thick. For the most part, the very stiff, silty tills of Soil Unit IVb sit directly below GMU3 (Soil Unit III) but locally they sit directly below the soft organic-rich clays of GMU2 (Soil Unit Ib).

GMU3 and 4 are both developed in Seismic Unit 4 and illustrate that there is significant lateral variation in the geotechnical properties of the sediments that comprise this Seismic Unit: transitional Clays (Soil Unit III) of GMU3 pass laterally into very stiff, silty, clay-tills of GMU4. The lateral variation that is observed within Seismic Unit 4 is not uncommon in glacial tills where sediments may have been deposited by a variety of depositional mechanisms and subjected to varying degrees of consolidation under ice sheets.

GMU4 is characterised by clay till. In places this GMU can comprise the entire of Seismic Unit 4, but it is mostly developed in the Seismic Subunits 4a and 4b. The clay till of Soil Unit IVb are associated with both structureless till-like deposits and with fine grained fan-systems that are genetically related to sand-rich delta/fan deposits that are developed along the eastern site of the Bornholm I Site. The sands are assigned to GMU5.

GMU5, as mentioned above, is characterised by the dense sands of Geotechnical Soil Unit IVa, though layers of stiff silty clay (Soil Unit IVb) may also be locally present. Unit 5 in the integrated Ground Model fills palaeovalleys that have been carved in the bedrock in the eastern and northern part of the Bornholm I site and it is considered to form the core of the bathymetric high that is observed in the Northern part of the Bornholm I site. GMU5, and its dense Soil Unit IVa sands, define a set of sedimentary fans that fringe the topographic high which separates Bornholm I from the Bornholm II Site. These sand-rich fans could represent deltas that have built into a standing body of water, possibly an ice dammed lake, or alternatively, they could represent subaqueous fans deposited by ice-front by streams exiting from below an ice sheet into a standing water body. GMU5, with its sand-dominated character although largely confined to the eastern part of the Bornholm I Site locally extends across the Site filling shallow depressions and possible channels in the bedrock.

GMU6 is the bedrock that subcrops below the Pleistocene and Holocene sediments. Three bedrock provinces have been defined. From South to North these are (i) largely gently dipping but locally folded strata of probable Cretaceous age that are dominated by limestones, chalks and siltstones; (ii) a broadly WNW to ESE zone dominated by very steeply dipping to vertical strata, and (iii) a northern province of tightly folded sandstones, marls and claystones that can possess thin coals. The northern province is believed to be of Jurassic age and is important from a geotechnical perspective in that many of the sandstones are very poorly cemented, such that geotechnical boreholes drilled through the bedrock in the northern part of the Bornholm I Site have recovered loose sand.

Geotechnical provinces
Challenging ground conditions are identified in Bornholm 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 considered to be 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 an 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, organic-rich clays (Soil Unit Ib) that define GMU2. Here the distinction is made between those areas without organic-rich clays, 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 Bornholm I 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 a large part of the site considering either drilling in the bedrock or a combination of drive and drilling. It needs to be noted that drilling large diameter monopiles has an added level of complexity in terms of installation.

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 Bornholm I 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 north of Bornholm, owing to the presence of locally very thick soft clays in GMU2, deep penetrations, of up to 25.6 m are predicted based on the standard spudcan size of a jack-up installation vessel. This location is also located at the area with deepest water depth.

2. Introduction

This section includes a brief introduction to the purpose of the project along with the desired goals to accomplish.

2.1 Project Summary

Ramboll has been contracted by Energinet Eltransmission A/S to optimize 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 the Bornholm I Site, which is based on geophysical data and results acquired by the GEOxyz in 2021/2022 and geotechnical data acquired by Gardline in 2022.

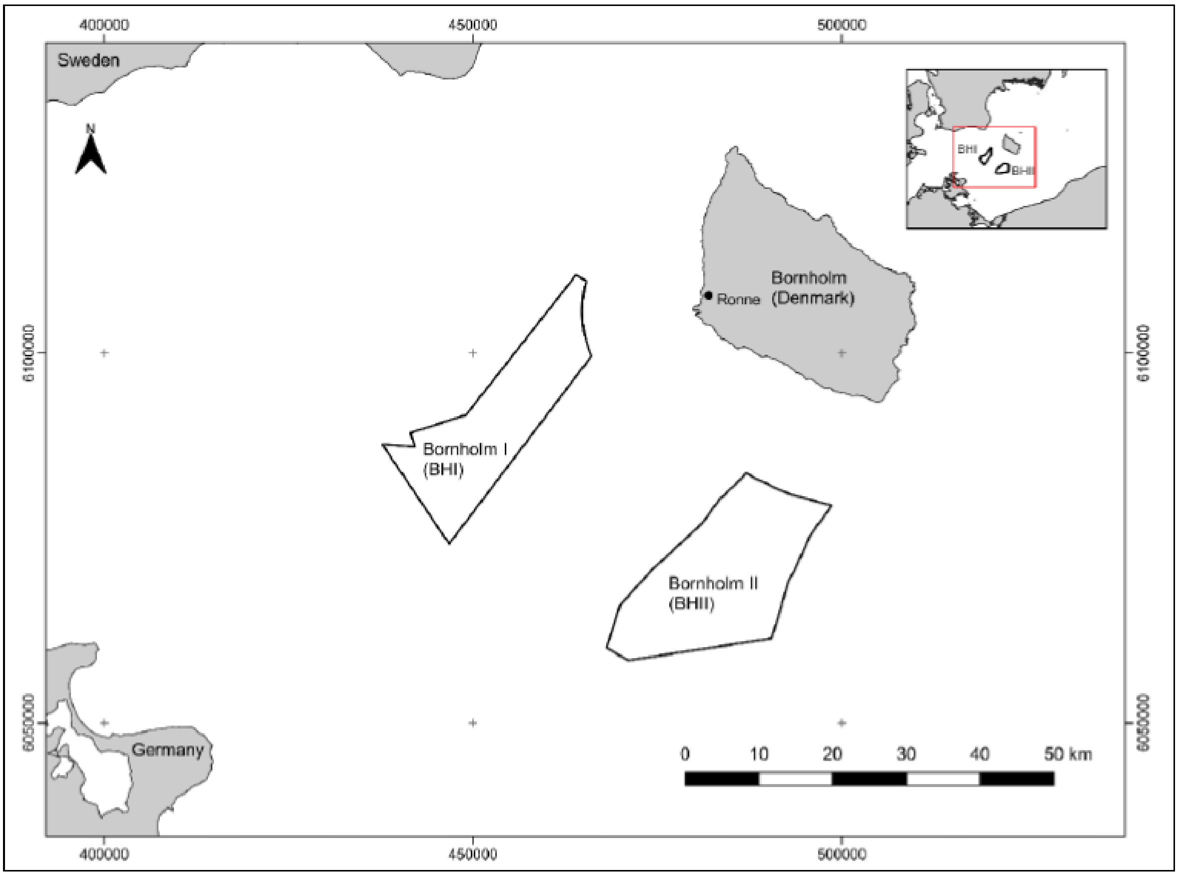


Figure 2-1. Location of the Bornholm I and II sites in the Baltic Sea. The polygons show the full extent of the sites, the original areas plus the added extensions.

2.2 Scope of Work

The results presented in this report include the agreed upon scope of work between Ramboll and the client: Conceptual Geological Model; Spatial Integrated Geological Model; Geotechnical characterisation of soil units and Geotechnical Zones.

The purpose of the Conceptual Geological Model is to illustrate the stratigraphic relationship between the soil units and their variation. Each soil unit within the Conceptual Geological Model includes a description of the lithology, age, and depositional environment in context with the geological history of the area.

The purpose of the Integrated Ground Model is to integrate the mapped seismic-stratigraphic unit boundaries with geotechnical information into "engineering soil units and integrated into a 3D Integrated Ground Model with an Interpretative Report containing characteristic values of geotechnical parameters.

The relevant geotechnical properties of all units within the 3D Geological Model will be provided by Ramboll based on the 3D Geological Model and results from the geotechnical survey.

A geotechnical zonation will be provided detailing the key elements that would influence the engineering design of structures (wind turbine foundations, substations, cable corridors, etc.) to be located in the site.

3. Bornholm I – site location and data gathering campaigns

3.1 Introduction

The Bornholm I survey site is located 15 km to the south-west of the Danish Island of Bornholm in the Baltic Sea (Figure 3-1) and it covers an area of 340 km^2. The site was extended to include two additional areas to the north and south of the original Bornholm I Site to increase the proposed total windfarm capacity by 1.5 GW. The ground model described herein covers both the original and the extended parts of the site. GEOxyz originally subdivided into four tiles for the reporting of the data collection but this subdivision has been dropped; the Ground Model is viewed as a single entity across the entire site.

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

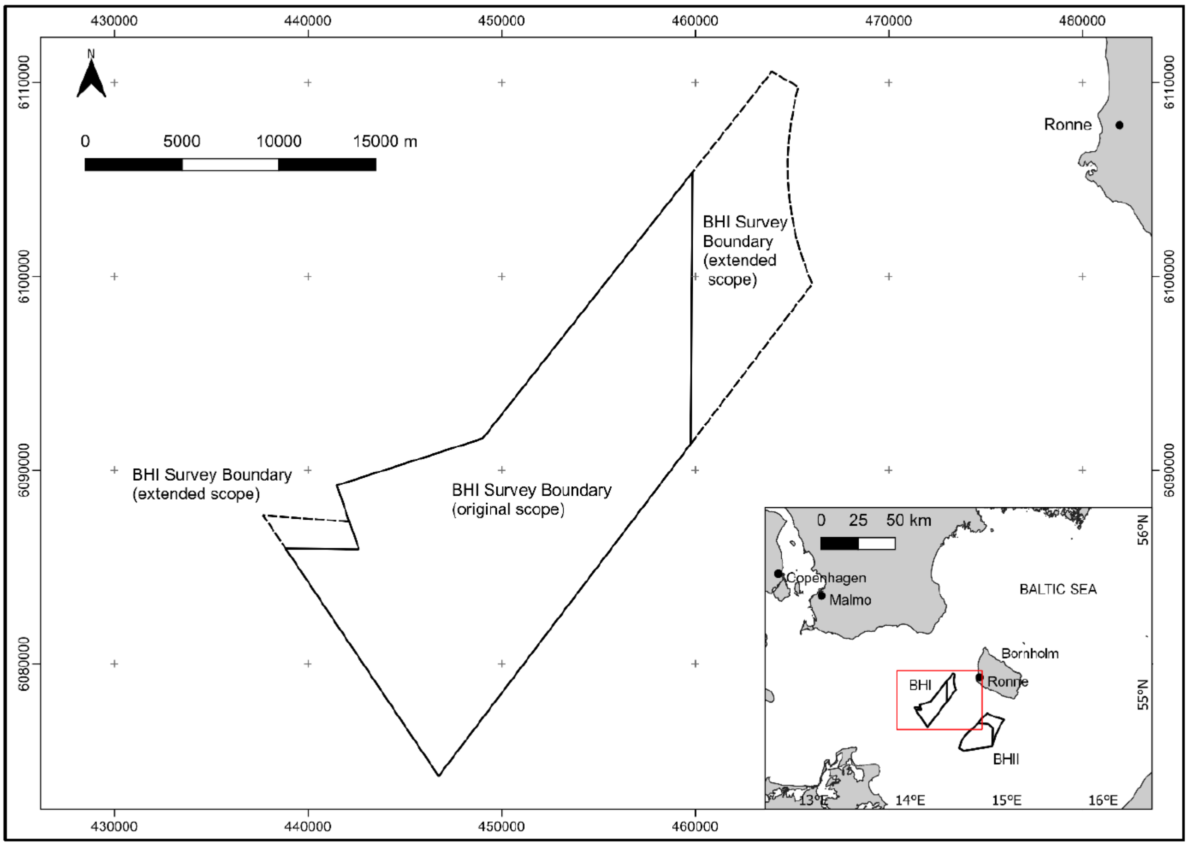


Figure 3-1. Map taken from the geophysical survey report (GEOxyz, 2022) which illustrates the original and extended parts of the Bornholm I site.

Table 3.1. Summary of the Site investigations that have been performed at the Bornholm I 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 and exclusion areas

There are a number of known infrastructures that cross the Bornholm I site. These include the Baltic Pipe gas pipeline that runs from Norway, across Denmark to Poland, as well as several cable routes (see Figure 3-2). In addition to these existing infrastructures there is an exclusion zone over the centre of the site related to a NATO exercise zone. This exclusion zone has had a clear impact on the gathering of ground information as no CPT nor Borehole could be located within this zone (see Figure 3-3).

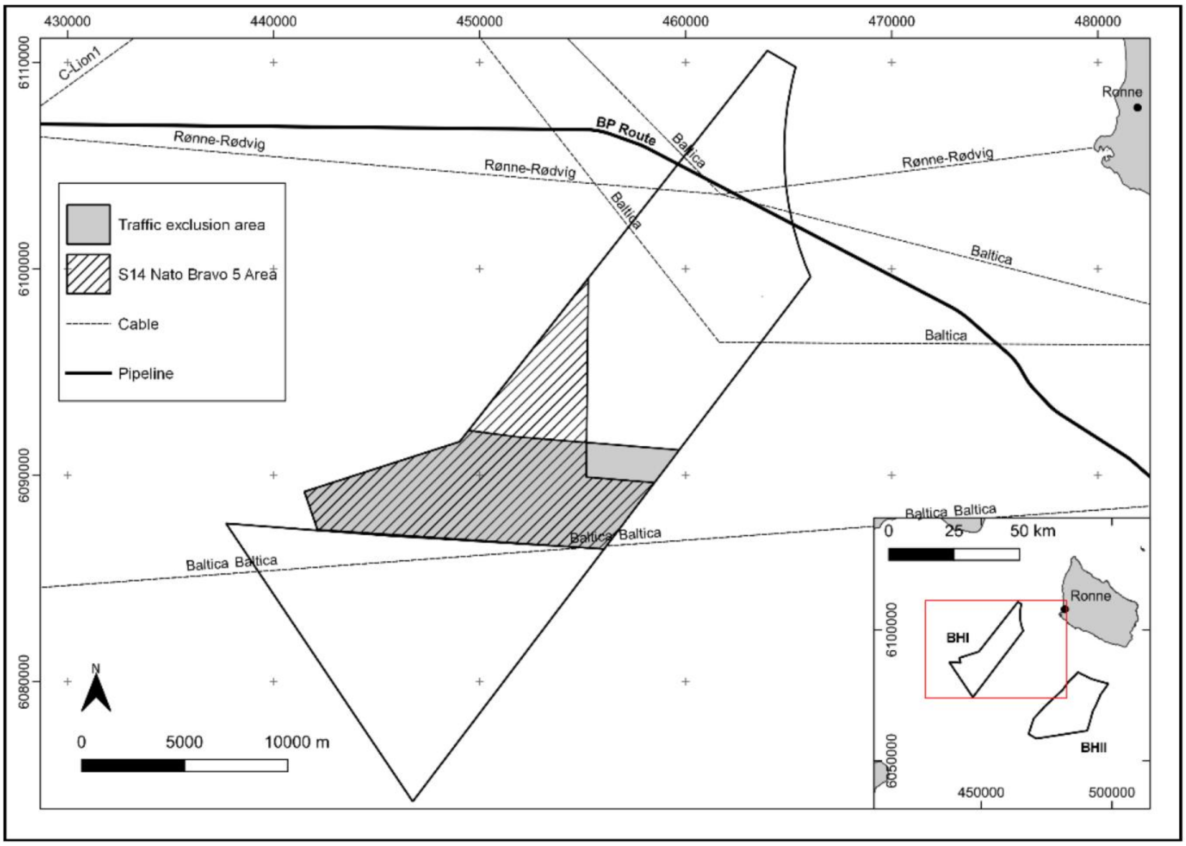


Figure 3-2. Map taken from the Geophysical Survey Report (Ref (GEOxyz, 2022)) illustrating the existing infrastructure at the Bornholm I site along with the NATO-related exclusion zone.

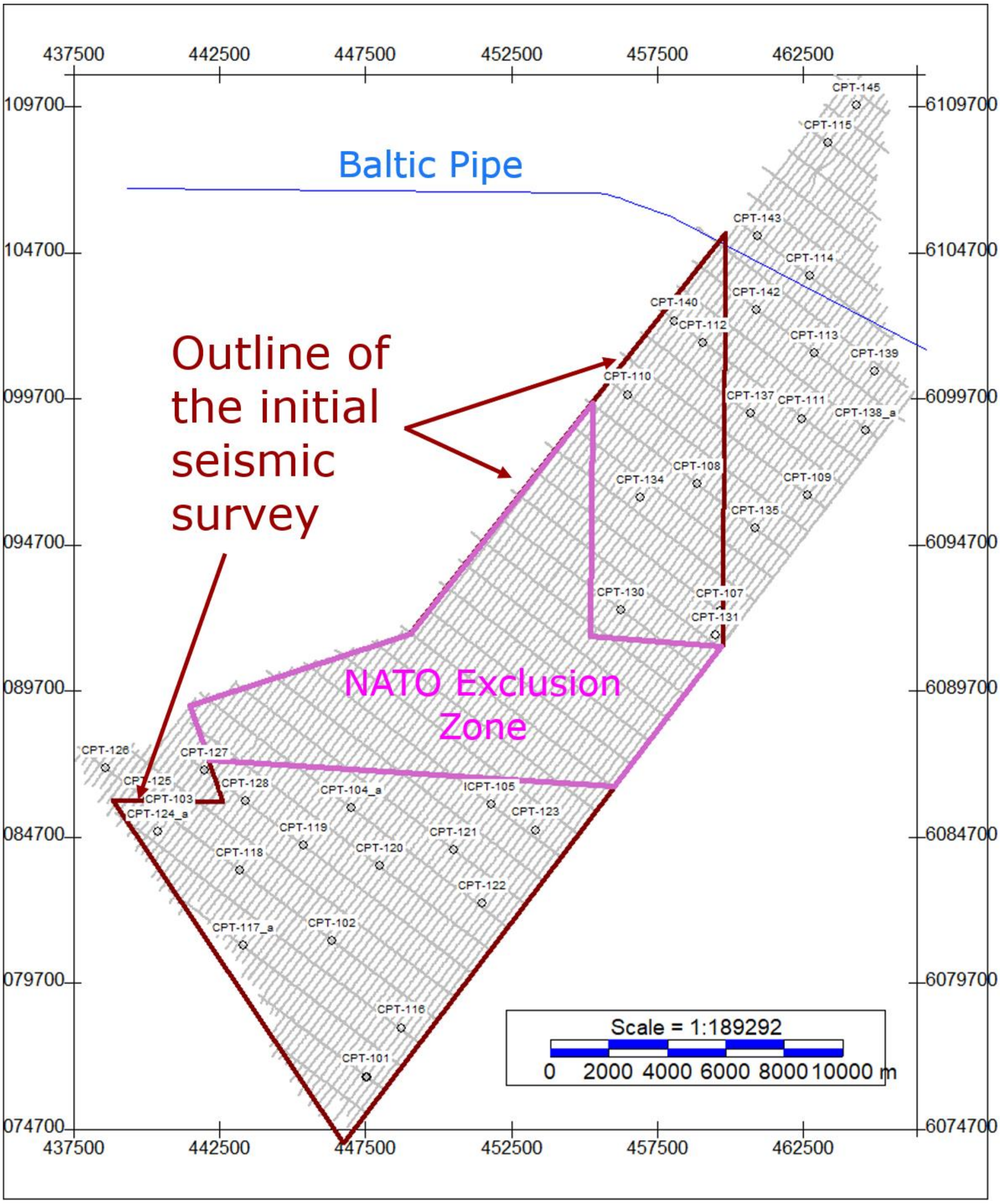


Figure 3-3. Map from the Kingdom Project illustrating the impact the NATO-related exclusion zone has had on the gathering of ground information: no CPTs nor Boreholes are located within the exclusion Zone.

4. Databases and data quality

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

4.1 Applied geodetic systems

The Ground Model co-ordinate system follows that used by the geophysical and geotechnical survey operations which were conducted with respect to the ETRS89 Ellipsoid, UTM Grid Zone 33N EPGS 25833. The grid system is presented in Eastings and Northings (metres). Full details of the datum and projection parameters are provided in the site survey report (GEOxyz, 2022).

The vertical datum for the project is Mean Sea Level (MSL) as defined by the Technical University of Denmark geoid model DTU21MSL. Height data during the geophysical survey was acquired relative to the ellipsoid and reduced to the project vertical datum and the depths reported in the Ground Model Report follow those used in the geophysical survey which were related to DTU21MSL.

Table 4.1. Datum parameters for the surveys

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 surveys

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

Ramboll's characterisation of the ground information is based on the geophysical and geotechnical investigations of the Bornholm I site (see Table 3.1). The seismic database was provided to Ramboll as a Kingdom Project, with the Geotechnical Data having been delivered in AGS format. Written reports accompanied both the Geophysical (GEOxyz, 2022) and Geotechnical (Gardline, 2023) digital datasets.

A desktop study undertaken prior to the start of the data gathering by GEUS (Jensen, 2021) was also made available to Ramboll. This report provided much of the regional geological background for the work herein and it may be viewed as an important starting point for the evolution of the Ground Model described here.

4.2.1 Geophysical Data Base

The geophysical data consisted of 5819 line kilometres of ultra-high resolution seismic (2D-UHR) collected in a grid with an in-line spacing of 250 m and cross line spacing of 1000 m and 1718 line km of sub-bottom profiler (SBP), side-scan sonar (SSS) and magnetometer (MAG) collected in a grid with an in-line spacing of (62.5 m and cross line of 1000 m).

4.2.2 Geotechnical Data Base

During the 2022 Geotechnical Campaign ground information was recovered from 39 separate geotechnical locations. These data came from 14 Boreholes (BHs) that were spread over 14 separate locations and were supplemented by 75 seabed Cone Penetration Tests (CPTs) that were distributed across 39 separate sites. Figure 4-1. illustrates the locations of the boreholes and CPTs. As noted above (Section 1) there is a large gap in the ground information over the NATO related exclusion zone.

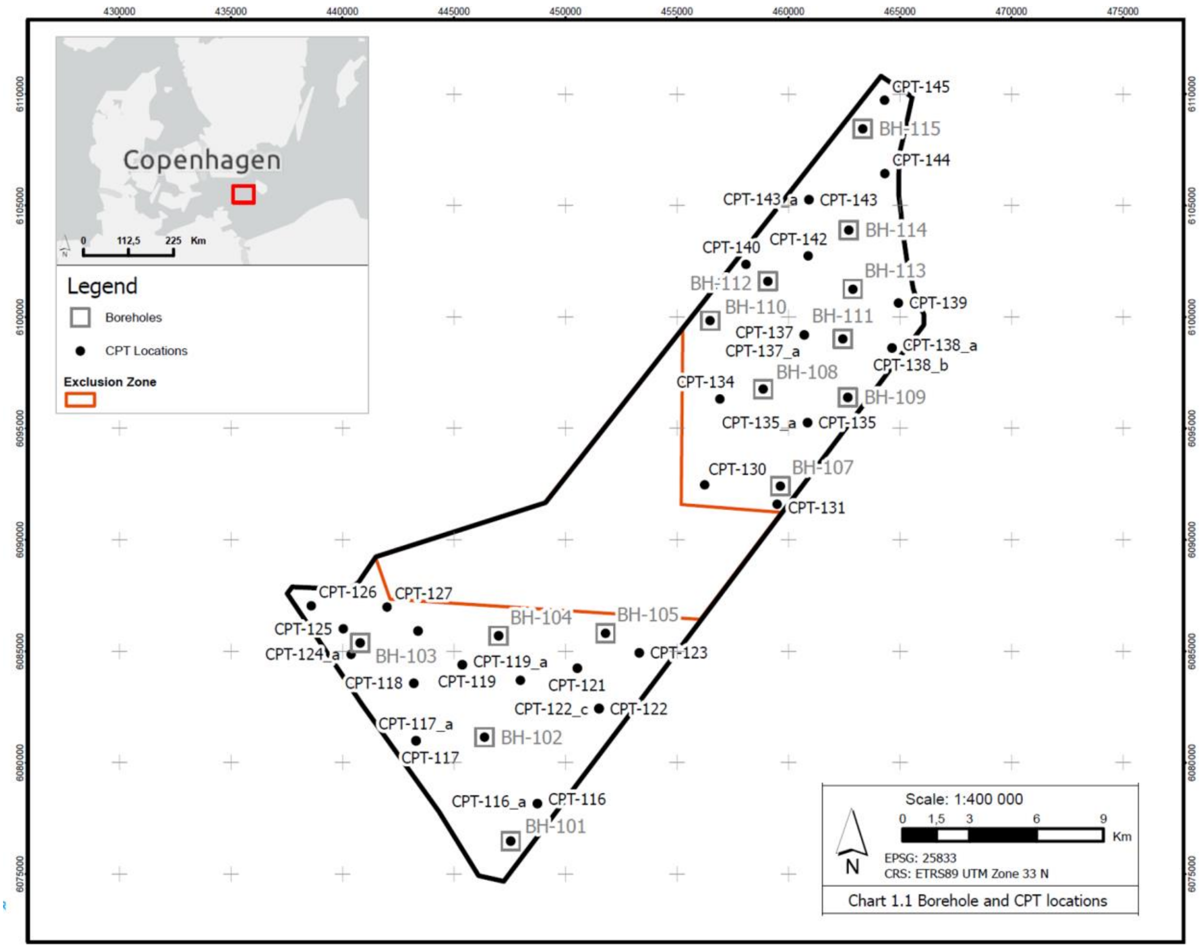


Figure 4-1. Maps illustrating the locations of the Boreholes and CPTs that have been utilised to characterise the geology of the Bornholm I Site.

4.3 Data Quality

The geophysical data received by Ramboll was of good quality. In the Bornholm I site there were a few minor issues with the Depth Seismic though these were not followed up since the interpretive work was undertaken in the time domain.

4.3.1 Sub-bottom Profiler

The sub-bottom profiler dataset acquired by GEOxyz is considered to be of good quality and penetration throughout the survey site (GEOxyz, 2022). Penetration was generally less than 10 m, and occasionally much shallower. Since most of the sediment succession penetrated by the SBP seismic has been characterised geotechnically as belonging to a single Soil Unit (SU_Ib) Ramboll has not focused its efforts on re-evaluating the SBP seismic interpretations. Work has focused addressing the issues that arose on the deeper parts of the stratigraphic succession that are only imaged on the UHR dataset.

4.3.2 2D UHR Seismic

In the Geophysical Survey report (GEOxyz, 2022) the Ultra High Resolution Seismic is described as being of good quality with generally low noise levels. It is noted that there are localised parts of some lines which show a reduction in dominant frequency and that there is some phase distortion. This is due to the receiving streamer being at too great a depth and/or weather-related noise. These degraded areas in the data are regarded as having had a negligible effect on the overall interpretation of the data. The data imaging is good to between 50 to 70 m below the seabed, especially when the bedrock strata do not have steep-dips. Locally the bedrock is tightly folded, and imaging of the strata becomes poor when the beds reach near vertical (Figure 4-2).

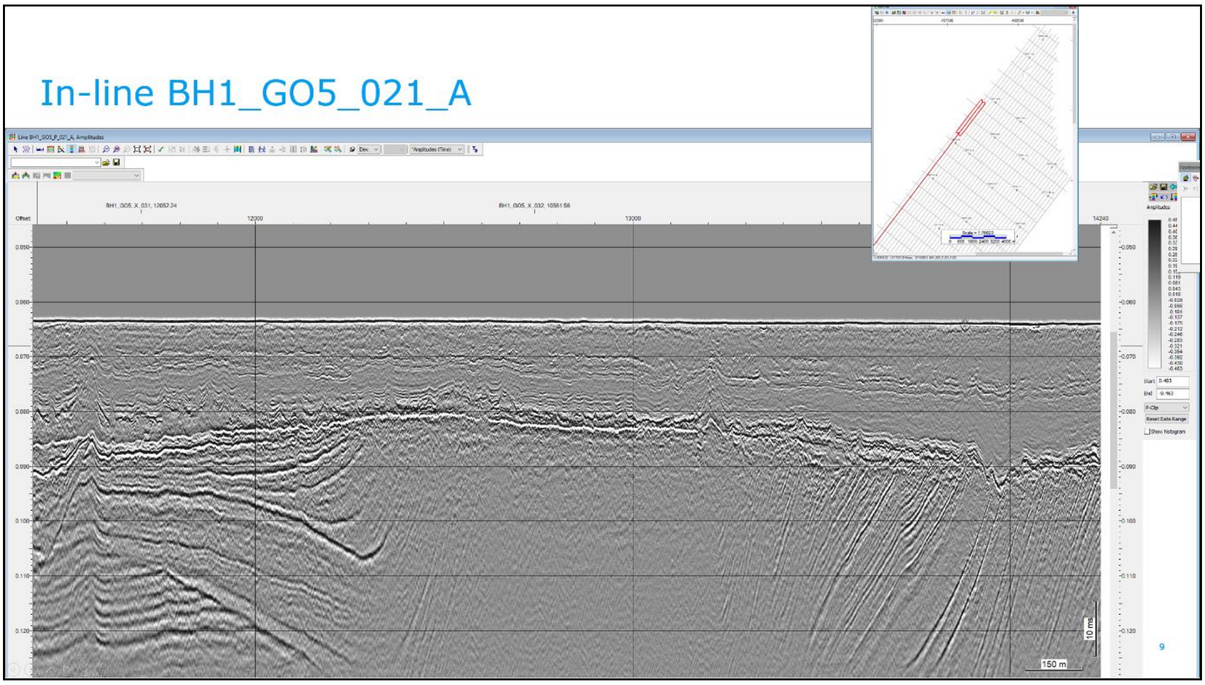


Figure 4-2 In-line 021_A illustrating how the imaging of the bedrock, not unsurprisingly, degrades in areas of near vertical strata.

According to the Geophysical Survey Report (GEOxyz, 2022) the dominant frequency of the data is in the order of 700 Hz. This corresponds to a 1.4 ms wave period and a wavelength of around 2.3 m (1600 m/s, 700 Hz). The vertical resolution is approximately 0.5 m[1] so that it is

[1] Based on the theorectical value of dz=λ/4

theoretically possible to map separate events or reflections as vertically close as ~1 m apart. Along-line lateral resolution of these data is reduced to around 2 m by migration. Perpendicular to the line, where data are unmigrated, the imaging may come from a zone with an 8 m radius (70 ms TWT, 700 Hz and a 1600 m/s velocity). GEOxyz converted the seismic data to zero phase and statics have been applied to place the centre peak of the water bottom signal at the position of the time version of the Multi Beam Echo-Sounder data seabed model.

4.3.3 Bathymetry vs. Seabed Depth

Ramboll has not remapped this Seabed Seismic Horizon on the time data. However, the seabed on the depth data was mapped to understand the variation between the bathymetry created from the gridded seabed seismic pick on the depth seismic and the MBES generated bathymetry map that had been supplied in the Kingdom Project. Figure 4-3 illustrates the difference between the bathymetry map based on the Multi Beam Echosounder (MBES) that typically has a standard deviation of 0.2 m. There are however minor differences between the seabed mapped depth pick and the MBES bathymetry map (see Figure 4-3).

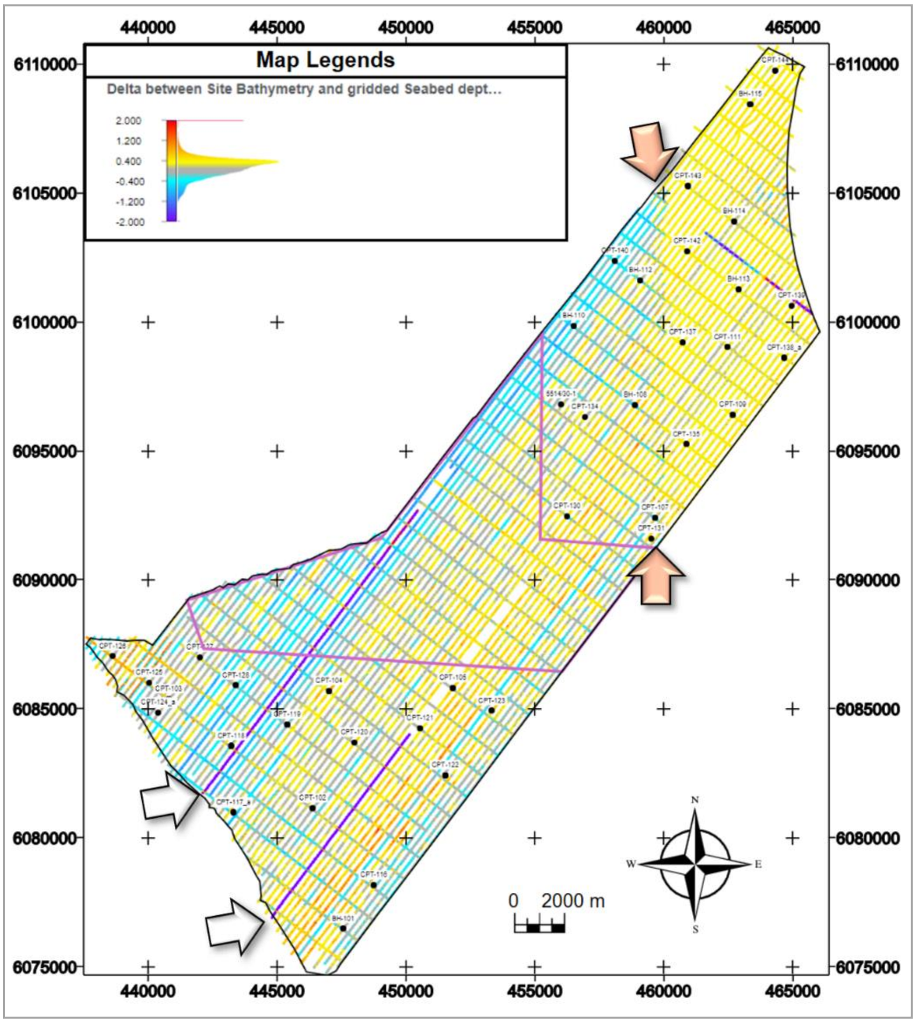


Figure 4-3. Map illustrating the difference between the Bathymetry measured by the Multibeam Echosounder tool and the depth grid created from mapping the seabed Seismic Horizon on the Depth Seismic. Note the small differences between the original and extension surveys (pink arrows) and that several of the depth lines required depth shifts (white arrows).

4.3.4 Lateral squeezing of the depth seismic data

One interesting observation was that some of the depth seismic lines look to be locally 'squeezed' such that the lateral distance of features observed in the depth domain is shorter that the time image of the same features. This was noted on the GO5_X_026_A cross line (Figure 4-4) but the same issue might be present on more lines. This misalignment of horizons with the depth converted data resulted in the decision to perform the geological modelling based on the time domain data and perform a separate depth conversion based on a refined velocity model (Section 6.2).

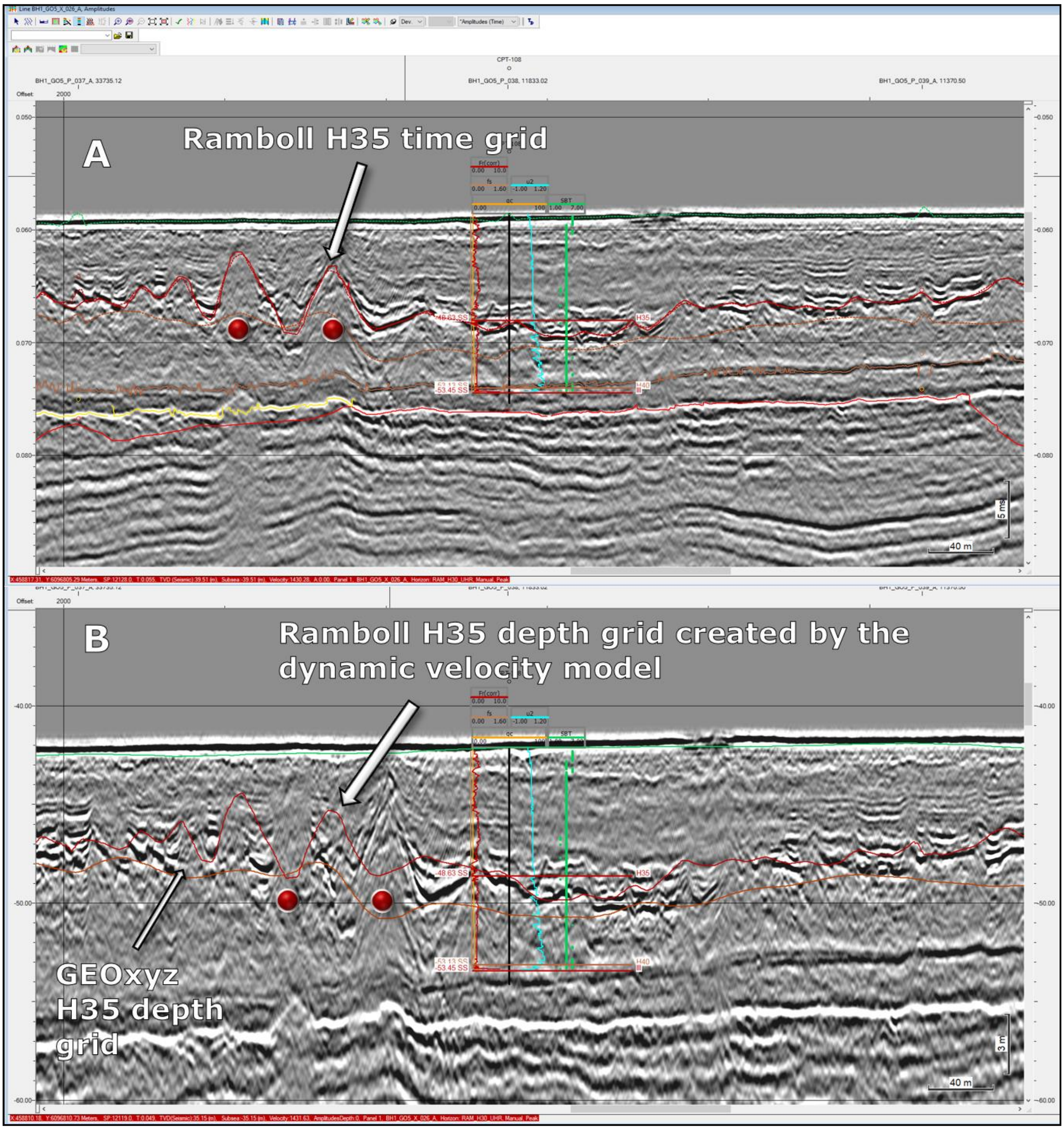


Figure 4-4. Comparison of seismic cross-line GO5_X_026_A in the time (A) and depth (B) domain. Note how the two moraine ridges mapped by the H35 Seismic Horizon in the time domain (red dots in the top image) are offset from the depth grid created by the dynamic depth conversion module in Kingdom when viewed in the depth domain – B – bottom image). The geology imaged in the depth domain seismic appears to be squeezed on this line.

5. Bornholm I – site setting

This section summarises the characteristics of the Bornholm I site in terms of the seafloor bathymetry, nature of the seabed sediments and the regional geological setting as well as its depositional history.

5.1 Site topography and seabed morphology

Water depth varies moderately across the Bornholm I site from ca. 27 m in the far south to over 45 m in the North. There is a gradual increase in water depth from the southern part of the site towards both the West and North. Two geological elements appear to be controlling the overall bathymetry of the site. The first is the bedrock: the gradual deepening of the seabed is mirrored by the structural depth of the bedrock. Areas where the bedrock has been mapped structurally shallow correspond to the shallowest water depths with bedrock depths generally increasing both to the West and North as is noted for the seafloor bathymetry (compare Figure 5-1 and Figure 5-2). The structural high that sits between the Bornholm I and Bornholm II Sites is clearly an important control on the bathymetry of the entire area.

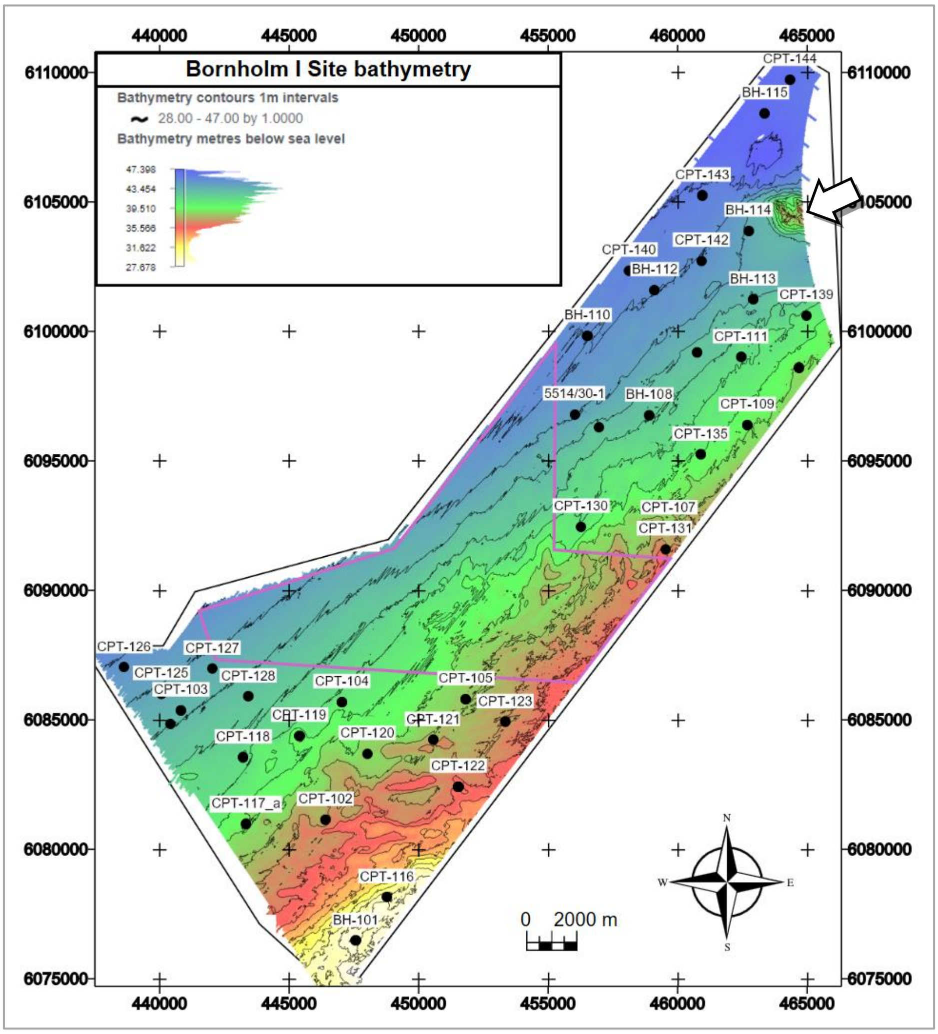


Figure 5-1. Map of the seafloor illustrating how the bathymetry deepens gradually from the South towards the West and North. Note the one anomaly (arrowed) that sits in the northern part of the site where there is a distinct topographic ridge on the seafloor. A zoomed in view of this topographic feature is depicted in Figure 5-3 and its origin is discussed at length in Section 7.6.5.

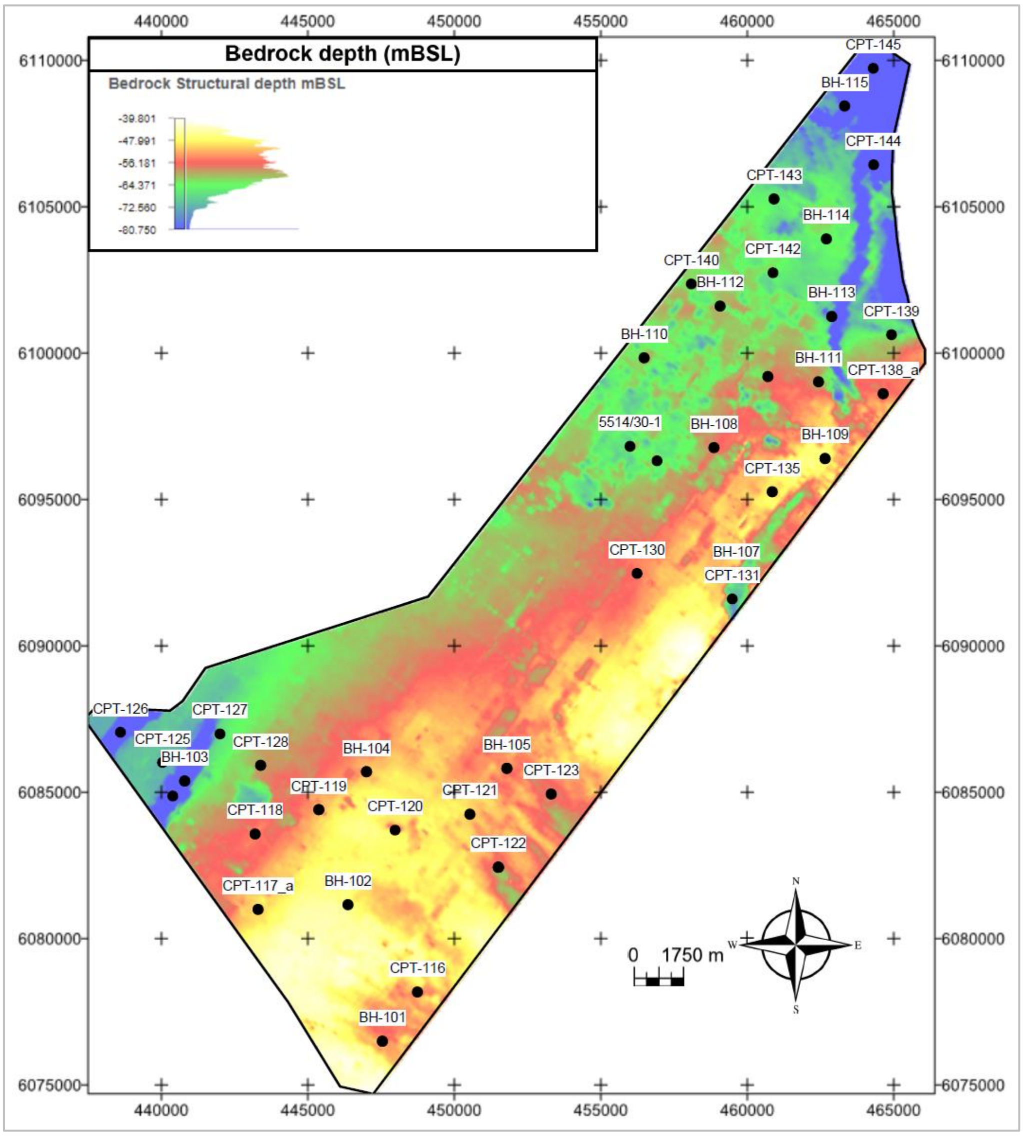


Figure 5-2. Structural depth (mBSL) of the mapped top Bedrock across the Bornholm I Site. Although locally incised by palaeovalleys there is a gradual deepening of the bedrock towards the West and the South as is observed in the seafloor bathymetry. Although there is not a one-to-one correlation it does suggest that the modern-day bathymetry of the site is at least partly controlled by the underlying bedrock topography.

Aside from the gradual slope of the seafloor towards the west and north there is a very distinct bathymetric feature developed on the seafloor in the northern part of the site (Figure 5-1). A zoomed in image of the feature is shown in Figure 5-3 and illustrates that the crest of the bathymetric high is dominated by a series of elongate undulose ridges that form gentle arcs aligned broadly NW to SW (Figure 5-3). The ridges locally possess slopes in excess of 5° (Figure 5-4).

Seabed target maps created based on the interpretation of the low frequency SSS data and backscatter datasets illustrate this area as being dominated by stones and "stone-reefs[2]" (GEOxyz, 2022), see Figure 5-5. Ramboll favours a glacial origin for this feature, with the ridges

[2] Collections of larger rocks, which lie firm on the seafloor and therefore do not move from waves or the current.

likely representing abandonment moraines. Further discussion of this geological feature is provided in Section 7.6.5.

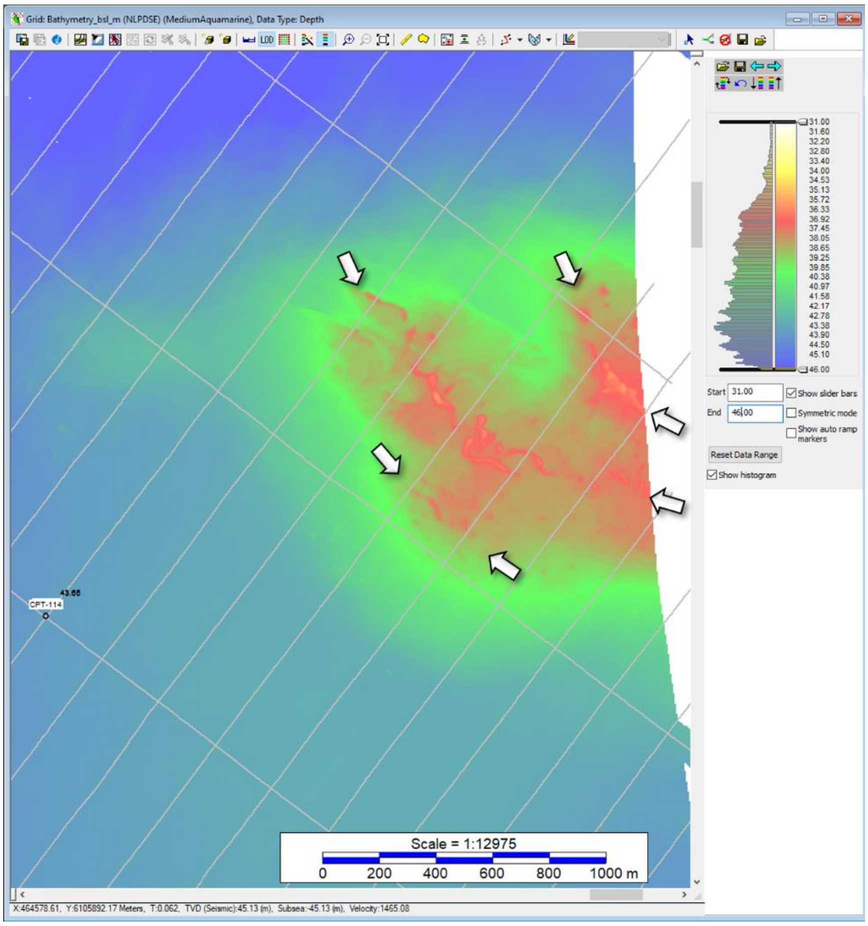


Figure 5-3. Zoomed in view of the seafloor topographic feature that is present at the northern part of the Bornholm I site (see Figure 5-1 for location). Note the irregular undulose ridges that form NW to SE aligned arcs that are developed on the seafloor. These features are considered to represent relict moraine ridges (see Section 7.6.5 for discussion).

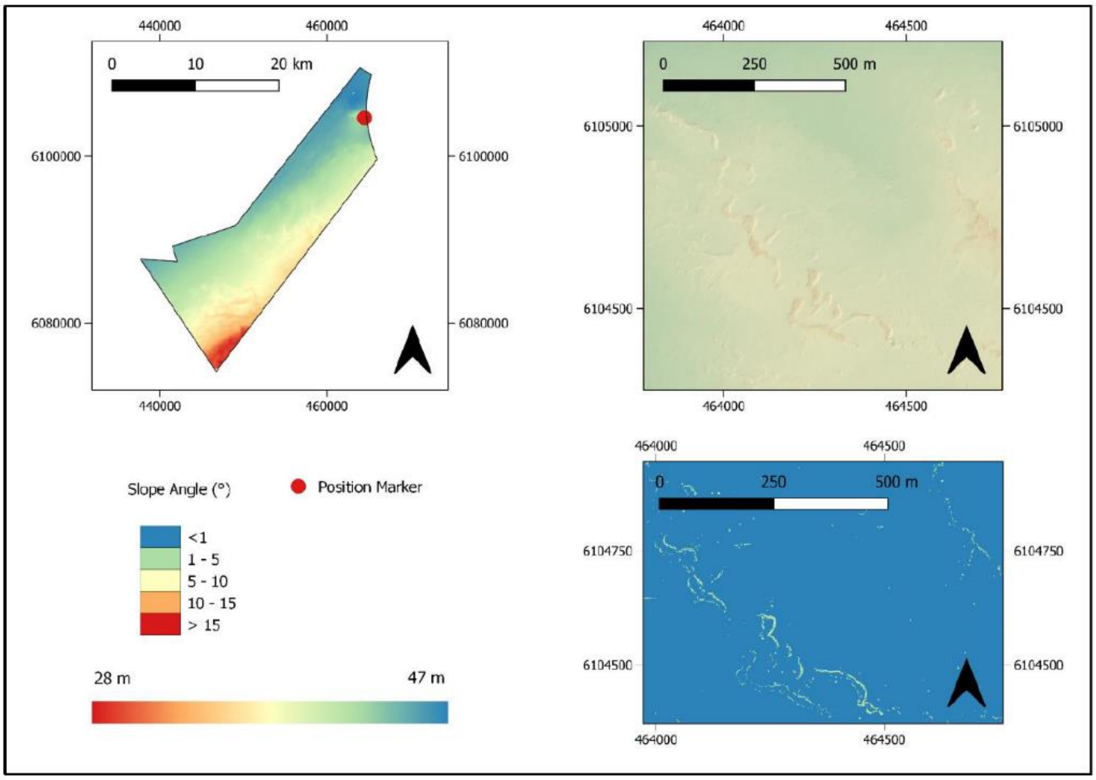


Figure 5-4. Image taken from the Geophysical Report (GEOxyz, 2022) which illustrates that the ridges observed on the seabed in the northern part of the Bornholm I Site can have slopes of between 5 and 10°.

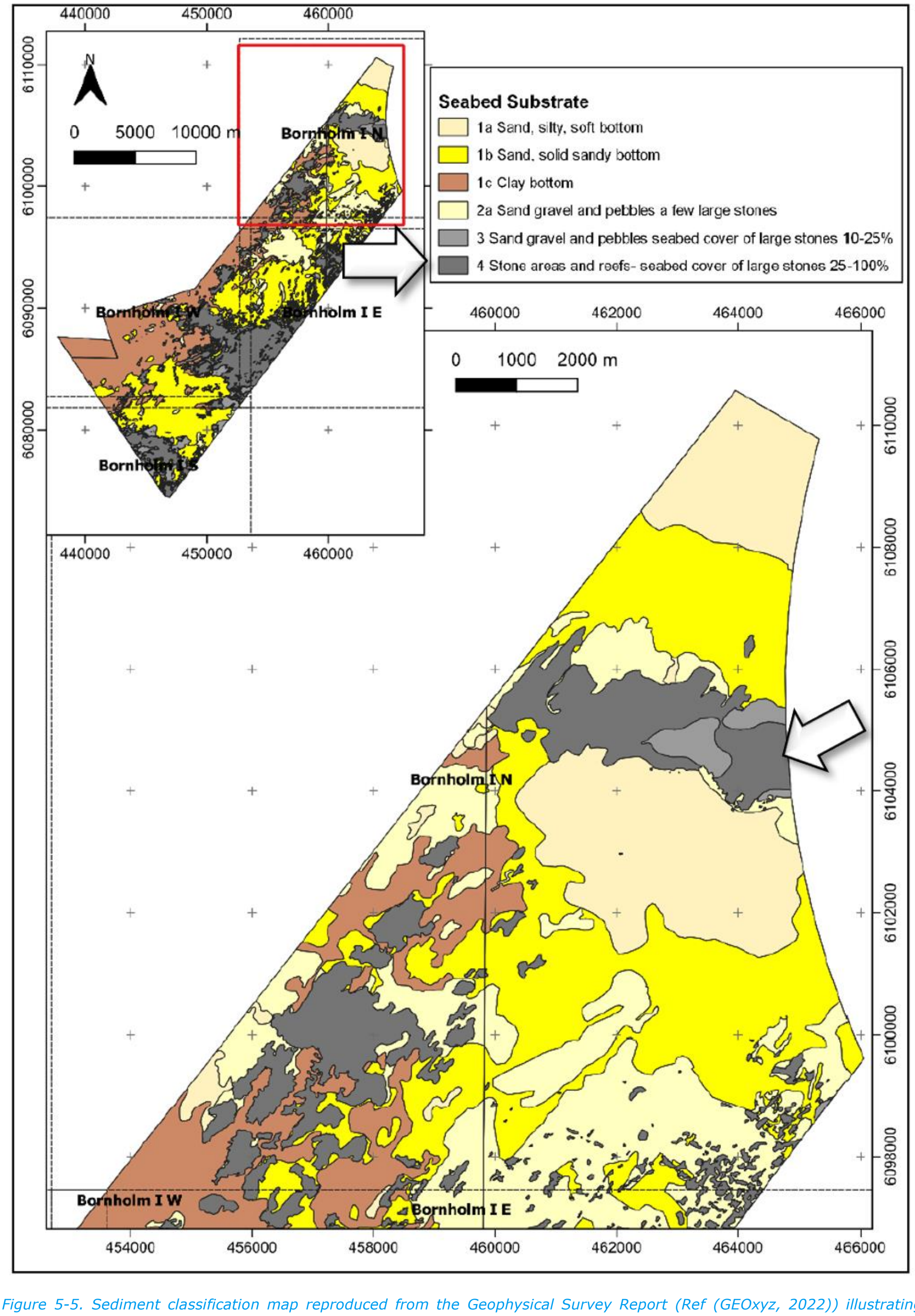


Figure 5-5. Sediment classification map reproduced from the Geophysical Survey Report (Ref (GEOxyz, 2022)) illustrating how the seafloor across the bathymetric high is dominated by sediments comprised of stones, with larger stones representing 25 to 100% of the seabed.

5.2 Seabed – substrate type

An interpretation of the seabed geology for Bornholm I is presented in the Geophysical Survey Report (GEOxyz, 2022). The evaluation was made from interpretation of the acquired low frequency SSS data and backscatter imagery. GEOxzy's final classification focuses on seabed sediment particle size and is represented in Figure 5-6.

Comparison with the bathymetry map illustrates that there is a broad correlation between decreasing grain size with increasing water depth. This is most evident in the southern and central parts of the Bornholm I site where there is a clear transition from sand (locally gravel and pebble-rich) to clay substrates with increasing water depth. This transition is less obvious in the northern part of the site but even here there is a clear transition, north and south of the bathymetric high noted above (Figure 5-3), from gravelly and stone sands to silty sands and generally soft-bottom conditions (Figure 5-6).

In the centre of the site there is a lobe of gravelly and stony sand on the seabed that broadly corresponds with the subcrop of the glacial sediments of Seismic Unit 4 below the present layer of modern (Holocene) seabed sediments (see Section 7.6, Figure 11-8). It is likely that coarse sediment particles within the till (pebbles and gravel size grains) have been reworked into the modern seabed across this part of the site.

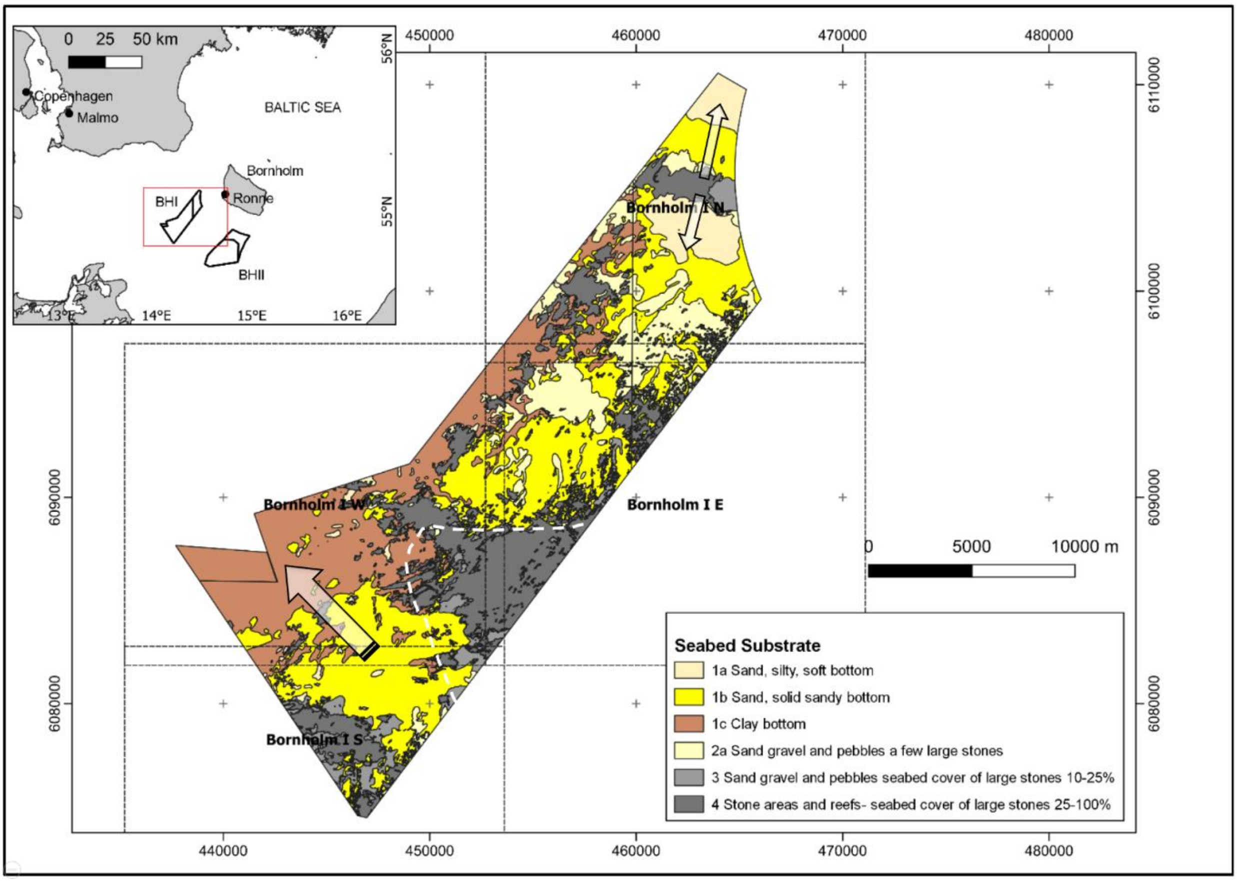


Figure 5-6. Bornholm I seabed surface substrate classification as provided in the final Geophysical Survey Report (GEOxyz, 2022). Note the general transition from sand to clay with increasing bathymetry in the southern part of the Bornholm I site (large arrow). In the north the gravelly and stony sands that dominate the seabed over the bathymetric high pass north and south into soft silty sands (small arrows). Note that the lobe of stone-dominated seabed (demarked by the white dashed line). This lobe broadly corresponds to the area in which Seismic Unit 4 subcrops directly below the modern-day seabed sediments (see Section 7.6 for discussion).

The Geophysical Survey Report notes that the north and east of the BHI site is heavily trawl scarred (GEOxyz, 2022). Areas of boulder fields and scattered pitted areas are present along with erosional features that cross the southernmost area of that section. Ripples and mega ripples have been identified intermittently across the site.

5.3 Regional Geology: context for Bornholm I

Energiøen commissioned a geological Desk Top Study from GEUS (Jensen, 2021) prior to the start of the data gathering campaigns across the Bornholm Sites. It is not the intention to duplicate that work here, rather, the regional geological history is reviewed in light of the observations that have been made on the Bornholm I site. The reader is referred to the Desk Top Study (Jensen, 2021) for the full view of the region.

5.3.1 Structural setting

The Bornholm I site is located within the Rønne Graben that itself is part of a series of structural elements that form part of the lateral ramp between the 30-50 km wide, WNW-ESE-trending Sorgenfrei–Tornquist Zone and its extension to the southwest, the Teisseyre-Tornquist Zone. Together these features separate the Baltic Shield, the Skagerrak-Kattegat Platform and the East European Precambrian Platform in the northeast from the Danish Basin in the southwest (Figure 5-7).

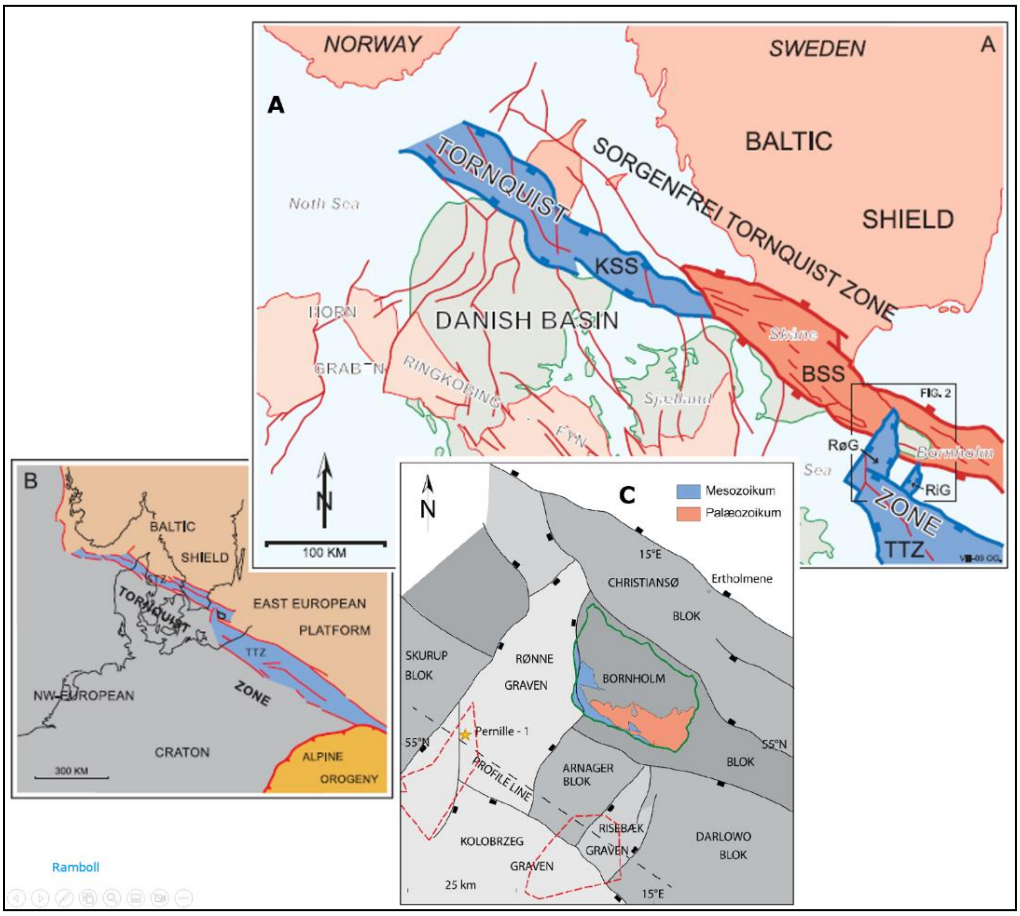


Figure 5-7. Compilation of maps that summarise the main structural elements in the region of the Bornholm I Site. The key feature is the regional Sorgenfrei-Tornquist Zone (STZ) with its Kattegat-Skagerrak segment (KSS) and Bornholm-Skåne segment (BSS) and the structural elements around Bornholm. Note that the Sorgenfrei-Tornquist strike slip zone continues to the southeast having stepped around the island of Bornholm, via the Teisseyre-Tornquist Zone (TTZ) and that this major structural element separates the Baltic Shield and East European Platform from the Northwest European platform. Map C illustrates how the Bornholm I site sits within the Rønne Graben, which is part of the lateral ramp between the Sorgenfrei-Tornquist Zone and the Teisseyre-Tornquist Zone. Maps taken from several sources (Graversen, 2010) and (Jensen, 2021).

The Sorgenfrei–Tornquist Zone is a very long-lived structural element that dates back to Early Palaeozoic time. It is characterised by complex strike-slip faulting and structural inversion (Liboriussen, 1987), (Mogensen, 2003) & (Erlström, 1997). This old crustal weakness zone has been repeatedly reactivated during Triassic, Jurassic, and Early Cretaceous times with dextral transtensional movements along the major boundary faults. Within the Bornholm I site deformation is best characterised as transgressional with evidence of steep, near vertical strike-slip fault zones that appear to be related to extensive folding of what are believed to be Jurassic clastic successions. The island of Bornholm, with its core of granitic basement rock, appears to have acted as a relatively rigid block around which deformation was focused (Deeks, 2012).

Bornholm I is located within the NE-SW trending Rønne Graben that developed as a right-stepping release step-over that linked the Sorgenfrei-Tornquist strike slip zone to the Teisseyre-Tornquist Zone. It is considered to have been initiated in Late Carboniferous to early Permian time, with the graben, and its associated sedimentary basin, being active through the Triassic, Jurassic and Early Cretaceous (Jensen, 2021). The presence of potential slumps and slide scars within the Late Cretaceous succession would support deposition during a period of active tectonism. The Pernille Well (5514/3-1) has proven strata as old as Silurian age sit at depths within the Rønne Graben.

The GEUS Desk Top Study illustrates a geological cross section that runs across the Rønne Graben south of the Pernille Well (5514/3-1). The cross section, reproduced in (Jensen, 2021) approximates to the position of cross-line GO5_X_023 on which Borehole BH-107 has been sited. BH-107 encountered chalk at a structural depth of 68.47 mBSL (30.5 m below the seabed), which corresponds with interpretation represented in Figure 5-8. The Pernille well penetrated the unconformity between the Cretaceous and the Jurassic and records a 66 m thick interval of lower Cretaceous calcareous marls that sit unconformably above a heterolithic package of intercalated loose sands, sandstones, clay, and silt that have been assigned to the Lower Jurassic.

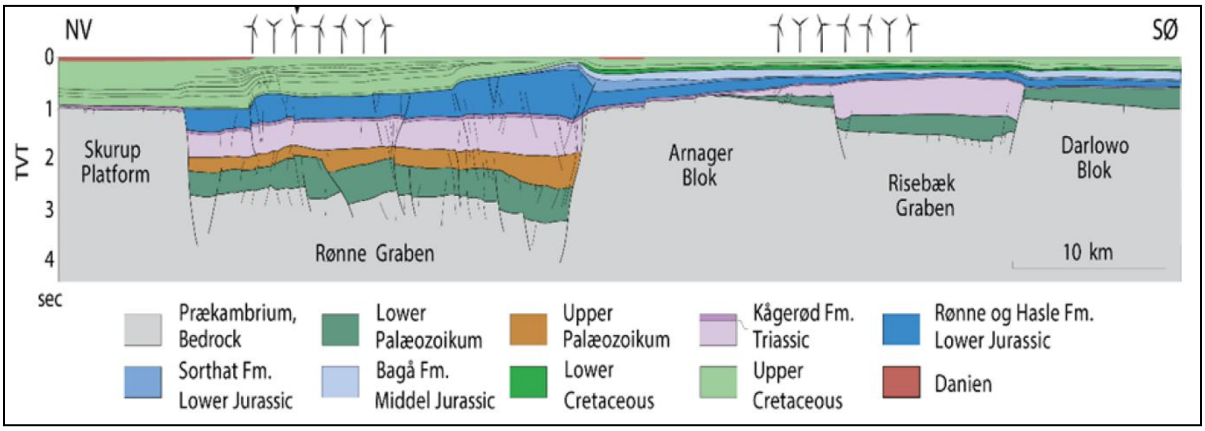


Figure 5-8. Cross-section reproduced in the GEUS desktop study (Jensen, 2021) that transects the Bornholm I site (the line of this profile is illustrated in Map C). Created from a deep seismic line this cross-section has the chalk of the Upper Cretaceous sitting unconformably over Jurassic strata.

5.3.2 Palaeozoic – Mesozoic Geology

The Pernille (5514/3-1) Well located in the Bornholm I site was drilled to a terminal depth of 3624.5 m at which point it was within graptolitic mudstone rocks of Lower Palaeozoic (Silurian age). This illustrates the thick succession of sedimentary rocks that sit within the Rønne Graben. Upper Palaeozoic strata of Permian and possible Carboniferous age sit uncomfortably on the Silurian. Permian strata are dominated by terrestrial to shallow marine and occasionally evaporitic sediments. Some 270 m of sandstones, possessing traces of anhydrite, are assigned to the Rotliegendes with these sandstones overlying a sequence of shales, claystones and thin sandstones that are of possible Carboniferous age (Norsk Hydro, 1989). These strata sit unconformably over the Silurian.

The upper part of the Triassic is dominated by a heterolithic succession of sandstones, thin limestones and shales and is overlain by Lower Jurassic strata that comprise interbedded sandstones, claystones and thin coal beds which were assigned to the Rønne Formation of the Bornholm Group. Of note to the Bornholm I Ground Model is the observation of loose sand grains in the cuttings samples from the top of the Jurassic succession. Here sand and clay have been recorded along with sandstone. The presence of intervals of largely uncemented sediments in these Jurassic strata is important since the same phenomenon has been recorded by some of the deep boreholes in the Bornholm I site. In particular, BH-114 and BH-115 have encountered sands at depths that the seismic indicates as being well within the bedrock.

The stratigraphy reported in the Pernille (5514/3-1) Final Well Report would suggest that there is a significant break between the Cretaceous and Jurassic with Lower Cretaceous marls lying directly on Lower Jurassic strata (Figure 5-9). This unconformity sits too deep at the location of the Pernille Well to be imaged on the current Bornholm I seismic sitting, as it does, at approximately 900 m below the seabed. However, a little towards the north of 5514/3-1 the strata are folded to the vertical such that Lower Jurassic strata are brought to shallow burial depths and subcrop directly beneath the Pleistocene sediments (Figure 5-10). The axis of the fold that brings the Jurassic to the subcrop is orientated NW to SE and this fold and its zone of deformation could very well be associated with significant lateral displacement along a strike slip fault.

A thick succession of Late Cretaceous chalks was proven by 5514/3-1. Seismic indicates that these sediments possess internal features that are consistent with extensive slumping of these pelagic limestones with numerous internal slide surfaces as well as slumped and deformed sediment packages having been imaged on the seismic. Given the location of the Rønne Graben within the overall Tornquist Strike-Slip Zone it is quite possible that some of the slides observed have been triggered by seismic activity. Such features are relatively common in the Chalk successions of the North Sea and have been reported from the Danish Sector.

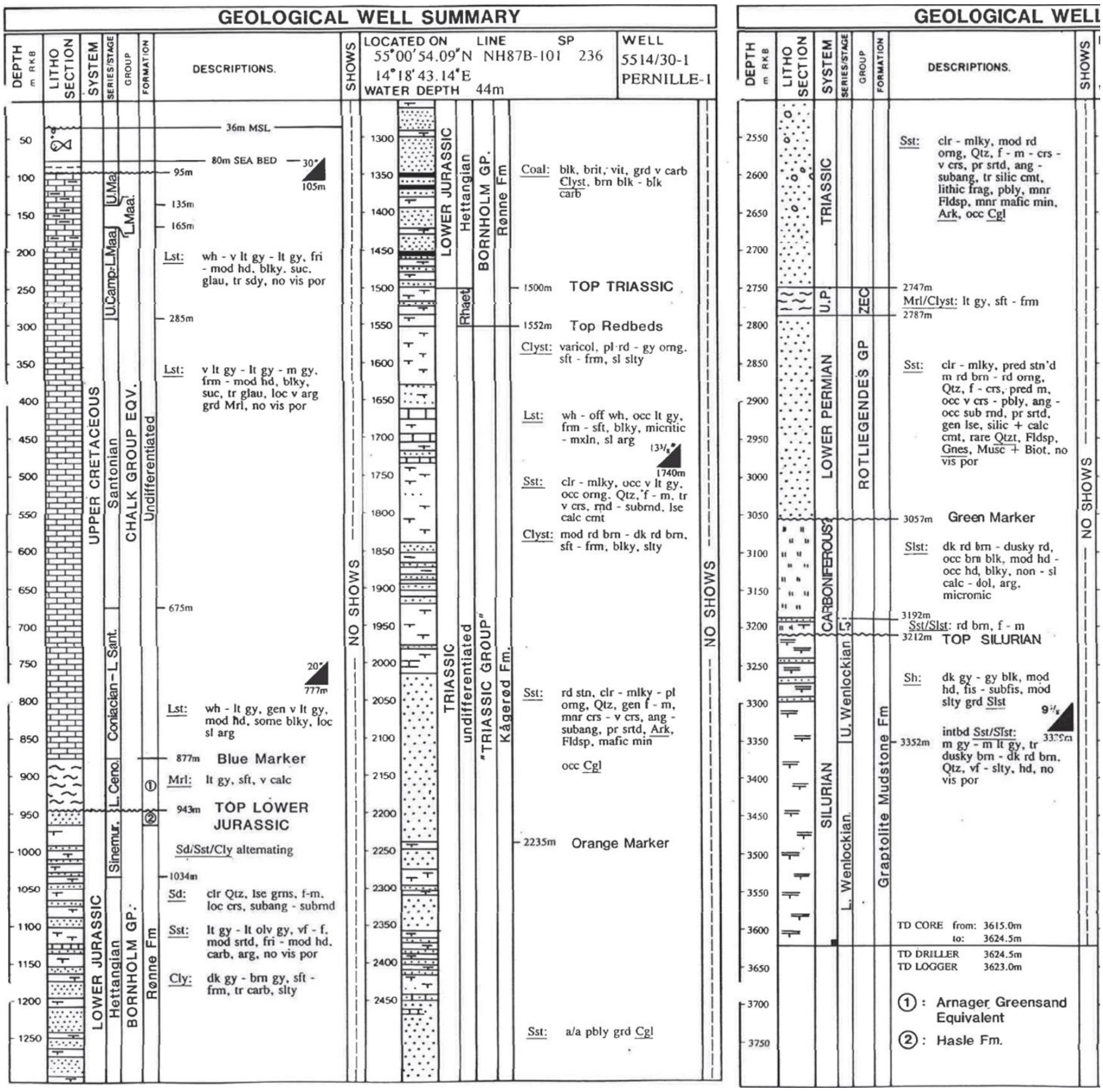


Figure 5-9. Summary stratigraphic column penetrated by the Pernille (5514/3-1) Well located in the Bornholm I site. This well was drilled to test the hydrocarbon potential of Palaeozoic strata in the Rønne Graben. Figure taken from Ref (Norsk Hydro, 1989).

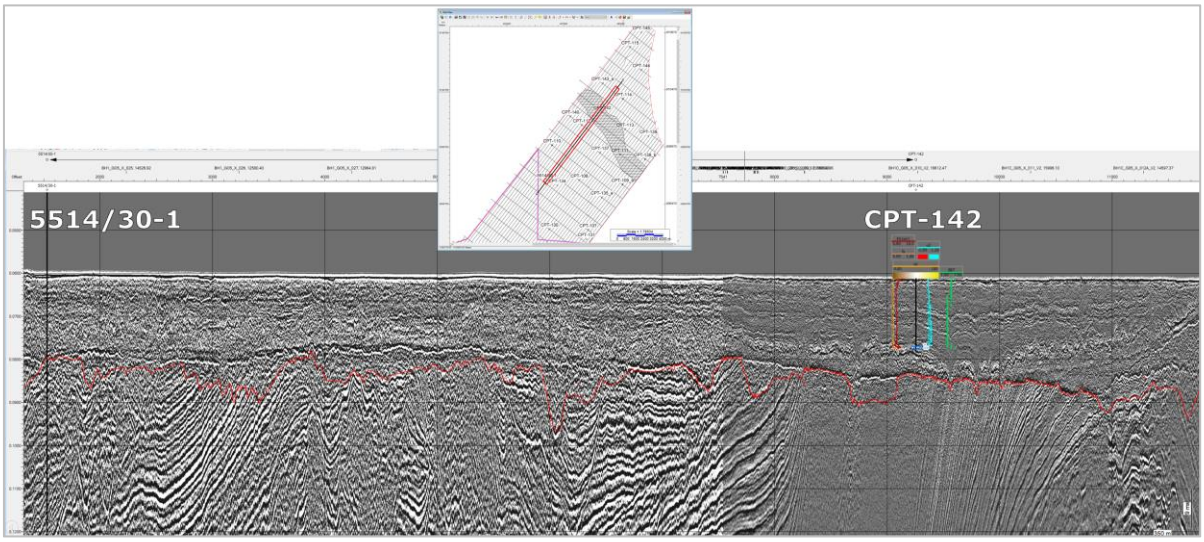


Figure 5-10. Composite seismic line through the Pernille (5514/3-1) Well (left-hand side) and running along in-lines from the original and extension surveys. The composite line is orientated towards the NE. Note the monoclinal syncline brings the deep Lower Jurassic strata penetrated in the well to shallow burial depths were it subcrops below the Pleistocene cover sediments. The chalk succession in 5514/3-1 displays a complex set of internal features with internal scour surfaces, soft-sediment deformation (folds and slumps) as well as small horst-like features. It has been subjected to a complex sequence of near-surface deformation events. The hashed polygon in the inset map illustrates the zone of near-vertical strata that mark the southern limb the imaged monocline.

5.3.3 Quaternary Geology of the Bornholm region

The Quaternary geology of the Bornholm region has been summarised in the GEUS desktop study (Jensen, 2021) with the area having been influenced by four separate glacial episodes between Late Saalian to Late Weichselian time; each event is separated by interglacial or interstadial periods when marine or glaciolacustrine sediments accumulated. The maximum extent of the Scandinavian Ice Sheet in Denmark was reached in 22,000 years Before Present (yrs BP) and was followed by a stepwise retreat with Bornholm being deglaciated shortly after 15 kyrs BP (Jensen, 2021).

At its maximum extent the Scandinavian Ice Sheet broadly followed the coastline of Norway and Sweden. It covered the present Zealand area and reached down to the northern part of Germany. The Kattegat region, which separates Denmark and Sweden, had not isostatically adjusted and relative sea-level was therefore high during the early phase of the deglaciation; the northern part of present-day Jutland was largely covered by sea. At about 16 kyrs BP the ice had retreated towards the Øresund region and the western part of Skåne, while the Lolland-Falster islands were still covered by the ice (Figure 5-12). A broad meltwater channel connected the ice margin with the Kattegat. Local lakes had also begun to develop along the ice margin in the south-western part of the Baltic Sea [(Jensen, 2021) (Björck, 1995)] and varved clays were deposited in the Baltic basin in front of the receding ice margin (Björck, 1995). These are the clays that are mapped out by Seismic Unit 3 and largely comprise the geotechnical Soil Unit Ib.

Investigations in Polish German and Danish waters indicate that by approximately 15 kyrs BP the ice margin was located just to the west of Bornholm. Several large valley systems have been identified in the bedrock of the Bornholm I site. They are oriented broadly NE-SW and would have been aligned broadly perpendicular to the former ice-sheet front. The head of one of these valleys is clearly imaged on the seismic (see Figure 5-11); the valley has carved into the chalk subcrop with its thalweg deepening rapidly to the Southwest, away from the valley inception point (see Figure 5-11). It is possible that both the bedrock valleys imaged in the Southwest corner of the

Bornholm I site developed as tunnel valleys at, or close to, the ice front margin as the ice sheet retreated from the Bornholm region.

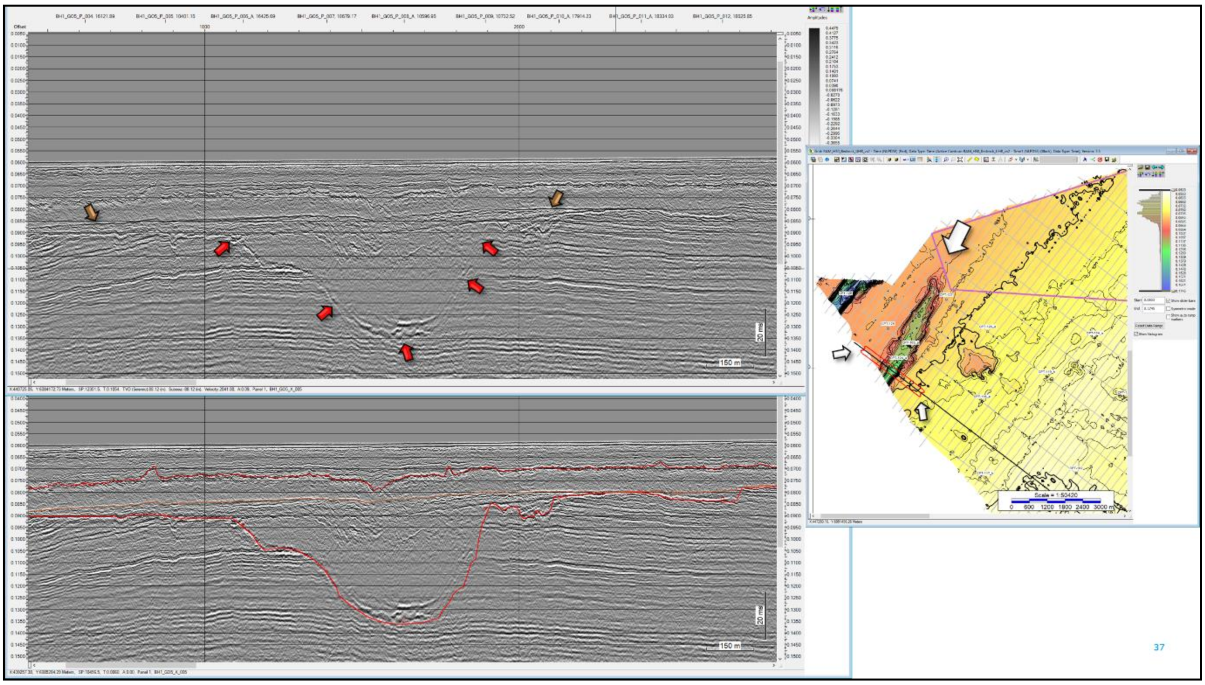


Figure 5-11. Time map of the top bedrock in the Southwestern part of the Bornholm I site illustrating a likely tunnel valley that has carved into the bedrock. A seismic section illustrates the cross-section geometry of the valley (red Seismic Horizon and arrows) as well as the lobe-shaped sediment package that is developed above the valley fill (brown arrow, reflector). This second reflector is the H40 and it displays a convex up character that down laps onto the bedrock. The topography of the imaged valley decreases rapidly to the northeast such that there is soon no impression of the valley on the bedrock at all. Note the straight nature of the valley and rapid deepening of its thalweg away from the inception point (large white arrow). A second, even deeper palaeovalley is present to the Northwest but is only partly imaged by the Bornholm I seismic. These two valleys continue into the German sector of the Baltic Sea where they have been mapped by Ramboll in previous studies.

As the ice retreated from the Bornholm area large lakes were dammed in front of the ice sheet. These lakes received water direct from the melting ice sheet as well as from rivers draining from Poland and Germany. Deltas developed along the fringes of the lakes and resulted in the deposition of sediment fans out into the standing bodies of water. Several potential fan systems have been mapped in the Pleistocene sediment cover of Bornholm I (Seismic Units 4b and 4c); in the east these fans are dominated by sand, but further west the sediment lobes are primary of clay and silt. Seismic lines clearly illustrate the lateral transition from sands in the east to finer silt/clay-rich lobes in the west (see Figure 7-26 & Section 7.6 for discussion). Across the Bornholm I Site, the last of the 'true' glacial deposits are considered to be the hummocky moraines that have been mapped out on the H30 (H35) Seismic Horizon. The topography of the ice-abandonment sediments (moraines) was then draped by lacustrine sediments deposited in the lakes that had developed in front of the retreating ice sheet. These sediments are represented by Seismic Units 2 and 3 and are dominated by Soil Unit Ib.

Throughout the melting and retreat of the Scandinavian Ice Sheet the Baltic Ice Lake experienced several damming and discharge events. Some of the discharge events were dramatic with one having been recorded through the south-central Sweden channel system in which the water column in the lake is believed to have dropped by approximately 25 m (Jensen, 2021). Regional studies indicate that the Bornholm region experienced two episodes characterised by freshwater conditions, and two stages of marine to brackish-water (Jensen, 2021). These periods were:

1. The freshwater South Baltic Ice Lake (12.5 – 10.0 kyrs BP).

2. The partly brackish Yoldia Sea (10.0 – 9.5 kyrs BP).
3. The freshwater Ancylus Lake (9.5 – 8.0 kyrs BP).
4. The brackish Littorina Sea (8.0 – 3.0 kyrs BP).

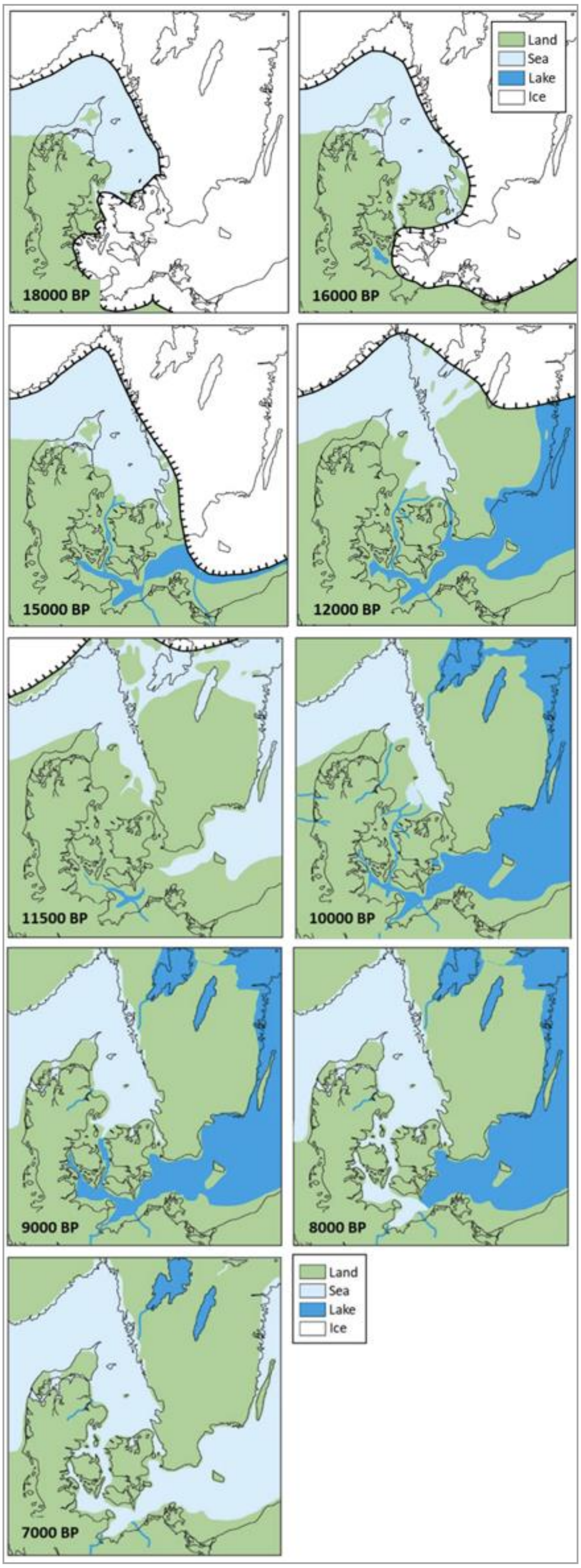
The transitions between these events were triggered by a subtle balance of relative sea level, that was driven by global eustatic sea-level changes and the glacial rebound of the area as the weight of the ice-sheet was gradually removed from the Scandinavian shield. Each stage of the Baltic Ice Lake was marked by the deposition of a different sediment package (Andrén E. A., 2000).

The lowest postglacial relative sea-level was reached in the southern Kattegat (35 m below present sea-level). As postglacial eustatic sea-level rise surpassed the rate of glacio-isostatic rebound the sea flooded through south-central Sweden into the former Baltic Ice Lake to create the Yoldia Sea (Jensen, 2021). This stage lasted approximately 800 years (Björck, 1995). The base of Yoldia Sea deposits is considered to be represented by H20 within the seismic data (Jensen, 2021), with the overlying Seismic Unit 2 sediments being primarily composed of reworked Baltic Ice Lake clays [(Jensen, 2021), (GEOxyz, 2022)].

The beginning of the Littorina Sea period is marked by a very rapid sea level rise (2.5 cm/year) which resulted in the widespread flooding of the south-western Baltic region as the landscape was drowned. The submerged landforms were associated with ice- and glacier- shaped troughs and fjords, which included 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. Present water level position was reached approximately 6000 years BP (Schwarzer K, 2008).

Above the hummocky terrain demarked by the H30 (H35) Seismic Horizon there is a change in the seismic sediment character, the sediments are typically bedded and in the western part of the Bornholm I site where the sediment succession is thickest several depositional units can be observed, typically separated by seismic discontinuities. These units observed on the seismic almost certainly correspond to different stages in the development of the Baltic Lake. However, to tie observed seismic discontinuities to specific Baltic Ice Lake stages would require detailed age-dating of cores recovered from this succession.

Figure 5-12. Maps depicting the palaeogeography of Denmark and southern Sweden during the gradual deglaciation following the last glacial maxima. Note how the nature of the depositional systems fluctuated with the large sanding bodies of water sometimes having open connections to the sea and thus having a marine and/or brackish character whereas at other periods they formed isolated bodies of fresh water. Figure taken from the GEUS desk study (Jensen, 2021) but partly based on the maps in (Björck, 1995).



6. Methodology

6.1 Seismic mapping

Ramboll has focused its efforts on certain parts of the sediment succession when integrating the CPT and Borehole data with the seismic stratigraphy. It became apparent very early that the top three Seismic units identified by GEOxyz (GEOxyz, 2022) generally have similar geotechnical properties (see Section 10). Conversely, it was apparent that the existing Seismic Horizon framework did adequately capture the sedimentary units in the deeper stratigraphy and the majority of Ramboll's work has focused on defining these features. The most obvious is the H45 sand system that has been integrated into the Geological Ground model.

6.2 Velocity model workflow

To be able to view the CPT and Borehole data in the time domain Ramboll has created a velocity model within the Kingdom Project itself. This allows CPT and Borehole data to be instantly viewed in the time domain thereby aiding the integration of these data into the Seismic Horizon framework. Likewise, it meant that Seismic Horizon depth picks can be made on CPT and Borehole logs whilst viewing the data in the time domain. The Velocity model was built in a stepwise manner gradually adding more layers. Every effort was made to align the Seismic Horizons with the Soil Units, but this was not always possible (see Section 11 for discussion).

Once the depth picks of the Seismic Horizons had been made in the Boreholes and CPTS the Velocity Model was updated and picks adjusted if there were issues in the calculated internal velocities. Three of the Bornholm I boreholes. BH-103, BH-104 and BH-108, have PS-log data, from which interval velocities have been calculated; the data are summarised in Table 6.1 below. Analysis of the PS-logging results provided realistic velocity ranges for each of the Seismic units, though some caution is warranted since PS logging has been undertaken on just three of the boreholes located on the Bornholm I Site and not all the seismic units defined in the project have been penetrated by these three boreholes.

Table 6.1. Summary of the P-Wave velocity data calculated from the PS-logs (m/s). See Chapter 7 for the definition of the seismic units.

Seismic Unit	Count	Mean	Min	Max	P05	P50	P95	P05-P95 range
Seismic 1	1	1603	1603	1603	1603	1603	1603	0
Seismic 3	10	1553	1439	1714	1453	1536	1675	221
Seismic 4	58	1995	1667	2344	1750	2000	2210	460
Bedrock	95	2052	1739	2558	1762	2041	2440	679

Of note with the summarised P-Wave velocities are the low velocities that have been recovered from Seismic Unit 3, with a mean velocity of just 1550 m/s. Given that this interval is overwhelmingly comprised of soft organic-rich marine and lacustrine clays, albeit with thin intercalated silts and sands, these low velocities are perhaps not so surprising. There is, however, a clear jump in the P-Wave velocities between Seismic Units 3 and 4 which is broadly defined by the H30 (H35) Seismic Horizon. This contact is generally marked by a transition into stiffer clays and silts, though this change can occur in the bedded facies that sit just above this surface (see Section 11.1 for discussion).

Bed rock velocities are higher than the sediment cover but display a higher variance in the recoded data (see Table 6.2). The greater variance generally reflects the wide variety of bedrock lithologies that has been encountered across the Bornholm I site with statistics for the different bedrock lithologies are provided in Table 6.2.

It must be stressed again that PS-logging was only undertaken in 3 of the boreholes and elements of the sedimentary cover, such as the sands systems defined by the H45 Seismic Horizon, have not been sampled, so the internal velocities in these sand successions remains uncertain.

Table 6.2. Summary of the Bedrock velocities broken down into their lithology classifications.

Seismic Units	count	Mean	Min	Max	P05	P50	P95	P05-P95 range
Siltstone	29	2135	1802	2558	1818	2101	2491	672
Chalk	10	2221	2143	2344	2143	2206	2328	185
Limestone	26	1947	1739	2429	1754	1914	2204	449
Marlstone	25	1927	1749	2076	1756	1948	2068	311
Mudstone	4	2381	2283	2443	2294	2399	2442	148
Quartzite	1	2500	2500	2500	2500	2500	2500	0

The methodology followed for the creation of a Velocity Model is outlined in detail in Appendix 7.

6.3 Integration of Seismic Units with the Geotechnical Soil Units – the Ground Model

Once the Geotechnical Soil Units had been defined (see Section 8) the boundaries between the various Soil Units were imported into the Kingdom Project as "base" Soil Unit picks and stored in the "Formation Tops" database in Kingdom. The Soil Unit boundary picks were subsequently compared with the Seismic Horizon picks and every opportunity was taken to ensure that the Seismic Horizon picks and Soil Unit picks corresponded. Since the seismic reflections are generated by contrasts in sediment properties it is not uncommon that the picked Seismic Horizons align with the Soil Units. Nonetheless, there were places where aligning the Seismic Horizon picks and Soil Unit boundaries created geologically unrealistic internal seismic velocities and, in these instances, the Seismic Horizon and Soil Unit picks remain different.

In most instances mapped Seismic Horizons could be matched to distinct changes in the Soil Units, and the Soil Units could then be populated as Ground Model Units spatially across the Bornholm I Site using the Seismic Horizon framework. Were there was no alignment between the Geotechnical Soil Units and Seismic Horizons, or when there were clear changes in soil properties within a given seismic unit, a more pragmatic approach had to be adopted in mapping out the Geotechnical Soil Units. Here the picks between the Soil Units were gridded and adjusted to the existing seismic framework in a manner that honoured the data. In particular, this approach had to be adapted to map the boundary between Ground Model Units 3 and 4 where the Geotechnical Soil Units III and IVb often occur within Seismic Unit 4 and the boundary has no corresponding seismic event. The procedure adopted is described in detail in Section 10, and more specifically in for the GMU3 and 4 (Soil Unit III and IVb) boundary in Section 10.4.

7. Seismic Units and Sedimentology

7.1 Introduction

This section describes how the structural framework of the Bornholm I site has been defined using mapped Seismic Horizons. It also details observed sedimentological and geological features. Each of the following sub-sections describes a Seismic Unit, how it has been picked seismically, and its sedimentological features. The relationship of these seismic units to the defined Geotechnical Units and thus the presented Ground Model is detailed in Section 10.

It must be stressed, up front, that not all of the defined Seismic Units have been used in the Ground Model; some Geotechnical Soil Units are present in multiple Seismic Units so there are areas where the Ground Model boundaries do not always correspond to a Seismic Horizon (see Sections 10 and 11). Table 7.1 shows how the various elements of the Velocity Model, the Seismic Horizons, the defined Seismic Units and the Geotechnical Soil Units correlate.

7.2 Terminology

To avoid issues with the how Seismic and Geotechnical units are defined and named the following convention has been adopted.

- Seismic Units are defined using Western Arabic numerals,
- Geotechnical Soil Units and the Ground Model subdivision employs a Roman Numeral system.

This might be somewhat confusing since original Desk Top Study by GEUS (Jensen, 2021) and the preliminary seismic mapping (GEOxyz, 2022) created seismic units that followed the Roman Numeral System.

Table 7.1. Seismic Units: table summarising how the defined seismic, sediment and geotechnical units correlate across the Bornholm I site.

Seismic sediment Unit	Top Seismic Horizon	Geotechnical Soil Unit	Integrated Ground Model Unit	Predominant sediment	Velocity Model Layer
Seismic Unit 1	H00 seabed	Soil Unit Ib	GMU2	Soft organic-rich clay	Layer 1
Seismic Unit 2	H00/H05	Soil Unit Ia	GMU1	Loose sand	Layer 1
Seismic Unit 3a	H05/H15/H20	Soil Unit Ib	GMU2	Soft organic-rich clay	Layer 1
Seismic Unit 3b		Soil Unit Ib	GMU2	Soft organic-rich clay	Layer 1
Seismic Unit 3c		Soil Unit Ib	GMU2	Transitional Clay/Silt	Layer 1
Seismic Unit 3d		Soil Unit IVa	GMU2	Dense Sand	Layer 1
Seismic Unit 4a	H30 (35)	Soil Unit III	GMU3/GMU4	Stiff Clay-Till	Layer 2
Seismic Unit 4b	H40	Soil Unit IVb	GMU4	Stiff Clay	Layer 2
Seismic Unit 4c	H45	Soil Unit IVa	GMU5	Dense Sand	Layer 3
Bedrock	H50	Variable	GMU6	Variable	Layer 4

The current Kingdom Project contains a total of 8 Seismic Horizons that have been mapped by GEOxyz and Ramboll. Four horizons were identified on the SBP data, and 4 horizons were mapped on the UHR seismic data. H30 (H35) has been mapped on both sets of data. Ramboll has worked almost exclusively on the UHR seismic since most of the geotechnical soil units have been defined at depths that are generally greater than the Sub-Bottom Profiler data can image.

Table 7.2. Ground Model Units ; table summarising how the defined Ground Model Units, Geotechnical Soil Units (see Section 8 & 10) correspond to the mapped Seismic Horizons and defined Seismic Units that are described in this Chapter.

Integrated Ground Model Units	Geotech Units	Seismic Unit	Bounding Seismic Horizons	Lithologies
GMU1	Soil Unit Ia	Seismic Unit 2a (Mounds)	Top - H00 Seabed Base - H15	Loose Sand
GMU2	Soil Unit Ib	Seismic Unit 1 Seismic Unit 2b (erosional valleys/iceberg scour marks) Seismic Unit 3	Top - H00 Seabed, H15 Base - H30	Soft Organic-rich clay
GMU3	Soil Unit III	Seismic Unit 4a	Top - H30 Base - H40 or Base SU_III in CPTs & Boreholes	Transitional to stiff Clay/Silt
GMU4	Soil Unit IVb	Seismic Unit 4a Seismic Unit 4b	Top - H40 or Base SU_III in CPTs & Boreholes Base - H45 or H50 (bedrock)	Stiff Clay-Till
GMU5	Soil Unit IVa	Seismic Unit 4c Seismic Unit 3d	Top - H45 Base - H50 (bedrock)	Dense Sand

Schematic sketches of the geology are presented in Figure 7-1 and Figure 7-2; they are orientated respectively NW to SE and NE to SW across the Bornholm I Site and illustrate the spatial relationships of the Seismic Units described in this chapter.

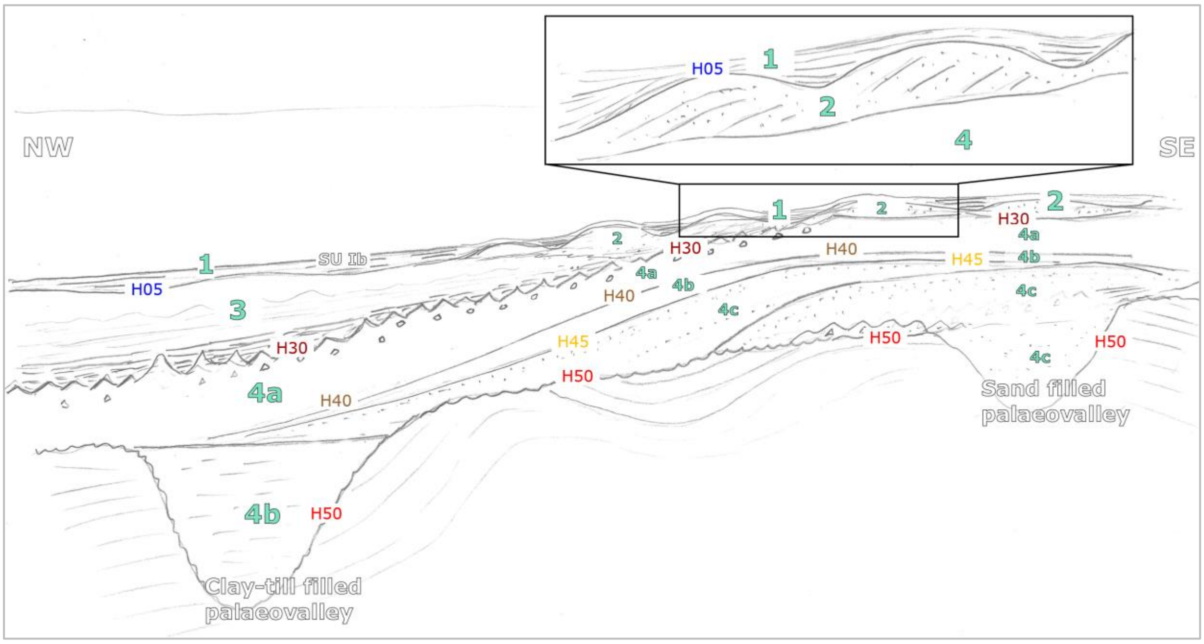


Figure 7-1 Conceptual sketch orientated broadly NW to SE across the Bornholm I Site, favouring the eastern side where the sand bodies that comprise Seismic Unit 4c are located. The sketch illustrates the relationship of the mapped seismic units and their bounding Seismic Horizons (see Table 7.1). For a section sitting at right-angles to this model see Figure 7-2.

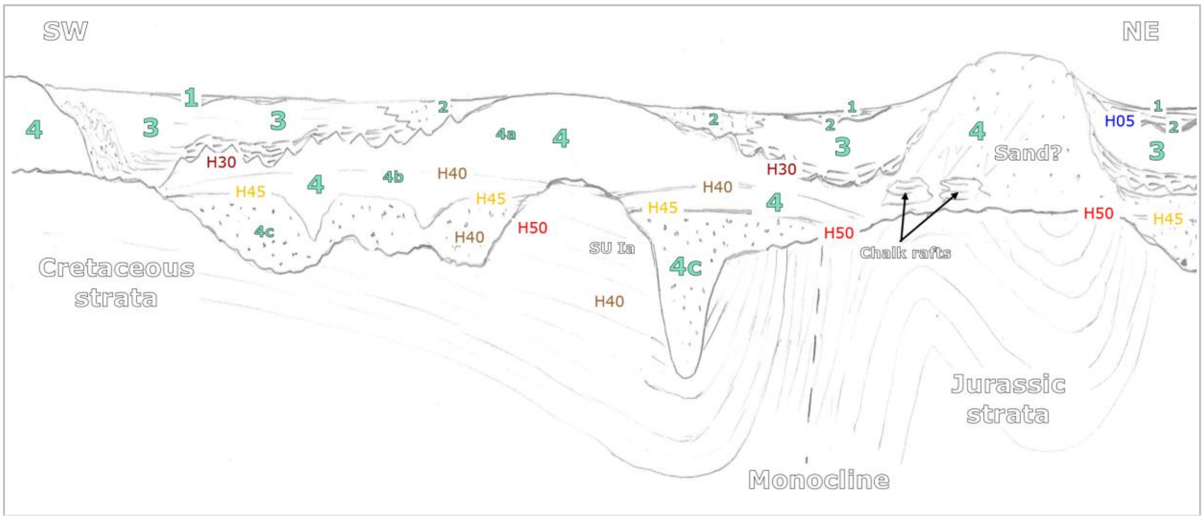


Figure 7-2. Conceptual sketch orientated in SW to NE orientation across the Bornholm I Site, orientated at right angles to that illustrated in Figure 7-1 showing the spatial relationships of the Seismic Units. The sketch illustrates the relationship of the mapped seismic units and their bounding Seismic Horizons (see Table 7.1).

The seismic unit classification employed herein to subdivide the Seismic Units follows that which was first established in the GEUS desk top study (Jensen, 2021) and which was subsequently utilised in the Geophysical Survey Report (GEOxyz, 2022). The one deviation is that the Seismic Units have been re-named using Western Arabic numerals as opposed to the Roman Numeral system since the latter has been adopted by the geotechnical team and is used to define the Bornholm I Soil Units.

It appears that the Seismic terminology employed in the earlier GEUS and GEOxyz reports has its ultimate source in the report that described the geology encountered during the Integrated Ocean Drilling Program's Expedition M0065 which drilled three holes in the Bornholm Basin located to the North and East of the island of Bornholm (Andrén *et. al*., 2014; Figure 7-3). The shallow sediment succession encountered in the Bornholm Basin shows by Leg M0065 boreholes shows similarities to those encountered in Bornholm I and II Sites.

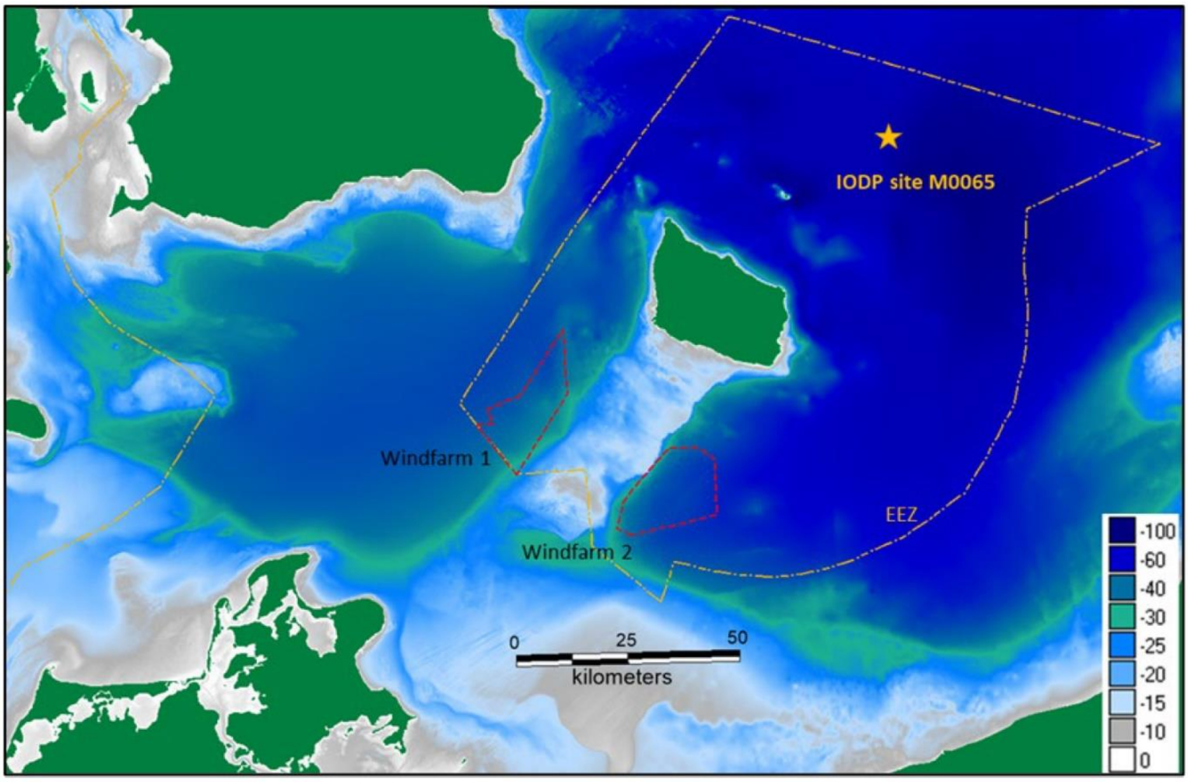


Figure 7-3. Map illustrating the location of the International Ocean Drilling Programs Site (M347) M0065 in relation to the Bornholm I and Bornholm II Sites. Map taken from Ref (Jensen, 2021).

7.3 Seismic Unit 1 – Holocene Sediments

Seismic Unit 1 is the shallowest Unit. It is defined by the H00 Seabed Reflector at its top and by the H05 Seismic Horizon at its base.

7.3.1 Seismic definition – H00 Seabed

The top of Unit 1 has been mapped on the seismic peak that defines that seabed. The characteristics of Seabed are described in the initial site investigation report (GEOxyz, 2022) and briefly in Section 5.2 and are not repeated here. The base of Seismic Unit 1 is primarily the H05 Seismic Horizon, though in the Eastern part of the site where the mounded facies of Seismic Unit 2 are developed it can be the H15 Seismic Horizon.

7.3.2 Internal Seismic Characteristics

Unit 1 has seismic characteristics which indicate that it is extremely soft/weak. Where Unit 1 occurs, the seabed is of very low reflection amplitude and the base, at the transition to sub cropping sediments, is of much higher amplitude, an amplitude similar to that of the seabed outside the distribution of Unit 1. These seismic characteristics indicate that Unit 1 has an acoustic impedance which is closer to that of the seawater than the other shallow geological units (GEOxyz, 2022).

7.3.3 Sedimentology and Geotechnical Characteristics

CPT logs and Borehole cores and logs indicate that Unit 1 is composed primarily of very soft organic-rich clay. Geotechnically, it falls into the Soil Unit Ib classification, and it has been assigned to Ground Model Unit 2 (GMU2). However, in the eastern part of the Bornholm I Site soft sands (Soil Unit Ia) have been encountered in CPTs in Seismic Unit 1 sediments (see Figure 7-4). It remains uncertain exactly where the sands transition into soft clay of Soil Unit Ib but Ramboll has provided a polygon that displays the most likely distribution of the Soil Unit Ia sands given the data to hand (Figure 7-4).

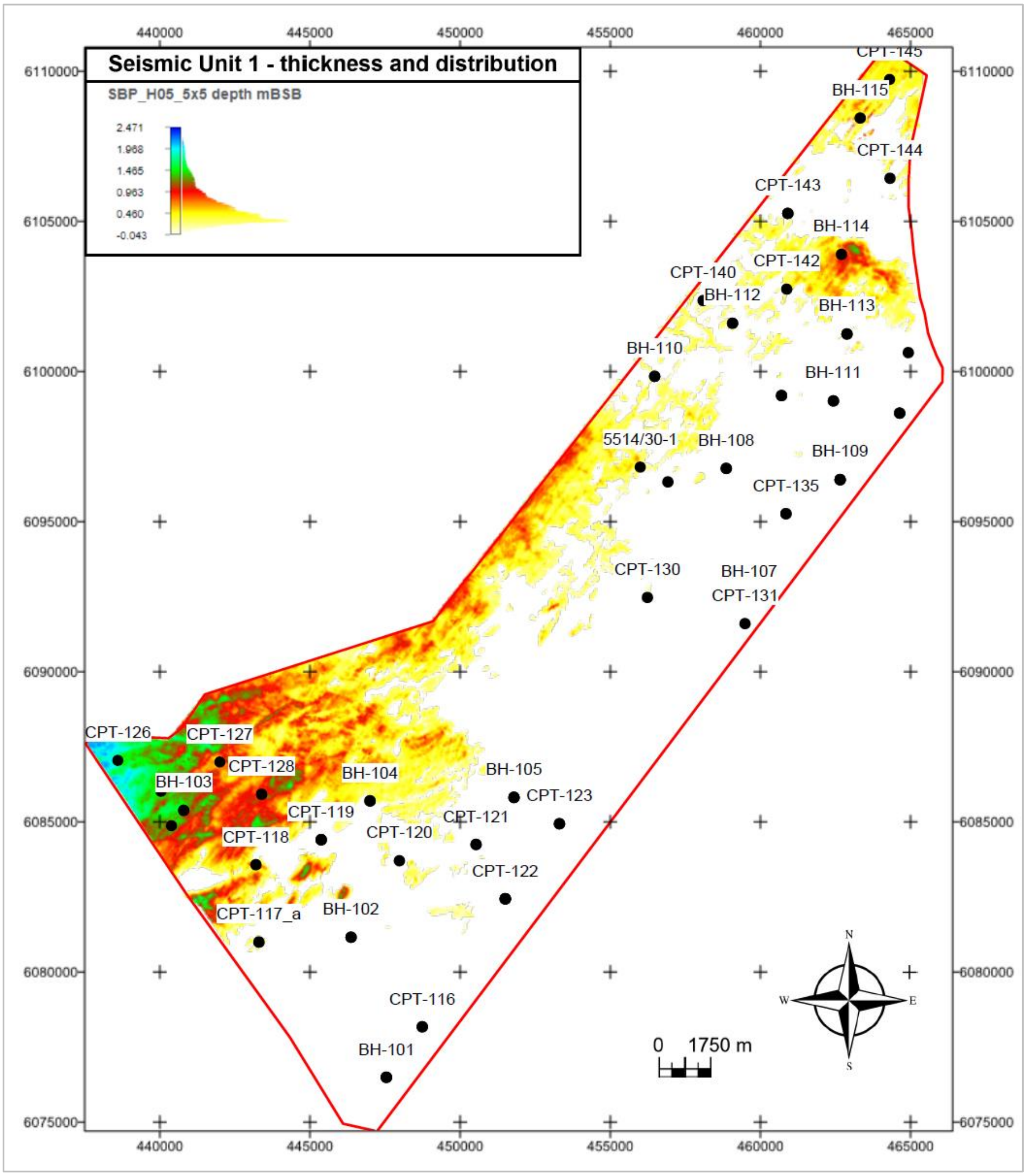


Figure 7-4. Map illustrating the thickness of Seismic Unit 1 along with those CPTs that have encountered shallow sand (Soil Unit Ia). The map shows potential distribution of the shallow sands that can sit both within Seismic Unit I and Seismic Unit 2.

7.4 Seismic Unit 2

Seismic Unit 2 is mapped entirely on the SBP dataset. Two geomorphological features have been mapped out in Unit 2, both of which predate the recent sediments of Unit 1. The first are a series of mounded bodies that are developed in the eastern part of the Bornholm I Site, particularly in the south.

7.4.1 Seismic Unit 2a Mounds – Seismic definition

The top of Unit 2 is defined by the H05 Seismic Horizon, though in places Unit 2 effectively forms the seabed substrate such that Unit 1 infills topography that sits around the mounds (Figure 7-5). Seismic Horizon H15 is picked at the base of the mounds where the internal reflectors down lap and at the junction between the coherent reflectors of Unit 2 and the more transparent seismic character of Unit 3 (Figure 7-5 to Figure 7-7).

7.4.2 Seismic Unit 2a Mounds – Internal seismic characteristics

Unit 2 mounds commonly have weak internal reflectors that either follow the convex-up geometry of the top of the mounds or are slightly more progradational, with internal reflectors dipping and downlapping the basal H15 Seismic Horizon.

7.4.3 Seismic Unit 2a Mounds – Sedimentology and geotechnical characteristics

CPTs and boreholes that have penetrated Unit 2 have typically encountered loose sands that are assigned to Soil Type Ia (Figure 7-5) and there is a good correspondence between these sands and the distribution of the thick intervals of mapped Unit 2 mounds. The mounds themselves tend to form elongated ridges that are, in the southern part of the site, orientated broadly East-West. When viewed on lines orientated along the modern-day bathymetric slope the mound can be seen to back-step up the slope, getting larger to the east (Figure 7-4). The mounds are considered to represent a series of drowned beaches created as the Baltic Lake level began to rise prior to flooding out and the transition to fully marine conditions.

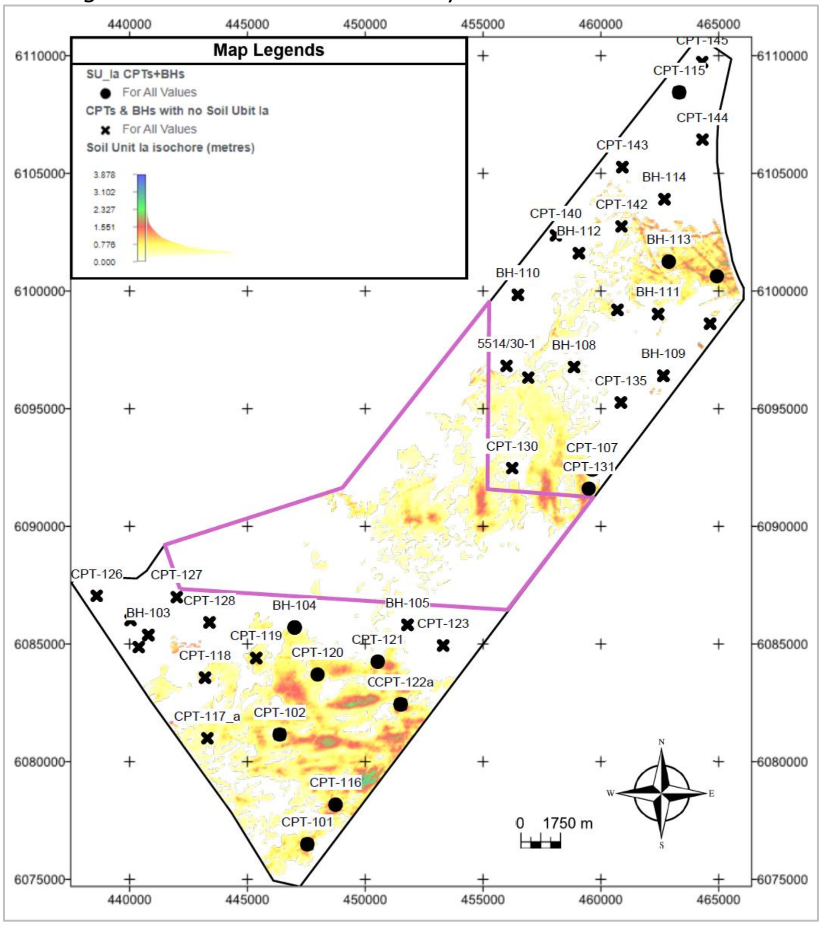


Figure 7-5. Distribution of Seismic Horizon H15, which marks the base of the seismic mounds in Seismic Unit 2. Also plotted are CPTs and Boreholes that have recorded loose sands of Soil Unit Ia (black circles), and those that have not (black crosses). The seismic mounds of Unit 2 likely represent beach to shoreface deposits that form elongated depositional thicks. It appears that these mounded features correspond well with the shallow sands encountered in the boreholes and CPTs and the distribution of H15 has been used to populate Soil Unit Ia in the ground model.

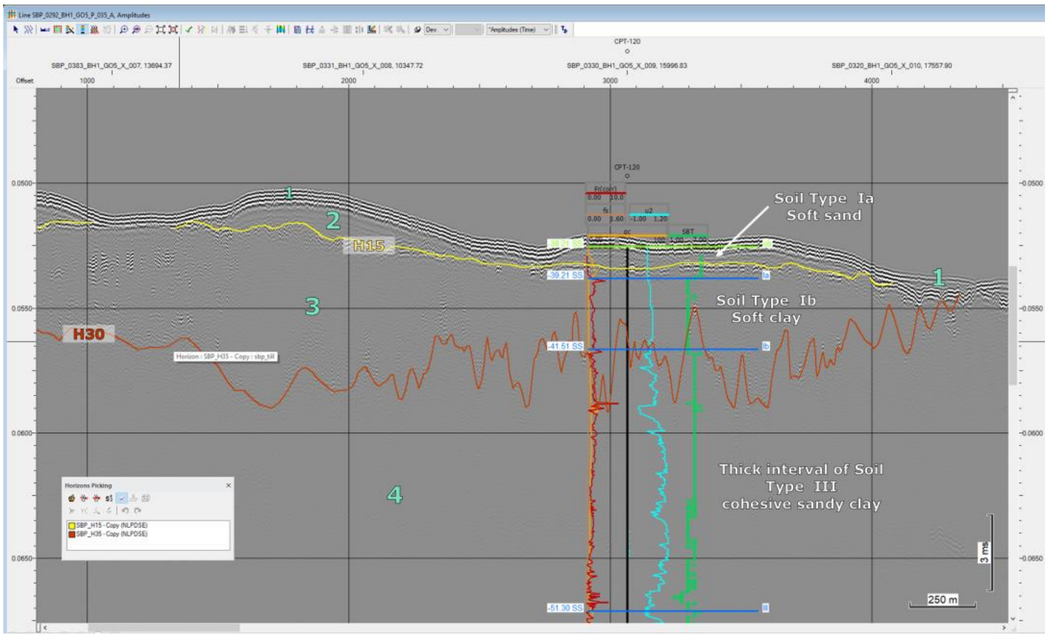


Figure 7-6. SBP line P_035_A passing through the CPT-120 location. Here the mounded features of Seismic Unit 2 are well developed and are observed to be composed of soft sand (Soil Type Ia). Weak internal reflectivity within the mounds generally follows the upper surface and downlaps onto the H15 Seismic Horizon. Note the contact between the Seismic Units 3 and 4 (green labels) marked by the H30 (H35) Seismic Horizon corresponds to the contact between Soil Type Ib (soft clays) and Soil Type III (stiffer, more cohesive clays). The defined Seismic Units are numbered in Green.

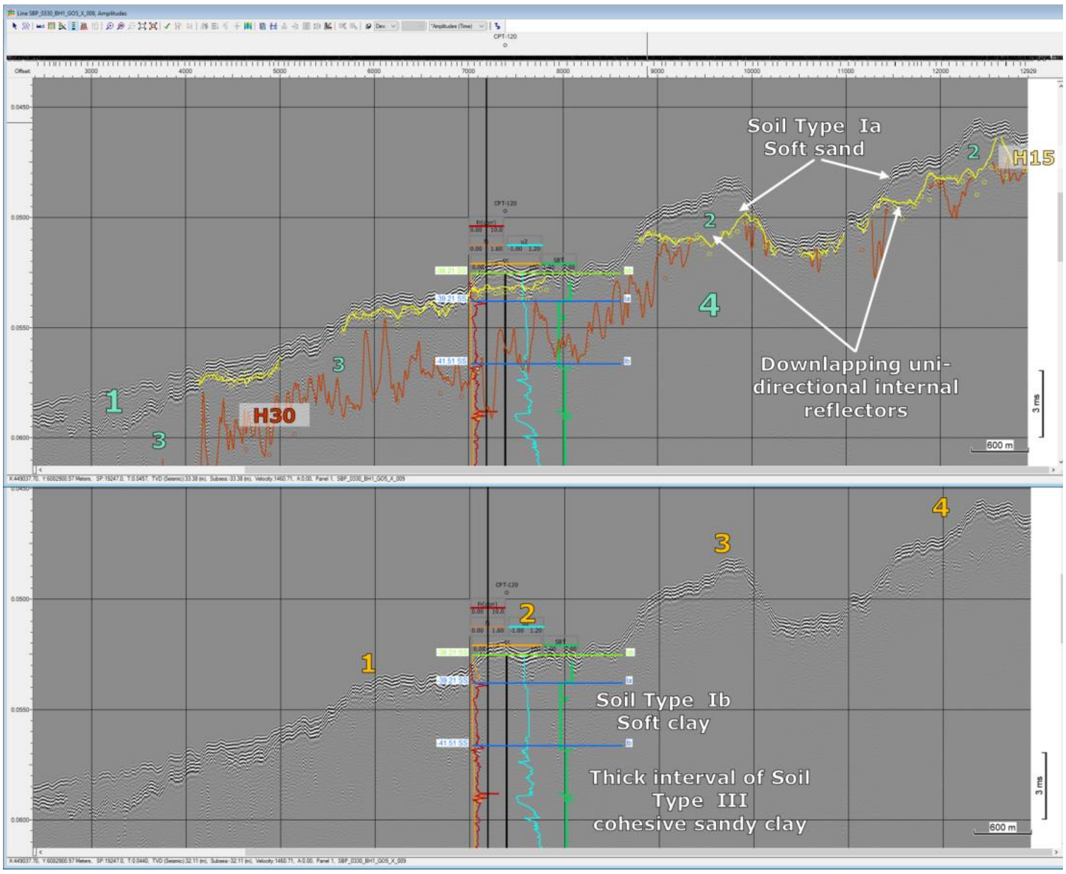


Figure 7-7. SBP X-line GO5_X_009 oriented NW to SE showing the spatial relationship of the Unit II mounds to the bathymetric dip slope. The mounds form a series of benches (1 through to 4) on the modern-day slope. In this cross-section they appear to increase in size as they step up the dip-slope towards the ridge that separates Bornholm I and II.

7.4.4 Seismic Unit 2b Channel features – seismic definition

The Unit 2 seismic channel features are defined by the H20 Seismic Horizon that has been mapped on the SBP data. The top of the features is normally the H05 Seismic Horizon. Over most of the Bornholm I Site the Seismic Unit 2 channels are only sporadically developed. But in the northernmost part of Bornholm I the channel-features appear to merge into a broad more continuous unit that can reach several metres in thickness (Figure 7-8).

7.4.5 Seismic Unit 2b Channel features – internal seismic geometry

The Channel features are characterised by moderate amplitude parallel reflectors that partly onlap the channel/scour walls and partly drape the topography (Figure 7-9).

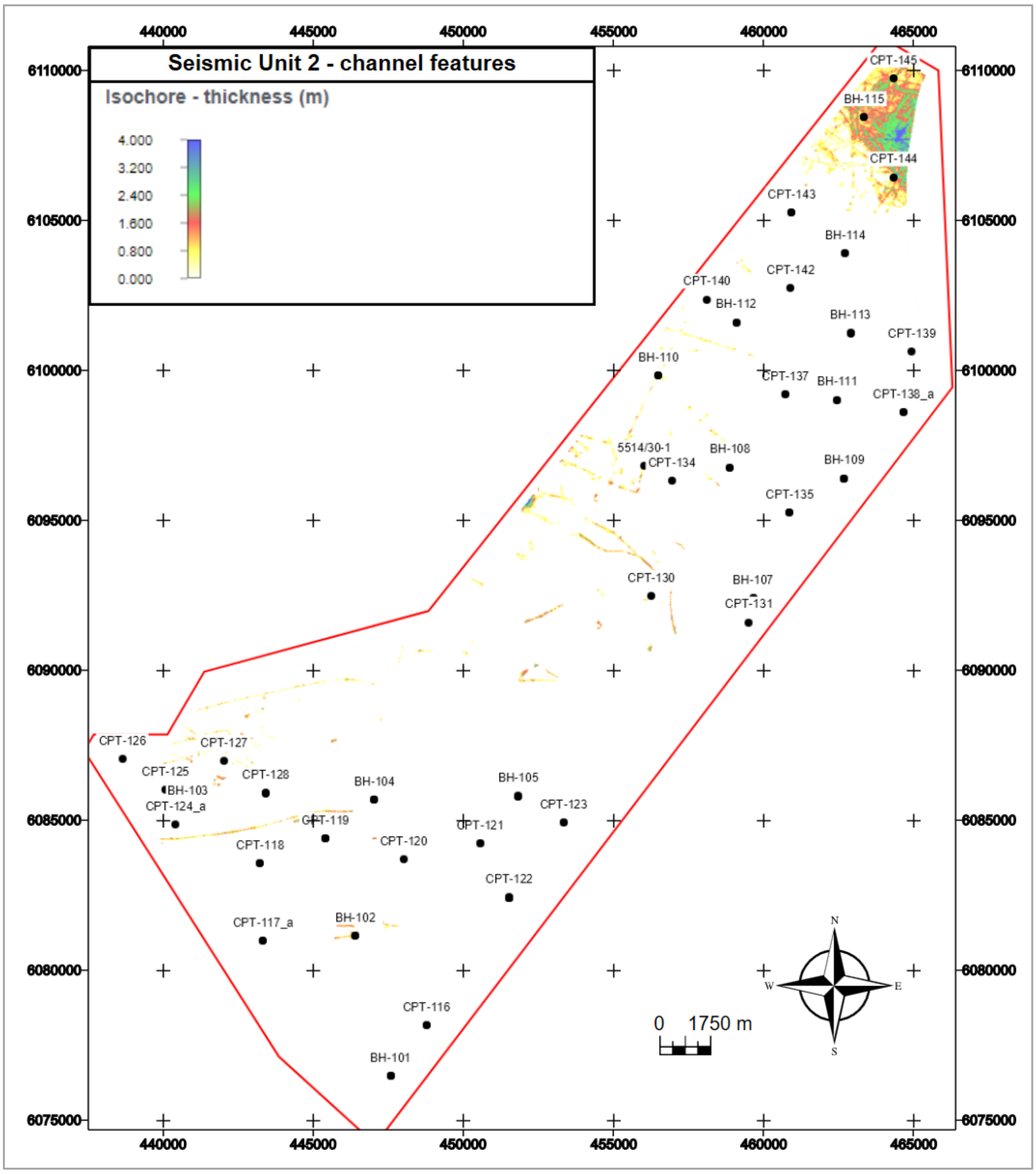


Figure 7-8. Seismic Isochore map illustrating the distribution and thickness of the Unit 2 channel features. Note the apparent amalgamation of these features in the northern part of the Bornholm I Site, where the Seismic Unit 2 channel features attain their greatest thickness.

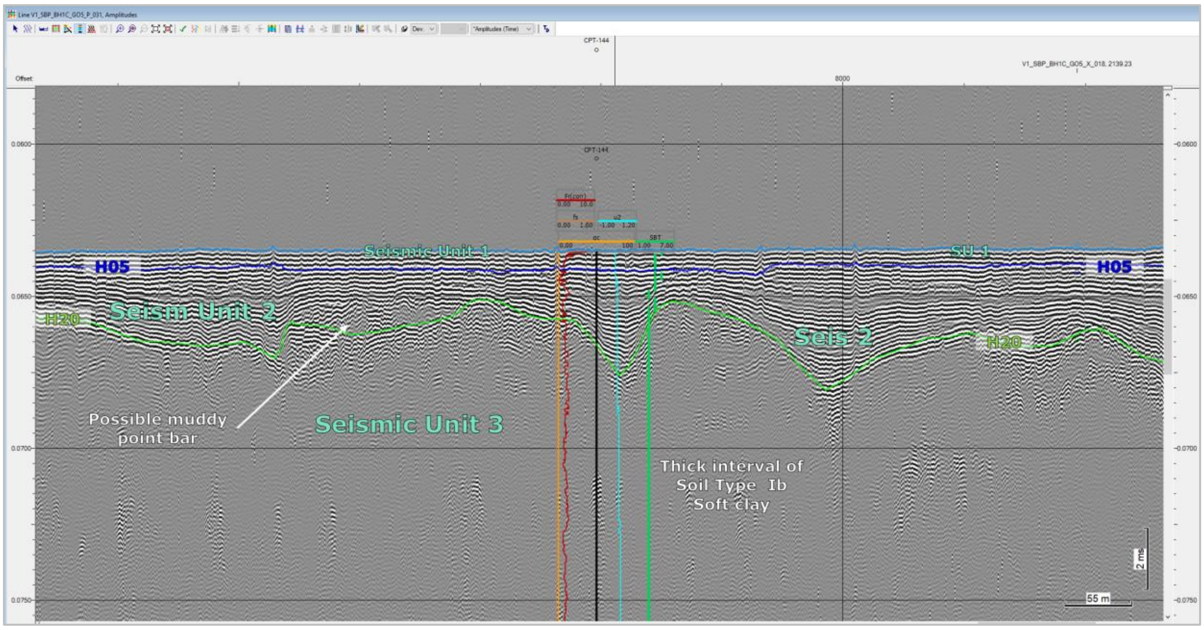


Figure 7-9. SBP in-line through the CPt-144 location illustrating the seismic character of the Unit 2 Channels. The CPTs display little change across the H20 Seismic Horizon with the entire succession, from the seabed, being dominated by very soft organic-rich clay Type Ib soils.

7.4.6 Seismic Unit 2b Channel features – sedimentology and geotechnical characteristics

All the CPTs and boreholes that have penetrated the Seismic Unit 2 channels have encountered very soft, organic-rich clays that are assigned to Soil Unit Ib. The parallel seismic reflectivity and onlap onto the margins of the channel features are indicative of a passive fill of the channels through suspension settling of fine-grained clays and organic detritus.

7.5 Seismic Unit 3 – Baltic Lake succession

Seismic Unit 3 is partly defined on the SBP data set and partly on the Ultra High-Definition seismic dataset. The top of the unit is defined by a combination of the H05, H15 and H20 Seismic Horizons whereas the base is defined by the H30[3] (H35) Seismic Horizon as it has been mapped on the UHRS dataset. The Unit consists primarily of clay (Soil Units Ib, II and very locally III; see Section 10), though there is a relatively thin belt of sand (Soil Unit IVa) in the very south of the site (see discussion in Section 7.5.7).

The thickness of Seismic Unit 3 consistently thins towards the east, as well as over the bathymetric high that is present in the north of the Bornholm I Site (Figure 7-10). Seismic Unit 3 also thins across a ridge developed at the southern part of the site (see Figure 7-10 and Figure 7-16.).

7.5.1 Seismic Unit 3 definition – H05, H15, H20

The top of Seismic Unit 3 is defined by a combination of Seismic Horizons H05, H15 and H20 depending on their distribution across the site. The base is defined by the highly irregular H30 (H35) Seismic Horizon that is discussed in depth in Section 7.6 below.

[3] Note that earlier studies named this Horizon the H35 (GEOxyz, 2022). In Bornholm I this Surface was renamed to H30 since it is such an important Seismic Horizon when it comes to the fundamental subdivision of the Geology and Geotechnical units across the site.

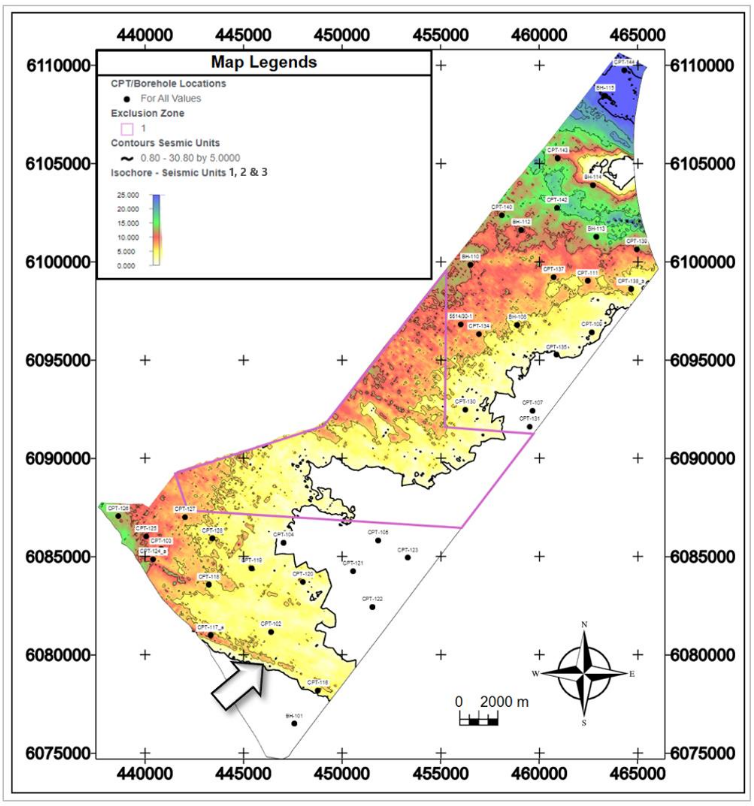


Figure 7-10. Isochore map of Seismic Units 1, 2 and 3 that essentially illustrates the depositional extent of Seismic Unit 3. The unit thins and pinches out along the eastern side of the site as well as onto two distinct ridges developed in the underlying Unit 4 succession, one in the North and one in the South (arrowed).

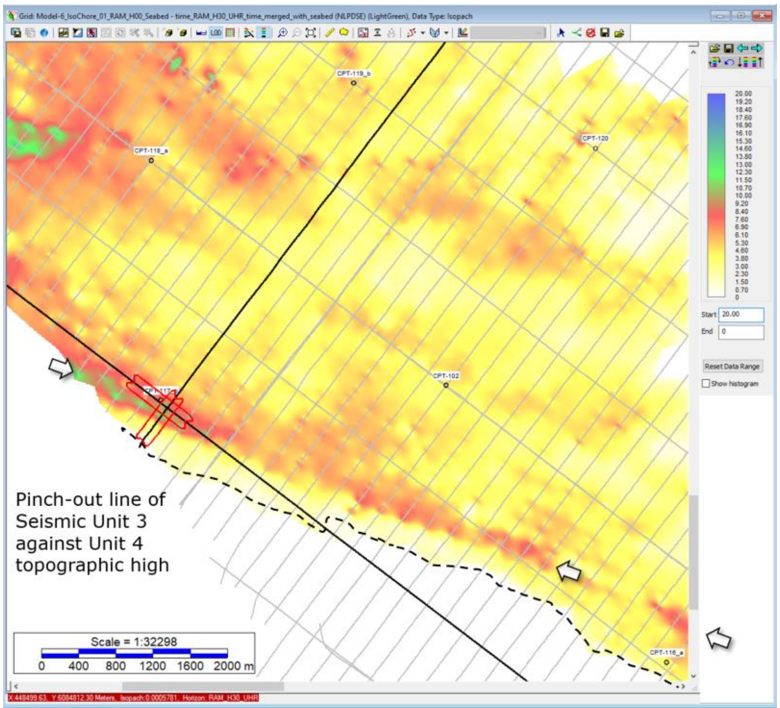


Figure 7-11. Isochore map of Seismic Unit 3 long the southern part of the Bornholm I Site. This map illustrates the pinch-out line for Unit 3 as mapped on the UHR Seismic. It illustrates that there is a local thick in the Unit 3 sediments that parallels the pinch-out line (white-arrows). The red outlines on the highlighted seismic lines show the location of the seismic horizons depicted in Figure 7-16.

7.5.2 Seismic Unit 3 - Internal seismic character

Four subunits can be recognised within Unit 3 based on the internal seismic character. The first three sub-units are best observed in those parts of the Bornholm I Site where Unit 3 is thickest (Figure 7-12 to Figure 7-14). From the top down these are:

1. Seismic Unit 3a – seismically transparent, with little or no seismic character (soft organic rich clays assigned to Geotechnical Soil Unit Ib).
2. Seismic Unit 3b – characterised by weak generally parallel seismic reflection pattern (soft organic rich clays assigned to Geotechnical Soil Unit Ib).
3. Seismic Unit 3c – defined by moderate to high-amplitude parallel reflectors (soft to medium stiff clays intercalated with thin sand and silt layers; primarily Geotechnical Soil Unit Ib, locally Geotechnical Soil Units II and/or III).

The fourth Seismic Subunit is restricted to the very southern part of the Bornholm I Site where Unit 3 abuts against a pronounced topographic step that is developed in the underlying Seismic Unit 4 sediments:

4. Seismic Unit 3d – moderate amplitude parallel to contoured seismic reflectors (medium dense to dense sand with clay interbeds; Geotechnical Soil Unit IVa).

Although these 4 Seismic Sub-Units can be identified visually, they are extremely difficult to map precisely. Since Seismic Subunits 3a, 3b and 3c are primarily dominated by the soft, organic-rich clays of Soil Unit Ib no attempt has been made to differentiate these units in the Ground Model, and they have not been mapped out seismically. Nonetheless, from a pure sedimentological perspective they are noted and described below.

7.5.3 Seismic Unit 3 – Sedimentology and Geotechnical Characteristics

Seismic Unit 3 is composed primarily of clay, though the clay tends to get siltier and sandier towards both its base, and towards its pinch-out line against the underlying Seismic Unit 4.

7.5.4 Seismic Unit 3a

The uppermost sub-unit, 3a, typically has a transparent homogeneous seismic character. It can comprise the bulk of Unit 3, especially where it reaches its maximum thickness in the western and northern most parts of the Bornholm I Site (Figure 7-12 & Figure 7-13). Its top is uneven and H20 channel- features can cut down into Unit 3 (Figure 7-12). Its lower contact with the weak parallel seismic facies that define Unit 3b appears to be a disconformity, that is locally erosional in nature; small erosive features, possibly former channels can be observed to cut down into the underlying bedded sub-Unit 3b (Figure 7-12).

7.5.5 Seismic Unit 3b

Characterised by weak, thin, low amplitude, parallel seismic reflectors Seismic Unit 3b is present throughout the site. Seismic reflectivity through the unit is generally weak; reflectors are normally parallel, though can be locally contorted. As with the overlying sub-unit 3a CPTs and core recovered from boreholes show this interval to be characterised by soft clay (Soil Unit Ib). Unit 3b may locally onlap topography developed on the underlying Glacial Unit 4 sediments but generally drapes across the underlying topography. The unit drapes across the large ridge developed in Unit 4 in the north of the Bornholm I Site but at its crest the parallel reflectors are observed to have been erosionally truncated below the H05 reflector (Figure 7-15).

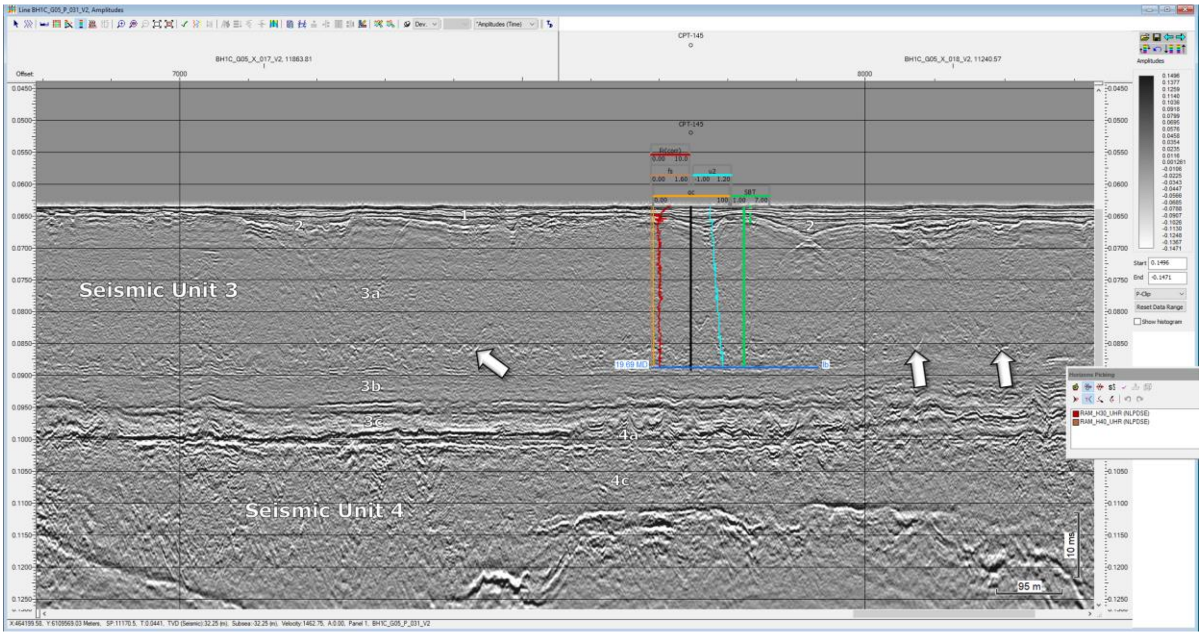


Figure 7-12. Seismic in-line G05_P_031_V2 from the very northwest of the Bornholm I Site where Seismic Units 1, 2 and 3 reach attain their greatest thickness. The main sub-units are illustrated. 3a consists of transparent seismic facies; 3b has weak parallel reflectors whereas 3c has more moderate amplitude parallel reflectors. The entire succession penetrated by the CPT-145 comprises soft clays assigned to Soil Unit Ib. The white arrows illustrate the disconformable to contorted contact between sub-units 3b and 3c.

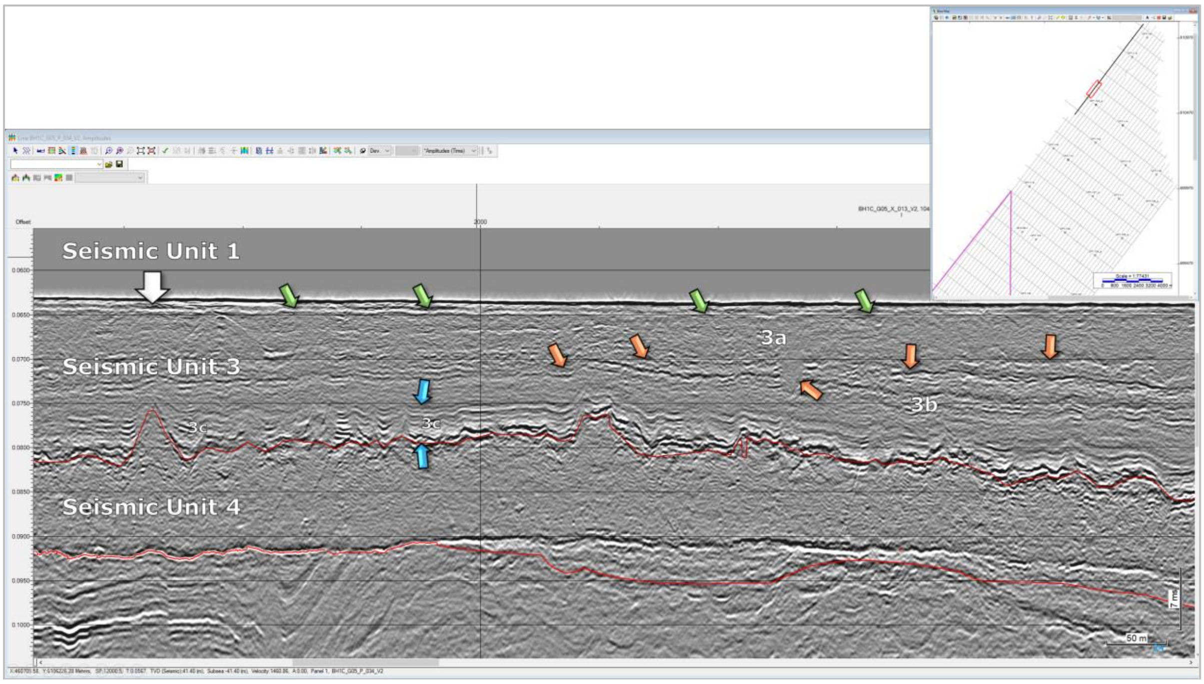


Figure 7-13. Seismic in-line G05_P_014_V2 illustrating the stratigraphy developed in Seismic Unit 3. Unit 3c (bracketed by the blue arrows) is dominate by moderate to high amplitude reflectivity and it onlaps and drapes the irregular topography developed on the top of Seismic Unit 4. Seismic subunit 3b has much weaker amplitudes and reflectivity, though its top appears to be a disconformity, locally erosional (orange arrows). Seismic subunit 3a is largely homogeneous in its seismic character but is capped by a potential erosive surface (green arrows) that corresponds to the H05 Seismic Horizon.

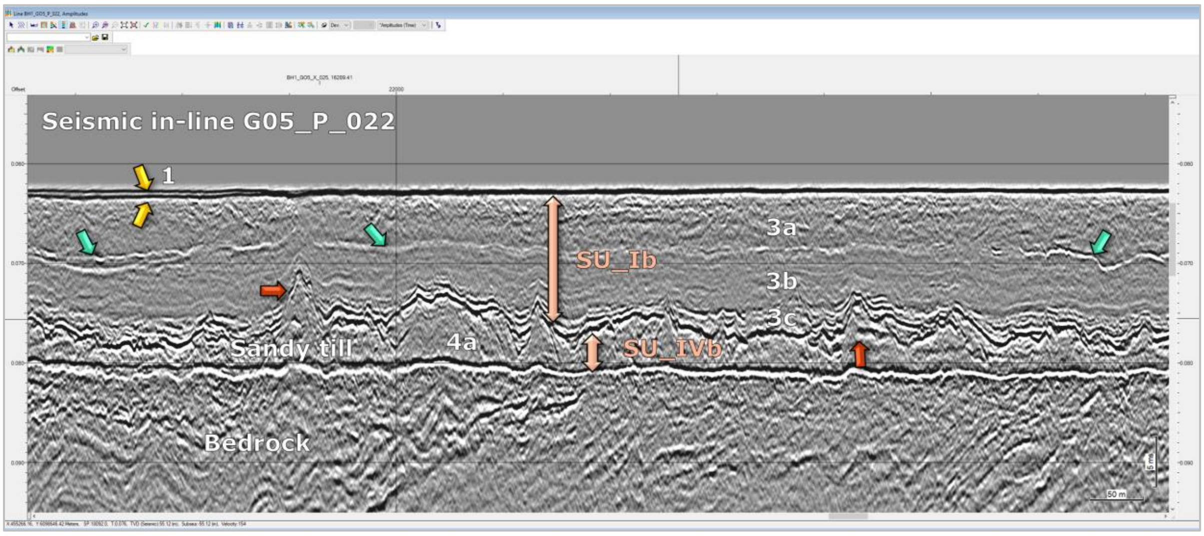


Figure 7-14. Seismic Line illustrating the partial onlap and burial of the Seismic Unit 4 sediments by the moderate to bright amplitude 3c interval. Note how Unit 4 hummocks can locally protrude up into the 3b sediments (left-hand side orange arrow). Unit 3b has much lower reflectivity though appears to be capped by an erosive surface (green arrows). Unit 3a is largely structureless, or homogeneous from a seismic reflectivity perspective. Also depicted are the typical soil units. Sub-Units 3a and 3b are predominantly soft clays (Soil Unit Ib).

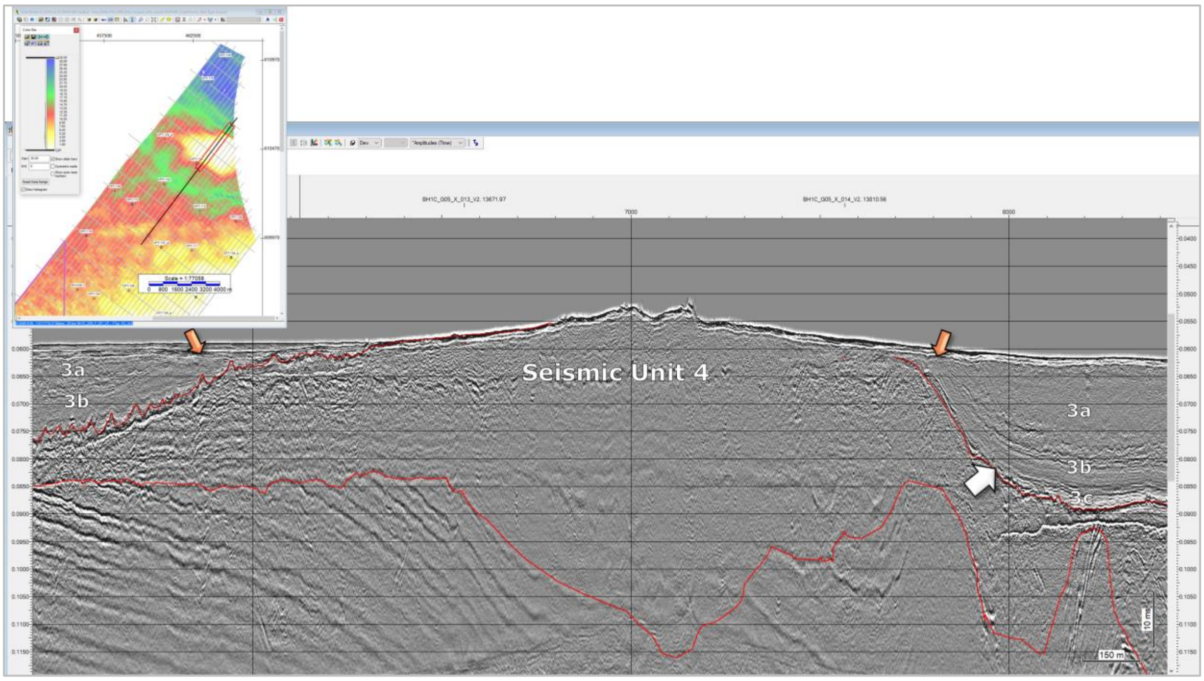


Figure 7-15. Seismic in-line G05_P_021 illustrating the partial onlap of Unit 3 (principally Unit 3c - white arrow) against the Seismic Unit 4 thick that is responsible for the bathymetric high in the north of the Bornholm I Site. Note how the thinly bedded sub-unit 3b largely drapes the ridge, though the bedding is truncated by the disconformity/unconformity that marks the top of Seismic Unit 3 (orange arrows).

7.5.6 Seismic Unit 3c

The basal sub-unit comprises a relatively thin interval with high amplitude reflectivity. Reflectors typically onlap the margins of high-relief hummocks developed at the top of Unit 4 and/or drape across the hummocks. Sub-Unit 3c onlaps and buries the irregular topography present on the top of Unit 4 and the strong amplitude reflectors of sub-Unit 3c are generally somewhat contorted, and laterally discontinuous as a result of burying the underlying hummocky topography.

CPTs and cores recovered from boreholes indicate an increasing presence of intercalated thin silt and sand beds in this interval, whilst the clays are typically stiffer than those present in the overlying Unit 3 subunits. This unit can be variable from a geotechnical perspective; it is classified in the Ground Model as Soil Unit Ib but can have thin intervals of Soil Unit II or even III. The interbeds of slightly stiffer clay and silt probably accounts for the brighter amplitudes as it consists of sediments with different acoustic properties.

7.5.7 Seismic Unit 3d

This subunit is present as a relatively narrow band that sits just north of the Seismic Unit 3 pinch-out along the southern part of the Bornholm I Site (Figure 7-16 & Figure 7-17). CPTs indicate the top of the unit is dominated by soft, organic-rich clays that transition downwards, through interbedded silts and clays into relatively stiff sand (Soil Unit IVa). The sands within Seismic Unit 3 appear to be confined to a very narrow belt that is associated with the pinch-out line of Seismic Unit 3 along the southern margin of the Bornholm I site (Figure 7-16 & Figure 7-17).

It is likely that Subunit 3d simply represents a thicker and more proximal equivalent to Subunit 3c; it is more sand prone since it sits closer to the primary sediment source that fed sand into the system.

Seismic imaging of this unit illustrates it to be relatively thinly bedded with beds being locally highly contoured. Soft sediment deformation in the form of slumps and folds are observed in Unit 3d. These soft-sediment deformation features are largely restricted to the vicinity of a topographic step in the Seismic Unit 4 sediments that can be mapped along the southern margin of the Bornholm I Site (see Figure 7-16 & Figure 7-17). Deformation is clearly syn-sedimentary with bed thickness changes consistent with sediments infilling accommodation space created by the deformation. Moreover, the deformation geometries are consistent with slumping and/or sliding of sediments towards the NE, away from the down-stepping Unit IV high (see Figure 7-16 & Figure 7-17).

7.5.8 Discussion

The four-part subdivision is based on the seismic character of Seismic Unit 3. Geotechnically Unit 3 is overwhelmingly dominated by soft clays (Geotechnical Soil Unit Ib), though these clays can transition into the transitional cohesive Soil Unit II clays near the base of the unit. This transition generally occurs at, or near, the transition to the subunit 3c that drapes and infills topography developed on the underlying glacial sediments of Seismic Unit 4.

Close to the pinch out line of Unit 3 the character of the sediments that comprise the unit can change. This is most apparent in the CPTs at the 117 location which encountered sand in Seismic Unit 3 that have characteristics of Soil Unit IVa; i.e. dense sand (see Section 8). An extra unit, Subunit 3d, has been assigned to these sands. Unfortunately, the full spatial extent of the sands remains unclear, but it is believed that they pass relatively quickly into the more normal clay-rich Baltic Lake sediments. It is quite likely that the 3d sands thin and pass laterally into subunit 3c since at the Bornholm 117 location they pass upwards into sediments more typical of Subunit 3c and ultimately into Seismic Subunit 3b type sediments.

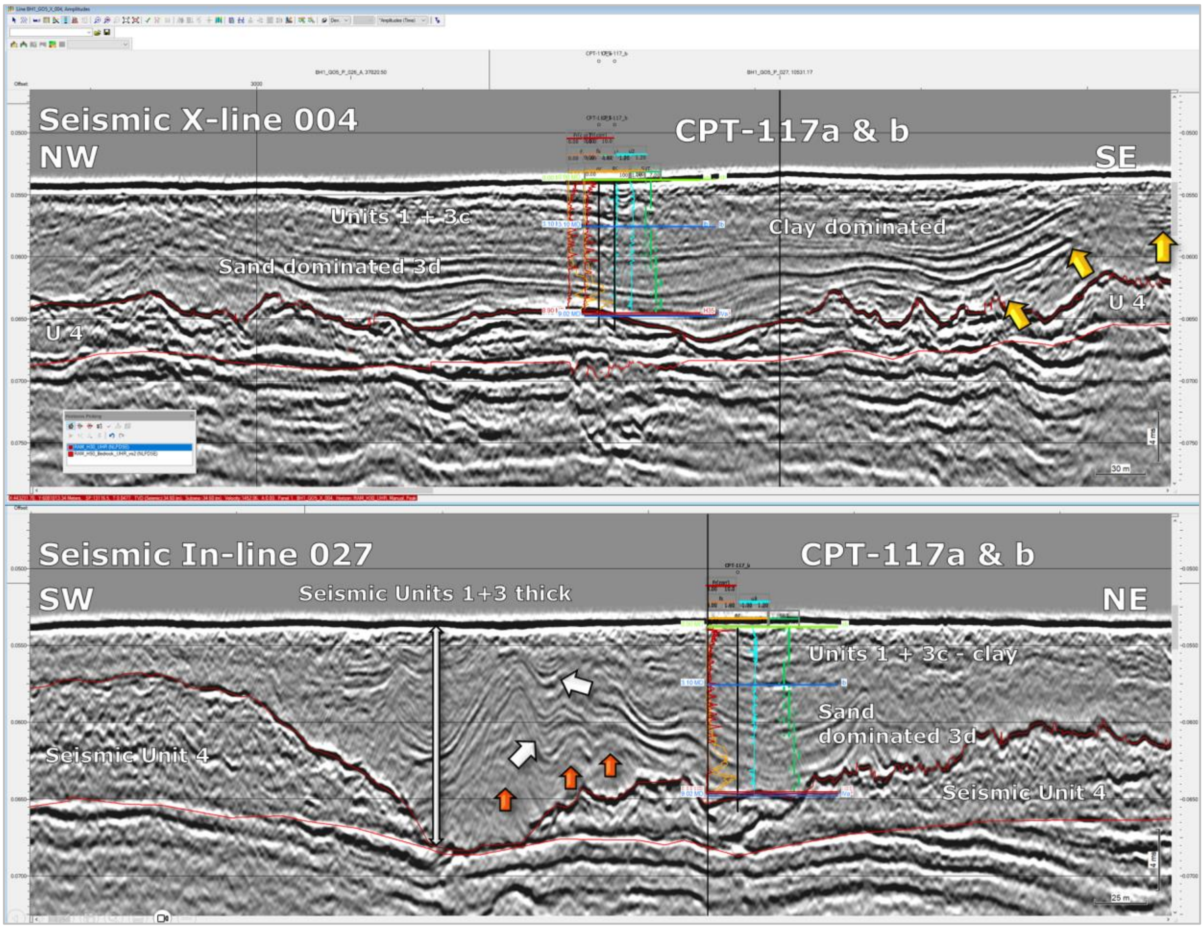


Figure 7-16. Cross-line (top) and in-line (bottom) centred on the CPT-117 location (see Figure 7-11 for the location of these lines – red outlines on the black seismic line traces). Note the interval of level bedded Seismic Unit 3 sediment is dominated by sand at this location; sand that transitions upwards through interbeds of clay into soft clays. When viewed on the SW to NE aligned seismic in-line (lower image) these sediments are observed to be deformed. This deformation, primarily slumping must have been syn-sedimentary early since local thickening in some of the beds can be observed adjacent to the folded/slumped strata (white arrows). Note how the amplitude of the slump folds decreases towards the NE suggesting that slumping likely occurred towards this direction and away from the relatively steep step that this developed in the Seismic Unit 4 glacial sediments.

In CPT-117a&b the encountered sand is believed to have been locally sourced. Sand accumulated along, and just basinward, of a distinct break of slope in the underlying Seismic Unit 4. Given the apparent limited distribution of sand in Seismic Unit 3[4] it is likely that these sands where locally sourced; possibly reworked from the underlying tills and moraines of Seismic Unit 4 as lake levels began to rise and the glacial landforms of Unit 4 were drowned. Alternatively, they could have been deposited from a river that flowed into the Baltic lake near this location bringing sand into the lake system. The break of slope at the top of the underlying Seismic Unit 4 created a sharp increase in palaeo-bathymetry which would have acted as a 'sink' for heavier sand grains as clays and silts were transported further offshore. Syn-sedimentary slumps and associated soft-sediment folds indicate lateral displacement of the deposited sediment, away from the Unit 4 break of slope. Slumping would have been driven by slope instability with movement occurring, in this case, towards the northeast away from the Unit 4 ridge. Instability of sediments that have been deposited into standing bodies of water is not uncommon. Rapid sedimentation rates can create unstable slopes that subsequently fail. The actual process of slumping can be triggered simply

[4] Limited in the sense that there are few CPT and Borehole penetrations into this package.

through slope instability, or it might even have been triggered by other events such as seismic activity.

Away from the pinch-out line of Seismic Unit 3, in areas where sub-units 3a, b and c accumulated, the succession shows similarities to the sequence of sediments encountered in the International Ocean Drilling Program's Site M0063 where 3 holes were drilled into the Bornholm Basin (Ref (Andrén T. B.-S.-B., 2014), reproduced in (Jensen, 2021). Detailed descriptions of the sediments, palaeontology and geochemistry of the cores recovered at IODP Site M0065 are presented in (Andrén T. B.-S.-B., 2014) but there is little discussion on the seismic character of the units penetrated. Conversely, the core descriptions of Unit III on the Bornholm I Site (Gardline, 2023) are insufficiently detailed for a direct comparison with those published from IODP Site M0065 (Andrén T. B.-S.-B., 2014). The one exception to this is that the deepest subunit at both M0065 as well as that from the Bornholm I cores. At both locations the cores recovered contained clays with thin intercalated sand and silt beds. The lowermost subunit in Unit III at the M0065 site is believed to have been deposited in the Baltic Ice Lake that developed in front of the retreating Weichselian Ice Sheet. A similar depositional setting for the base of Seismic subunit 3 is likely at the Bornholm I Site, where Subunit 3c is observed to both onlap and drape the topography that had been created following the deposition of the underlying glacial tills and moraines of Seismic Unit 4a (see discussion in Section 7.6).

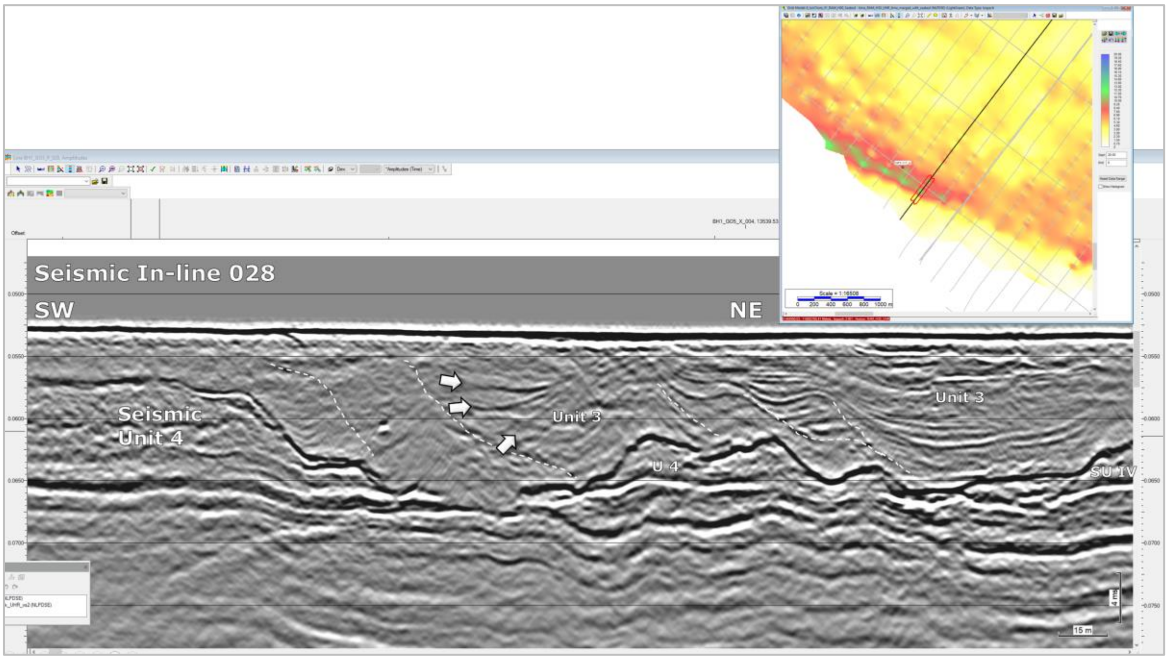


Figure 7-17. Seismic in-line 028 sitting just to the south of that illustrated in Figure 7-16. Here Seismic Unit 3 also displays evidence of slumping with arcuate failure planes. Note that beds thicken in towards failure surfaces (white arrows) and that they have rotated such that the deeper beds have high angles of dip. Slumping is again orientated towards the northwest away from the bench developed in the underlying Seismic Unit 4.

7.6 Seismic Unit 4 – Glacial influenced strata

Seismic Unit 4 comprises a succession of sediments that is bracketed by the H030 (H35) Seismic Horizon at its top (Figure 7-18) to the horizon H50 at its base. In the eastern parts of the Bornholm I Site Seismic Unit 4 sits close to the seabed with just a thin cover of Holocene sediments (Figure 7-19). The Unit buries topography on the underlying bedrock, and as a consequence, its thickness can vary dramatically across the Bornholm I Site (Figure 7-20). Where it fills palaeovalleys that have been carved into the bedrock its total thickness can be in excess of 50 m (Figure 7-20). Seismic Unit 4 has a complex internal character, but it comprises at least three depositional units. The geometrical relationships of these units are depicted schematically on Figure 7-1 and Figure 7-2; from youngest to oldest these are:

1. Seismic subunit 4a – glacial tills capped by hummocky moraines – (Soil Unit III and locally Soil Unit IVb).
2. Seismic subunit 4b – sediment fan(s) internally bedded, fine grained – (Soil Unit IVb).
3. Seismic subunit 4c – sediment fans, generally massive, sand dominated– (Soil Unit IVa).

Along the Eastern side of the Bornholm I Site, east of the pinch-out line of Seismic Unit 3 (see Figure 7-10) Seismic Unit 4 sits directly below a thin carpet of Holocene sediment. In contrast to the overlying Seismic Unit 3, Unit 4 tends to thin towards the west (Figure 7-20). In the northern part of the site there is a ridge-shaped WNW to ESE aligned thick in Seismic Unit 4, though the ridge thins towards the East (Figure 7-20).

In the south there is also a distinctive northward step in Seismic Unit 4, across which it can thin to nothing so that Seismic Unit 3 sits directly on the bedrock (see Figure 7-17 & map in Figure 7-20). This erosional gully where Seismic Unit 4 is absent is clearly visible on the Seismic Unit 4 isopach map (Figure 7-20). The top of Seismic Unit 4 appears to have controlled the thickness in the overlying Unit 3 sediments. Where The H30 (H35) surface that defines the top of Seismic Unit 4 is structurally high the thickness of Seismic Unit 3 is low, and *vice vera* (compare Figure 7-10 & Figure 7-20). This relationship between the structural elevation of Seismic Unit 4 and the overlying sediments illustrates that the depositional topography developed during the retreat of the LGM ice sheet has subsequently controlled, to a considerable degree, the thickness of the sediments that comprise Seismic Units 1 through to Unit 3.

Each of the Seismic subunits within Unit 4 are defined by seismic Horizons, with the H30 (H35) and the H45 Seismic Horizons having been implemented into the Velocity model since they define distinct Soil Units: very stiff sandy clay (Soil Unit IVb) and dense sands (Soil Unit IVa) respectively.

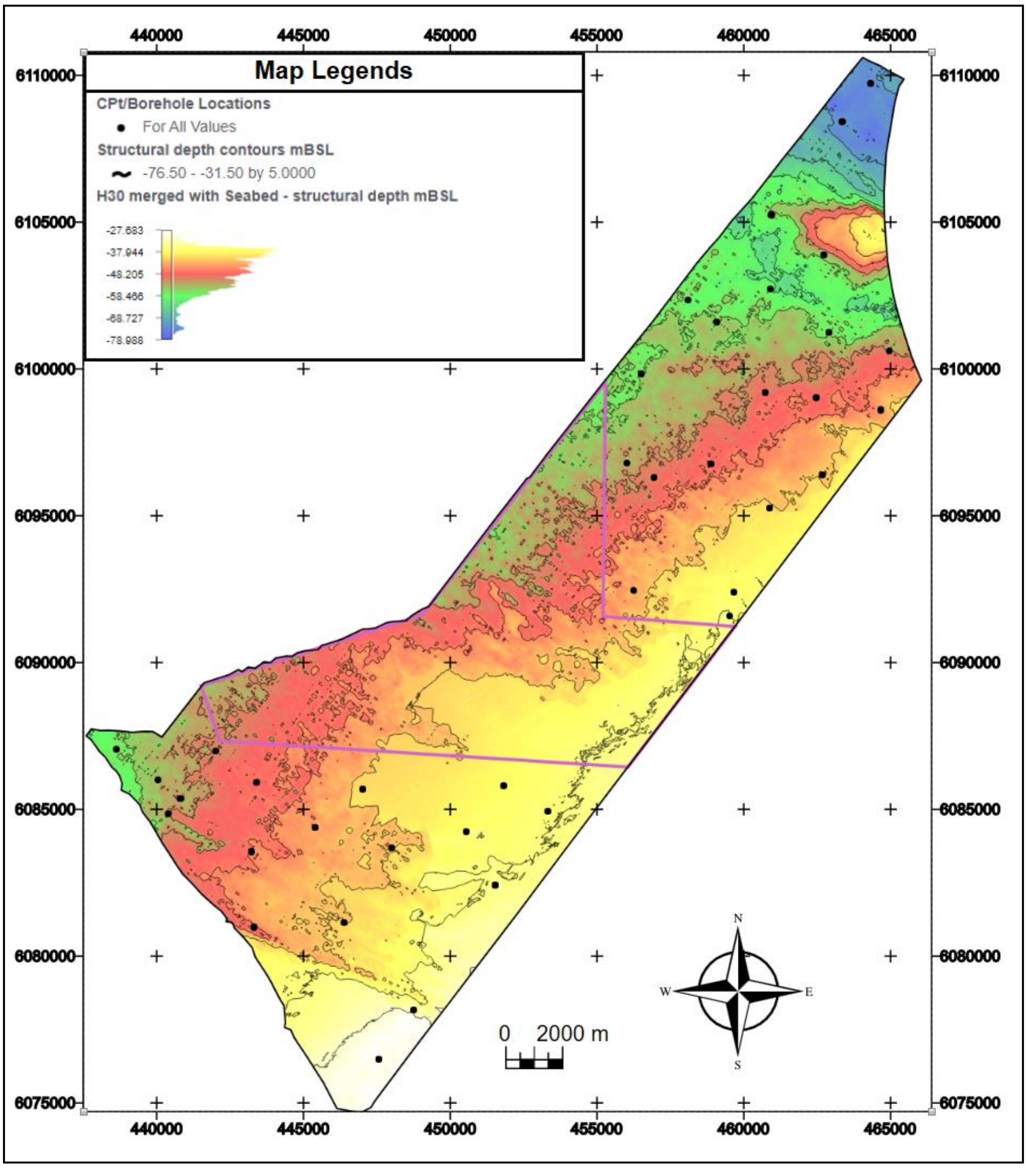


Figure 7-18. Structural map illustrating the top of Seismic Unit 4 created from merging the top of the H30 (H35) Seismic Horizon with the seabed in the eastern part of the Bornholm I Site. The H30 Seismic Horizon essentially merges with the base of the Holocene interval over the eastern part of the Bornholm I Site.

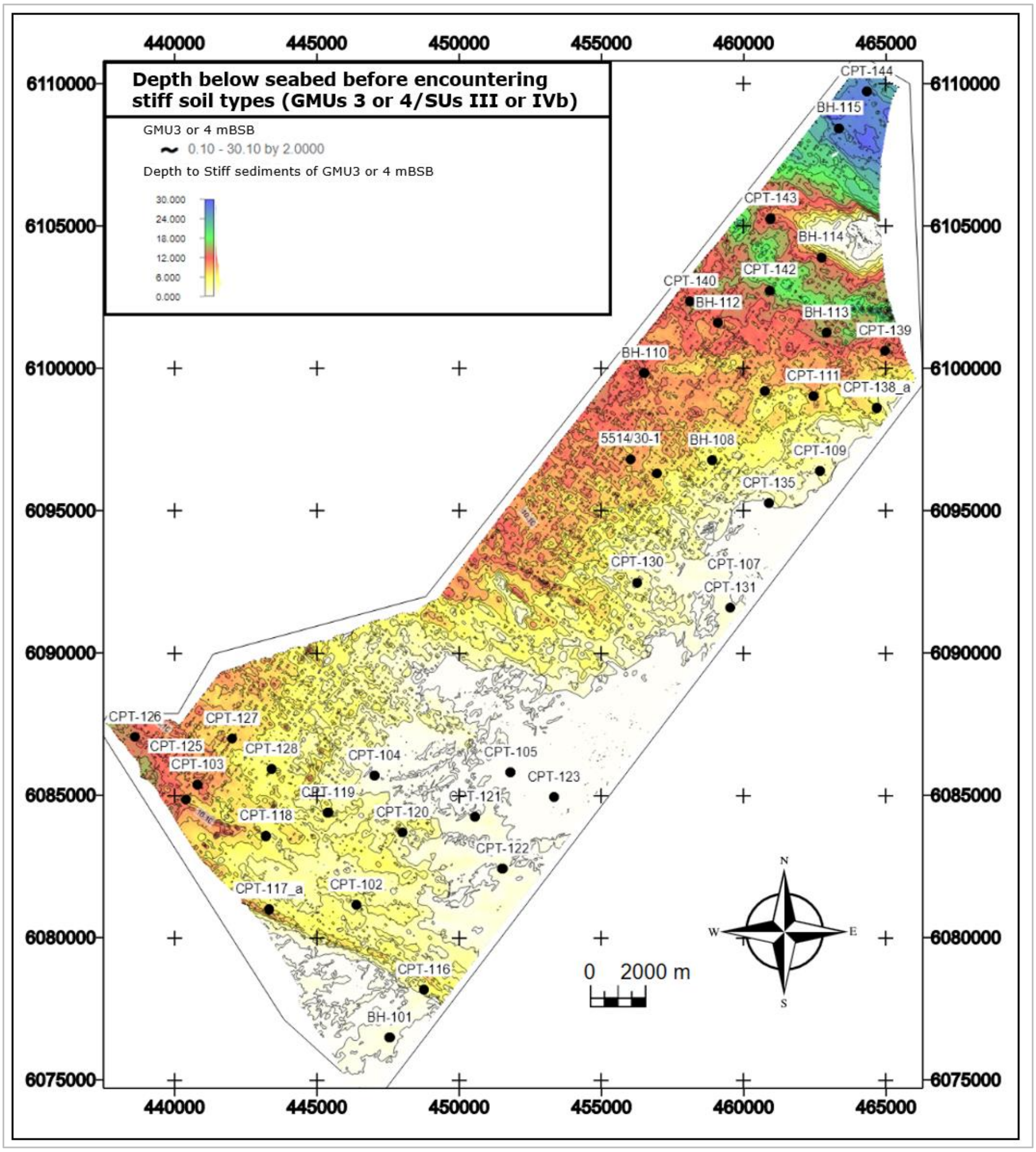


Figure 7-19. Depth below the seabed to the top of Seismic Unit 4 (GMU3 or 4). Note that there is a general increase in the depth of Unit 4 relative to the seabed in the West and North of the site.

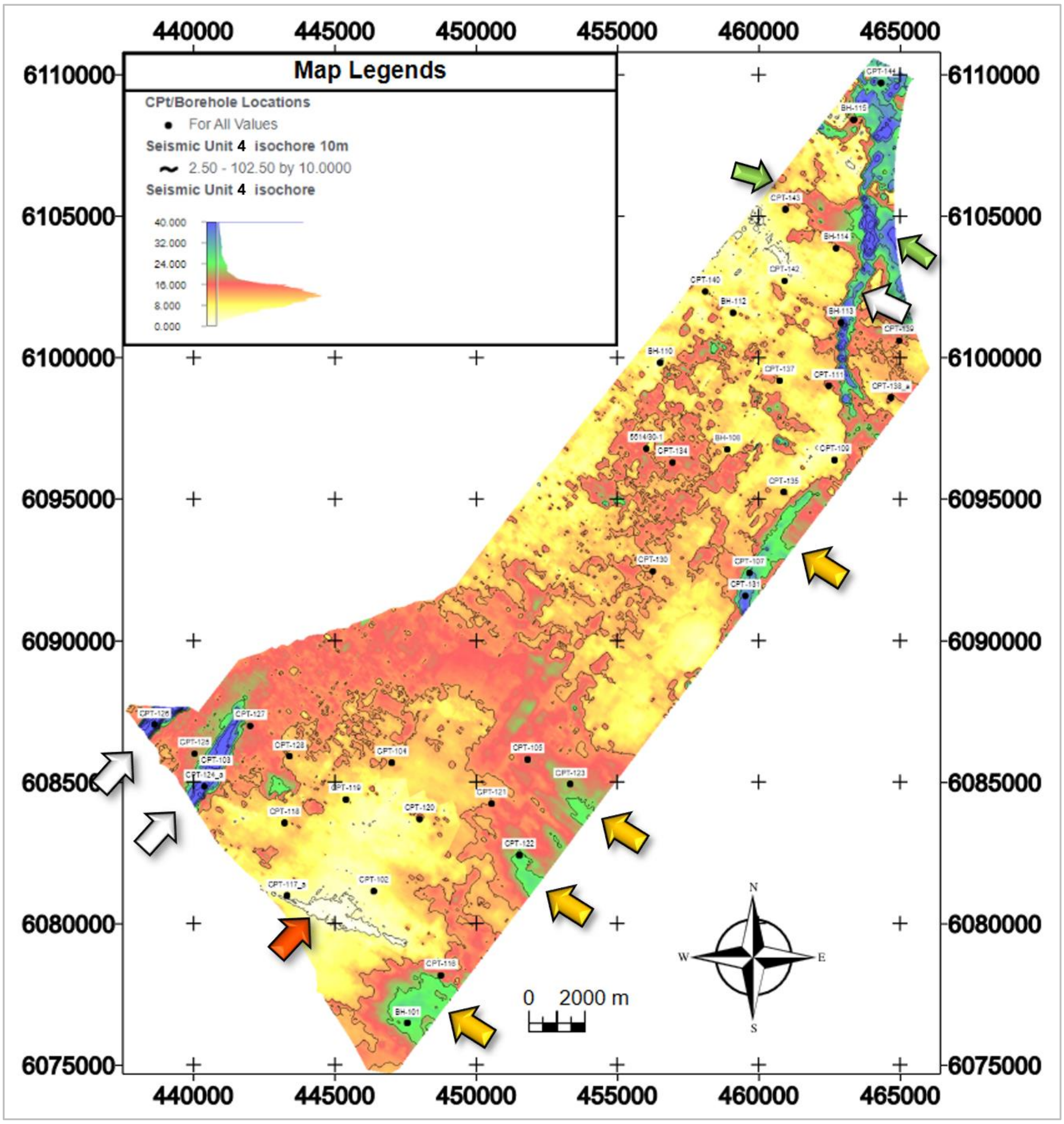


Figure 7-20. Map illustrating the thickness of Seismic Unit 4 across the Bornholm I Site. Unit 4 generally has a thickness of less than 15 m, with local thicks related either to the fringing sand systems (Subunit 4c – yellow arrows) or infilled palaeovalleys that have incised into the bedrock (white arrows). There is a distinctive ridge of Seismic Unit 4 sediments located in the northern part of the site; the ridge is thickest on the eastern side and gradually thins towards the northwest (green arrows). Seismic Unit 4 reaches its thinnest in the very south of the site (orange arrow) where there it is locally absent along a somewhat linear WNW to ESE trend that likely represents an erosional event that sits north a 'step' in the Seismic unit 4 sediments (see Figure 7-16 & Figure 7-17).

7.6.1 Seismic Unit 4a – glacial drift sediments (Tills and Moraines)

Subunit 4a defines the upper part of Unit 4 and it incorporates the very distinctive hummocky moraines that are characterised by strong sandy Clay soils (Soil Units III and IVb). It is interesting to note that many of the CPTs have reached their terminal depths at the top of this unit, with CPT operations having to be stopped short of the planned depths owing to the equipment reaching its maximum load or that the cone-tip had deflected to such a degree that the that the test had to be terminated.

7.6.1.1 Seismic Unit 4a Seismic Definition – H30 (H35)

The H30 Seismic Horizon defines the top of Seismic Unit 4. This Seismic Horizon was formerly named the H35 in the GEOxzy report (GEOxyz, 2022). It has been renamed to the H30 since it is probably one of the most important Seismic Horizons across the Bornholm I Site from a geotechnical perspective. H30 is a difficult Seismic Horizon to pick consistently. It attempts to map an extremely uneven surface that likely represents the top of a field of glacial moraines that were created during the retreat of the last glacial maxima (LGM) ice sheet. The H30 (H35) Seismic Horizon has generally been picked on a hard seismic event (an amplitude peak) but the seismic events are often laterally discontinuous. However, there is typically a package of three to four moderate- to high-amplitude couplets siting above the pick[5] and it is not uncommon for the pick to hop between different peaks. An effort has been made to place the H30 (H35) Seismic Horizon pick as the close to the contact between these moderate amplitude reflectors and the interval of more homogenous seismic character that sits below them.

The structural depth map for the H30 (H35) Seismic Horizon is displayed in Figure 7-21.

[5] The sediment interval represented by these moderate amplitude couplets are assigned to Seismic sub-unit 3c; see Section 7.5.6).

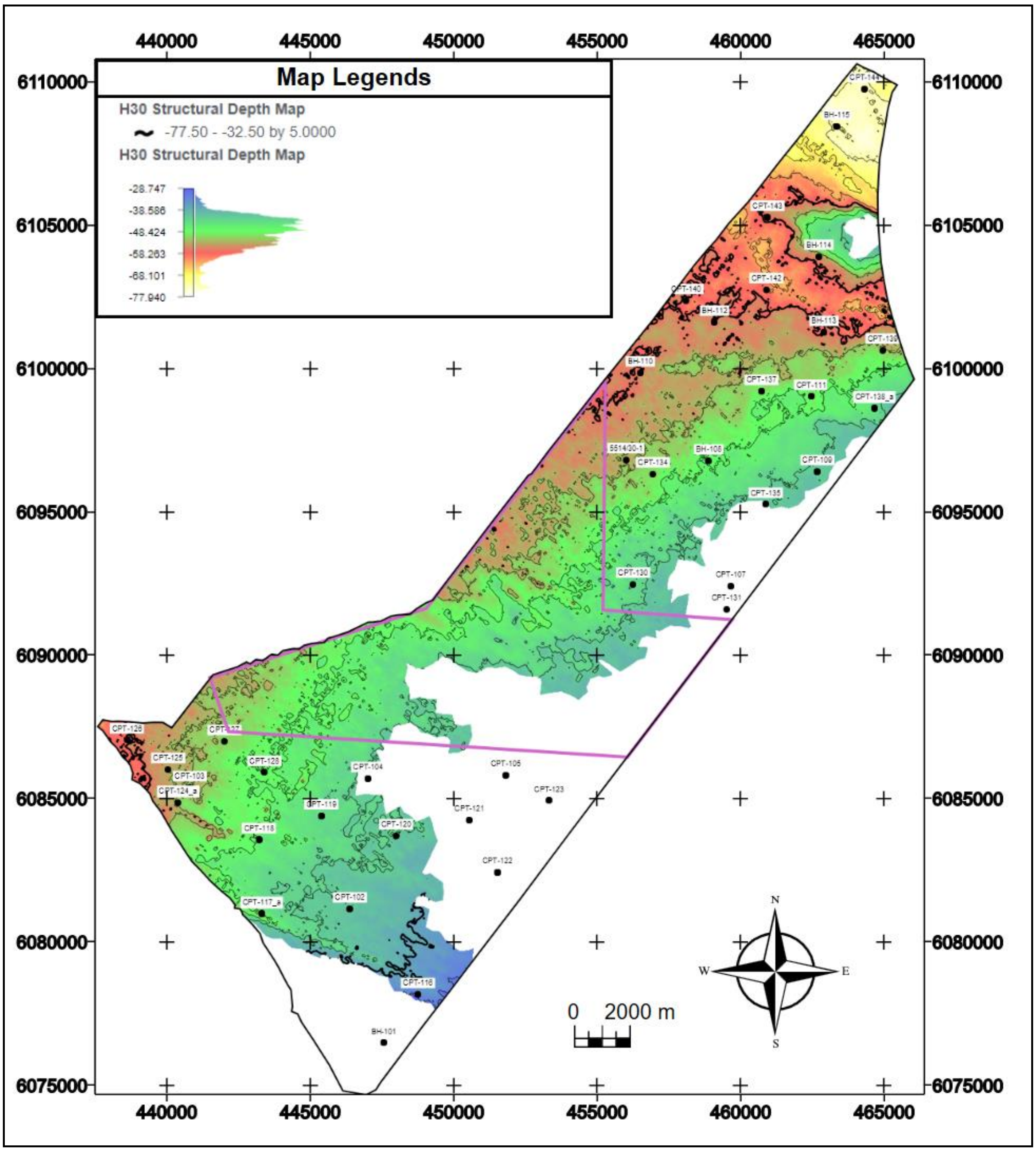


Figure 7-21. Structural depth map of the H30 (H35) surface created on the UHRS data. This surface marks the top of Seismic Unit 4. Depth is depicted in metres below Sea Level.

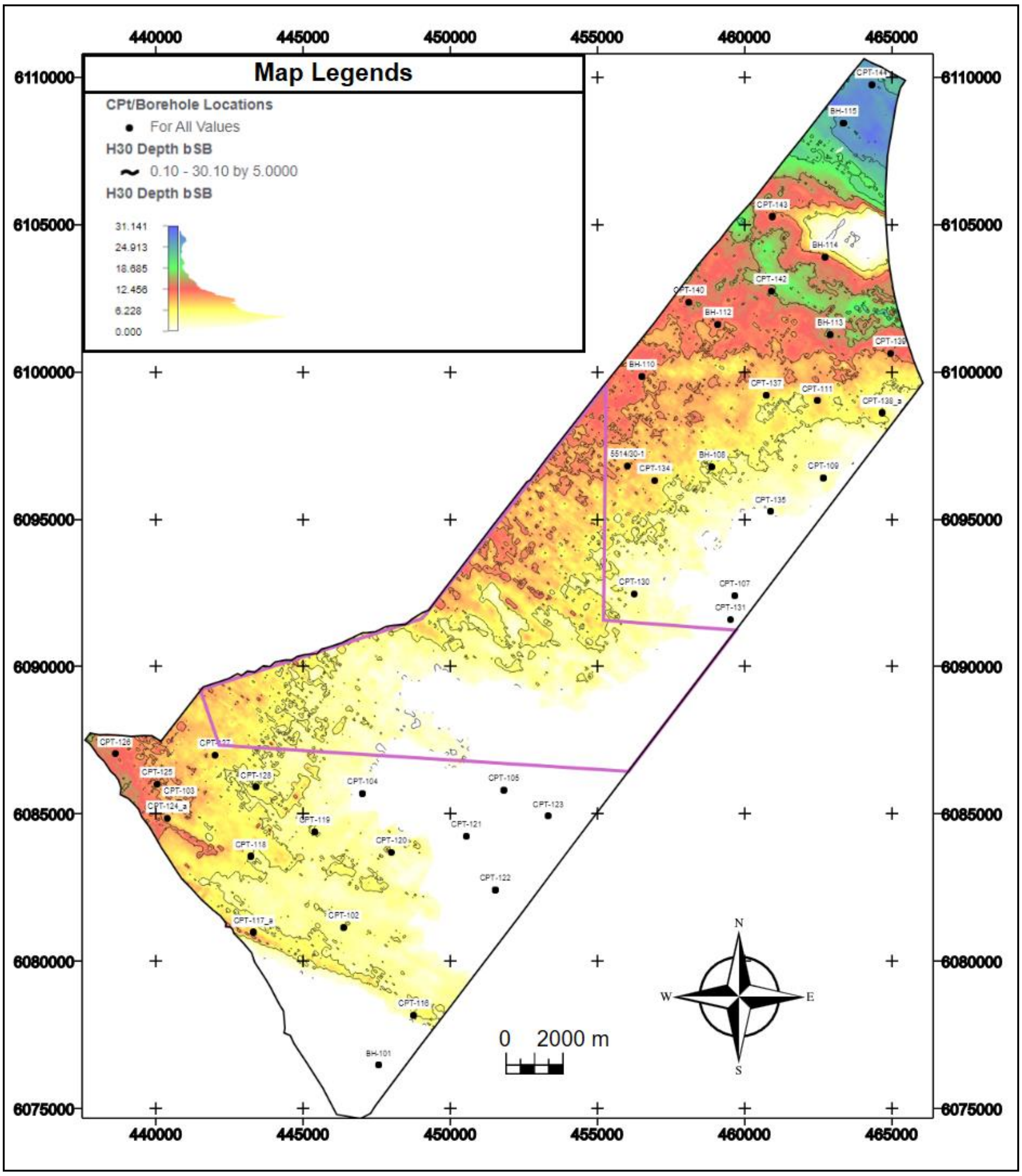


Figure 7-22. H30 (H35) Seismic Horizon depth below the seabed. Over a large part of the Bornholm I Site H30 has been truncated at or very close to the seabed. This is also the case for the bathymetric high in the north and the Seismic Unit 4 high at the south of the site.

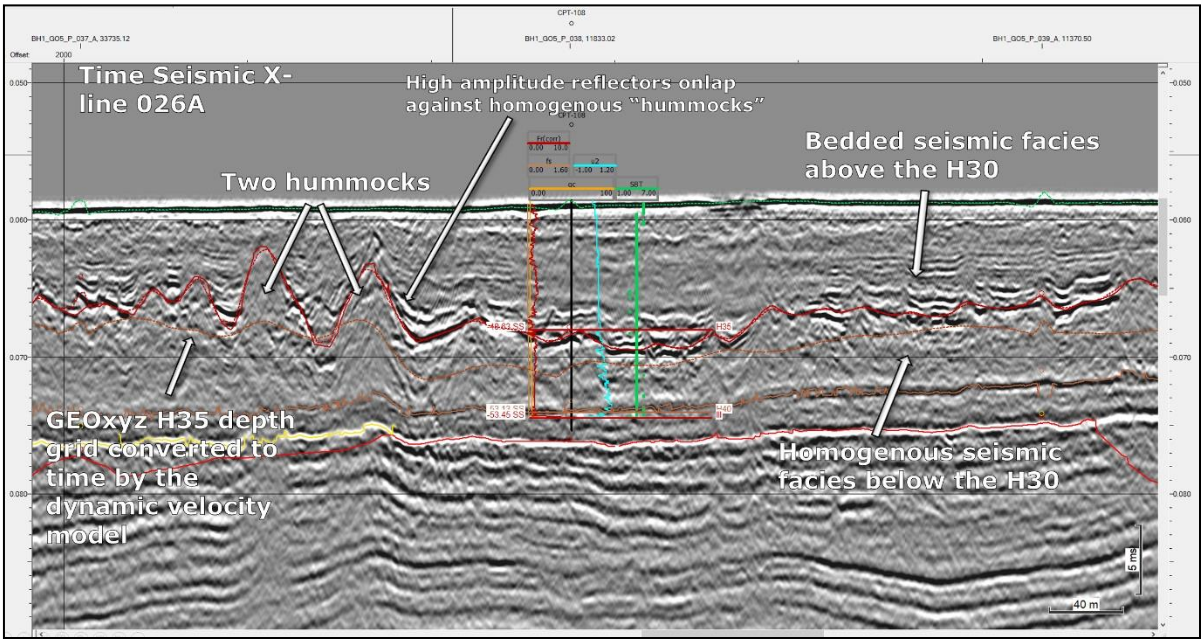


Figure 7-23. Snapshot of Seismic Line X-026A illustrating some of the seismic features that have guided the re-picking of the H30 (H35) Seismic Horizon around the locations from which ground data has been recovered (see text for discussion).

7.6.1.2 Seismic Unit 4a – Internal Seismic Character

Seismic Subunit 4a typically has a homogeneous, seismically transparent character with little in the way of structured seismic reflectivity (Figure 7-23), though it can have a 'pitted' appearance with numerous very short high to moderate amplitude events (see Figure 7-15 & Figure 7-23). In places there are internal reflectors that can dip at relatively high angles and which hint at extensive internal deformation.

7.6.1.3 Seismic Unit 4a – Sedimentology and Geotechnical Characteristics

Seismic subunit 4a sediments are characterised by very stiff clays to silty clays with thin layers/lenses of sand (essentially Geotechnical Soil Units III or IVb). It is possible that there are larger rock fragments, gravels, pebbles, cobbles and/or even boulders associated with the upper part of this depositional unit. As mentioned above many of the CPTs reached their terminal depth at, or very close to, the top of Seismic Unit 4 where they might have encountered coarser debris. The top of this unit is extremely uneven being characterised by a series of hummocks that are both draped, and onlapped by the Seismic Subunit 3c sediment package.

Given the present spacing of the 2D UHR seismic the true three-dimensional geometry of the hummocks remains uncertain. If they form ridges their orientation again remains unclear, with the only hints being provided by a dip-map that was created for H30 (H35) grid (see Figure 11-10) were curvilinear features trending broadly NW to SE can be picked up as intervals of slightly higher dip. Other than the dip map, the only possible hint of their potential geometry comes from the seabed relief developed across the bathymetric high that is present at in the northern part of the site (see Section 5.1 and Figure 5-3) where Seismic Unit 4 is mapped to the seabed. Even here it is not given that the lobate ridges and the hummocky topography mapped at the top of Unit IVa are actually the same features that are seen in cross section on the 2D seismic, even if they do sit at approximately the same stratigraphic level. Though it is notable that they do follow the general NW to SE trend identified in the dip map that has been gridded from widely spaced 2D seismic lines.

7.6.1.4 Seismic Unit 4a – Depositional setting

Seismic Subunit 4a has clearly been influenced by ice. Its sediments are considered to have been deposited as glacial drift; either as a till or as moraine. Two hypotheses are considered for the creation of the 'hummocks' that define the unit top. The irregular topography of horizon H30 is clearly related to the final retreat of the LGM ice sheet as it forms the surface onto which the younger Baltic lake-sediments accumulated. The first hypothesis draws on studies of landforms that have been created from retreating glaciers. Here hummocky moraines develop during periodic advances in the overall retreating ice. These temporary ice front advances result in the development of 'ice-front thrusts' that lift sediment up into the ice sheet as 'sediment thrust sheets' as well as bulldozing previously deposited tills and moraine into ridges. Subsequent melting and retreat of the ice front releases entrained sheets of sediment from the ice resulting in the development of irregular hummocky moraine fields (Hambrey, 1997).

An alternative hypothesis is that the hummocks formed from the melting of stagnant ice that had been partly buried by supraglacial stream sediments or even ice front lake deposits. Ice in such a setting tends to melt along zones (fractures) of weakness or in point locations (i.e. under a boulder) forming fissures and cones in the top of the ice that are then filled by sediment. Melting of the stagnant ice results in an 'inversion' of the former sediment filled fissures or cones creating an 'inverted' hummocky landscape (Clayton L., 2008).

In conclusion Seismic subunit 4a is considered to have been deposited during the Last Glacial Maximum both as a subglacial till during the ice sheet advance and as moraines during its subsequent retreat.

7.6.2 Seismic Subunit 4b – fine grained sediment fans

Seismic Subunit 4b is defined by the H40 Seismic Horizon at its top and either the H45 Seismic Horizon or the H50 Bedrock Seismic Horizon at its base. The key feature about the sedimentary systems defined by the top of the H40 Seismic Horizon is that they have fan or lobate shapes where the H40 Seismic Horizon typically has a convex-up geometry with it terminating (down-lapping) onto the bedrock surface (Figure 7-25).

Those few CPTs and Boreholes that penetrate Seismic Subunit 4b show it to be dominated by fine-grained sediments, predominantly very stiff clays to silts that have been assigned to geotechnical Soil Unit IVb. In the Ground Model the H40 Seismic Horizon has been used to help sub-divide Soil Units III and IVb (see Chapter 10).

7.6.2.1 Seismic Subunit 4b – Seismic Definition (H40 Seismic Horizon)

H40 is mapped on an amplitude peak (hard seismic event) though the strength of the amplitude can vary dramatically and in many areas, it is a weak event. Figure 7-24 illustrates the distribution of the H40 Seismic Horizon across the Bornholm I Site. It was decided not to incorporate the H40 Seismic Horizon in the Velocity model since the geotechnical properties of the sediments above and below it is often very similar.

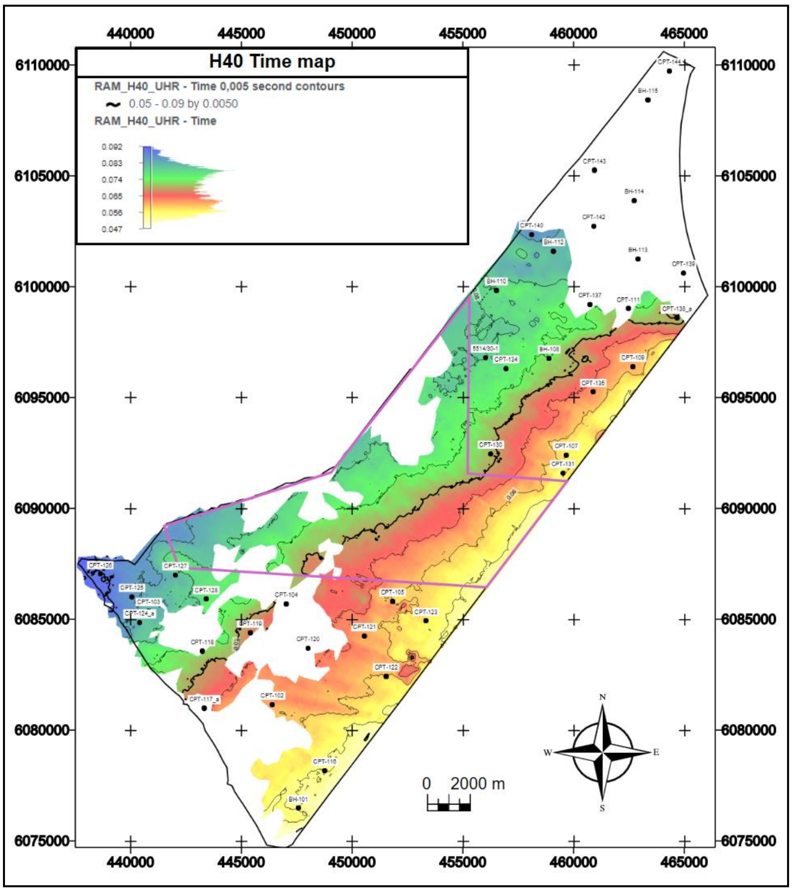


Figure 7-24. Time map of the H40 Seismic Horizon that defines the top of Unit 4b. Note that the distribution is similar to the Subunit 4c sand systems but extends further to the west.

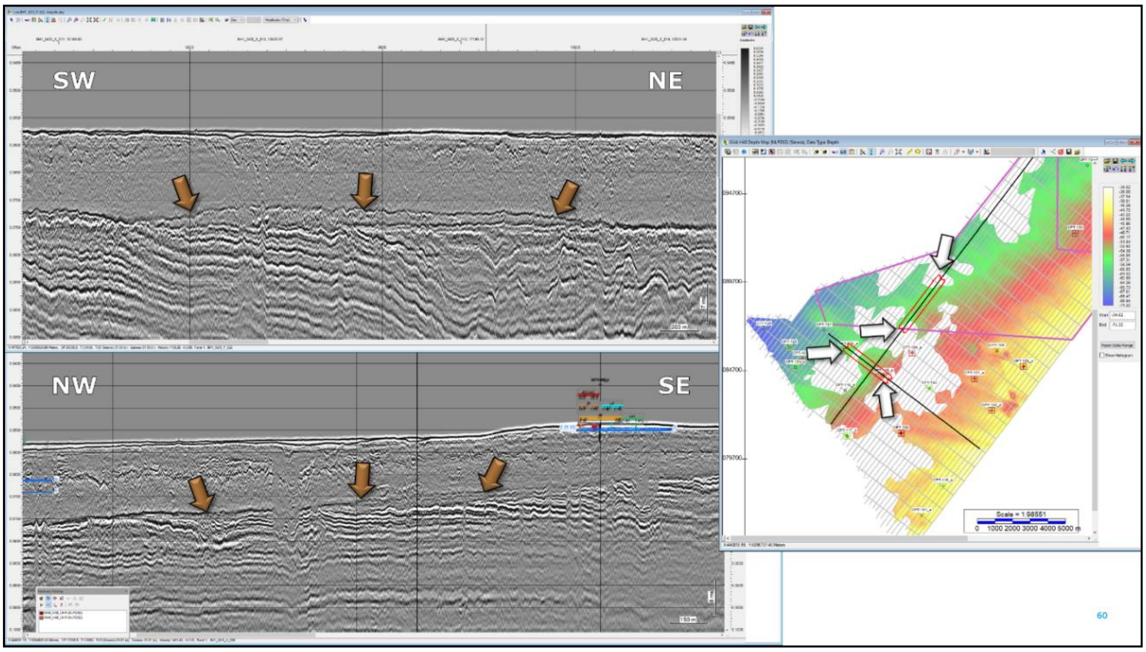


Figure 7-25. Seismic image of the distal H40 fans showing how they typically form lobate, convex upward sediment bodies that directly overlie the bedrock. Local preservation of internal bedding suggests deposition from current or gravity flows. Inset map shows the location of the seismic in-line (top image) and x-line (lower image) and the distribution of the H40 through the area.

7.6.2.2 Internal Seismic Character

Over most of the site Seismic Unit 4b is thin but it often contains weak, faint parallel reflectors indicative of internal bedding. These reflectors tend to be parallel to the upper H40 Seismic Horizon and they also display downlap geometries onto the bedrock (Figure 7-25 & Figure 7-26).

7.6.2.3 Sedimentology and Geotechnical Characteristics

The lobate, fan-shaped geometries defined by the H40 Seismic Horizon, together with thin internal bedding and downlapping internal seismic reflectors suggest deposition occurred in a sediment fan. The preponderance of clay sediment indicates a distal position on the fan(s). Geotechnically the clays are classified as being very stiff and strong sandy clay (Geotechnical Soil Unit IVb).

7.6.2.4 Seismic Subunit 4b – Depositional setting

The gross geometry of Subunit 4b with its convex-up upper surface and downlapping character indicate that it was deposited in a sedimentary fan. Since it can be traced into the sand-systems of Seismic Subunit 4c it likely forms the distal part of a delta that fed into an ice front glacier lake or even into a marine setting. Alternatively, the sediments may have been deposited from sediment plumes issuing from subglacial streams, in either case that are considered to have been deposited into a standing waterbody.

7.6.3 Seismic Subunit 4c – sand fan systems and palaeovalley fills

Seismic Subunit 4c is defined at its top by the H45 Seismic Horizon whilst its base is the Bedrock. CPTs and Boreholes indicate that the soft seismic event that defines its top corresponds to the top of an interval of dense sand that corresponds to the Geotechnical Soil Unit IVa.

Two separate systems have been mapped by the H45 Seismic Horizon (Figure 7-30). South of the bathymetric high the Seismic Subunit 4c sands are primarily developed along the eastern side of the Bornholm I Site. Here the H45 Seismic Horizon defines a wedge of westwards thinning sediment that has infilled topography on the bedrock (Figure 7-26 & Figure 7-27). North of the wedge-shaped sand-rich packages the H45 Seismic Horizon has largely been mapped at the top of a succession of sediment that fills palaeovalleys that have carved into the bedrock (Figure 7-31). Here the sands of Unit 4c are more confined valley fills and there is no geometric evidence that the sands formed depositional wedges. However, some caution is warranted since there appears to have been extensive glacio-tectonic deformation of the Seismic Unit 4 sediments in the northern part of the Bornholm I Site, and it is possible that former Unit 4c sand-wedges might have been 'deformed' to create the ridge of sediment that has created the bathymetric high that is evident today.

7.6.3.1 Seismic Subunit 4c – Seismic definition (H45 Seismic Horizon)

The H45 Seismic Horizon has been picked on an amplitude through (soft seismic event) that is locally developed below the H40 Seismic Horizon (see Figure 7-26 to Figure 7-28). Every attempt has been made to pick the H45 Seismic Horizon on the strongest soft event even though there might actually be several soft events present below the H40 Seismic Horizon; the multiple soft events may even merge (see Figure 7-27).

A structural depth map for the H45 Seismic Horizon is presented in Figure 7-29 and its thickness is illustrated in Figure 7-30.

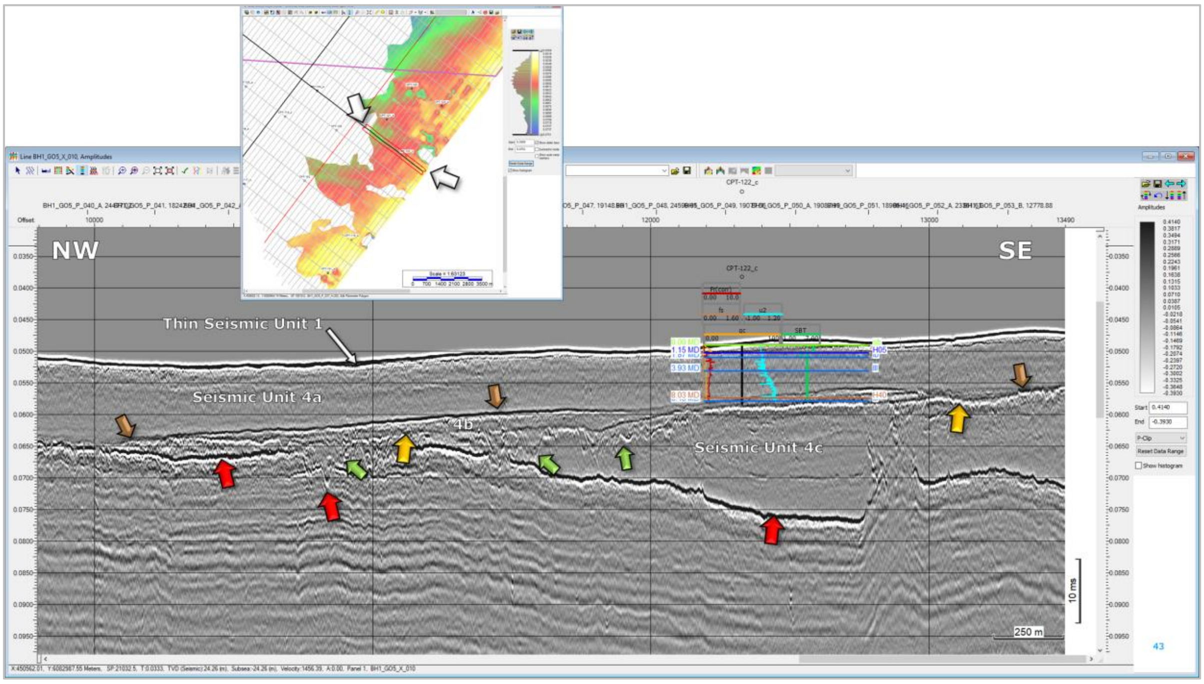


Figure 7-26. Seismic X-line G05_X_010 showing a cross-section through the southernmost sedimentary fan that is defined by the hard (peak) H40 Seismic Horizon at its top (brown arrows). Below this peak there is a strong soft event (H45 Seismic Horizon – yellow arrow) that marks the top of the sand-rich Seismic Sub-Unit 4c. Note that there are several small V-shaped incisions into this sand wedge (green arrows). Inset illustrates the position of the Seismic X-line and shows a time map of the distribution of the H45 Seismic Horizon.

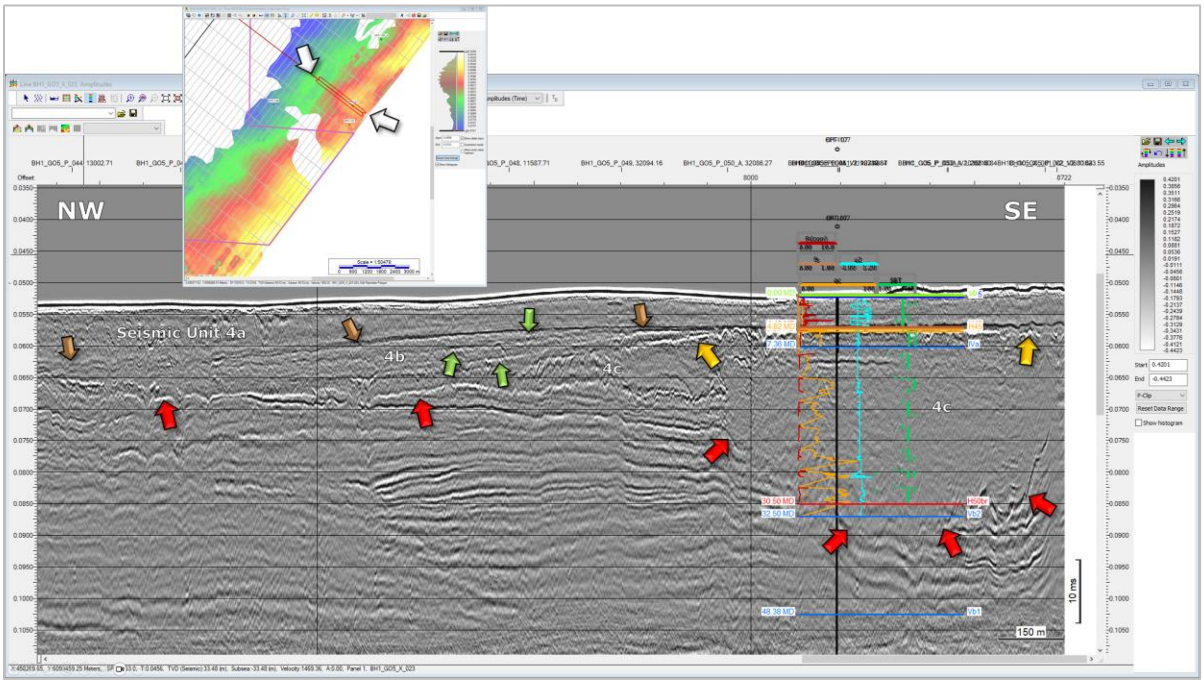


Figure 7-27. Seismic X-line G05_X_010 located north of the exclusion zone in the Bornholm I Site. This cross line illustrates a second fan/delta system that displays a similar geometry to that illustrated in Figure 7-26. The sand system has been penetrated by BH-107. The top of the fan is defined by the H40 Seismic Horizon (brown arrows) which downlaps onto the bedrock (red arrows). The bright soft seismic event (trough) denoted by the yellow arrows marks the top of the H45 Seismic Horizon. This seismic reflector marks the top of the Seismic Subunit 4c sands that are penetrated by both CPT-105 and BH-105. BH-107 recovered a thick interval of sand above the chalk bedrock.

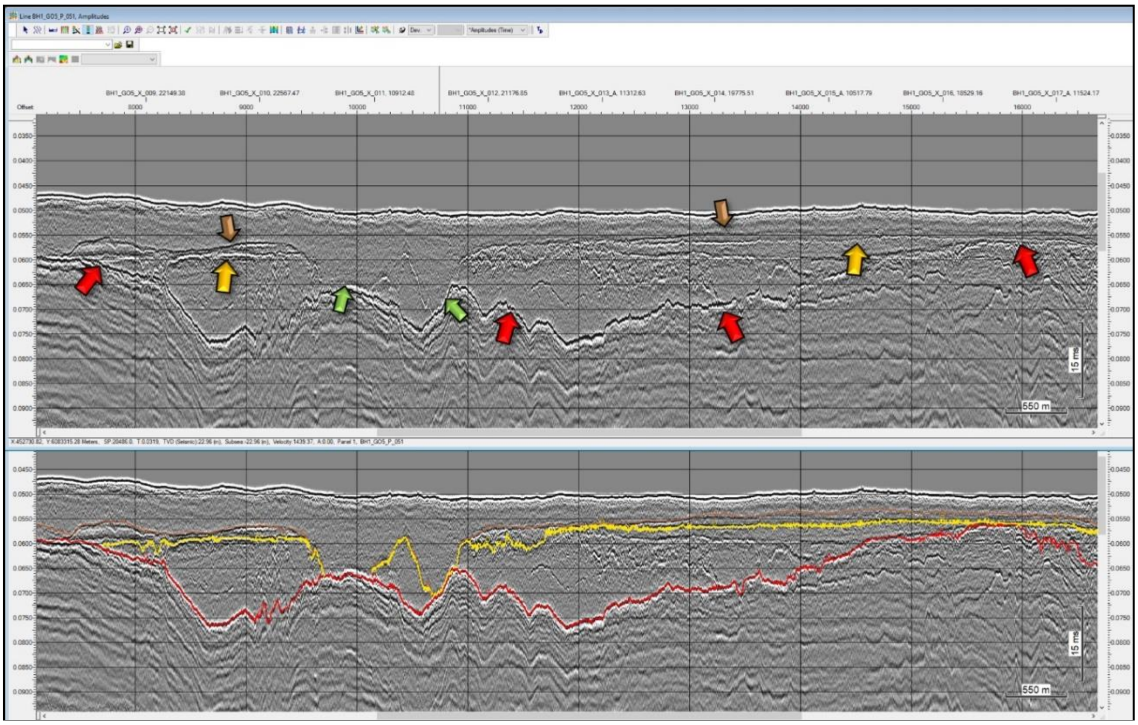


Figure 7-28. Seismic in line G05_P_051-illustrating how the H45 sand system sits in a topographic low with the bedrock (red arrows & Seismic Horizon). The top of the fan/delta system is marked by the hard seismic event that is mapped by the H40 Seismic Horizon (brown arrows & Seismic Horizon) while the top of the sands is defined by a strong soft seismic event (yellow arrows & Seismic Horizon). Note the thinning of the sand package caused by incision (green arrows).

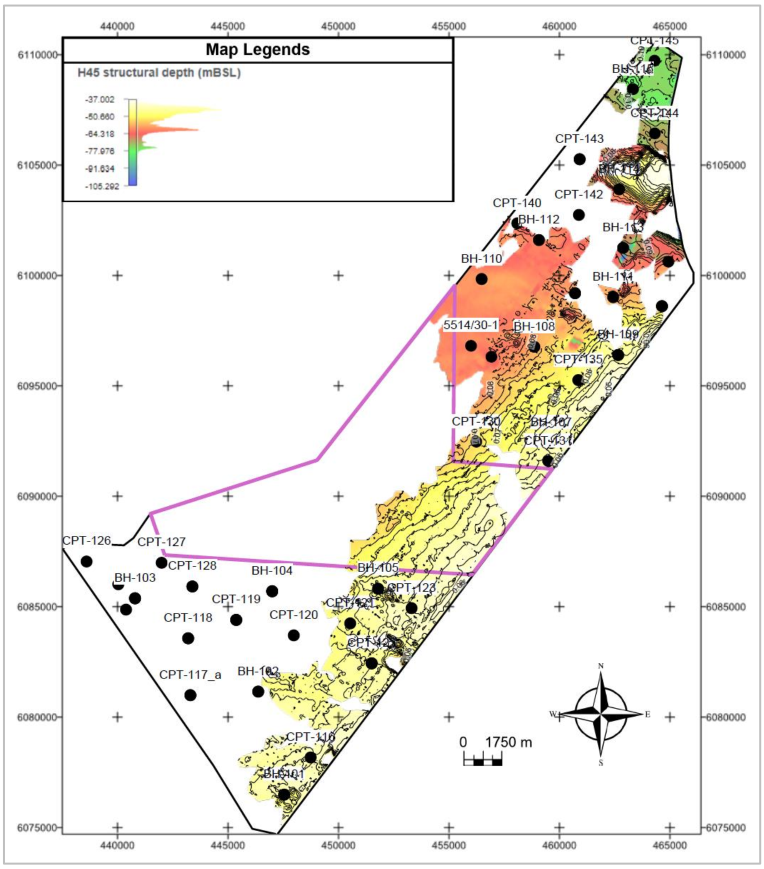


Figure 7-29. H45 structural depth map.

7.6.3.2 Seismic Subunit 4c – Sedimentology and Geotechnical Characteristics

There is little in the way of coherent internal seismic reflectivity in the Subunit 4c sands. There are often multiple soft seismic events that can be relatively uneven suggesting several potential erosive events have affected the sand units, with some lines showing clear incision and the development of V-shaped erosion events (see Figure 7-26 to Figure 7-28).

Geotechnically these the sediments are predominantly dense sand that have been assigned to the Geotechnical Soil Group IVa. Some intervals of strong sandy clay (Soil Unit IVb) may be intercalated with the sands, particularly towards the base of the successions.

7.6.3.3 Seismic Subunit 4c – Depositional setting

The geometries of Seismic Subunit 4c are consistent with deposition of the sands into a standing body of water with a deltaic setting the most likely. Several lobes are present along the eastern side of the Bornholm I Site each being associated with a local topographic low in the Bedrock. The sand lobes are not extensive, and sediment is considered to have been locally sourced. The sands and associated finer sediments of Seismic subunit 4b downlap onto the bed rock towards the west of the H45 reflector (Figure 7-26 & Figure 7-27). This 'fining' of the depositional system suggests local sourcing of sediment from the east. Incisions into the relatively flat-topped sand-systems indicate a complex depositional history that includes periodic erosion of the sands. Erosion of the bedrock high, the 'Arnager Block' (see Figure 5-7) that corresponds to the modern day 'Adler Grond – Rønne Banke' bathymetric high is perhaps the most likely source, though streams issuing from under an ice-sheet partly grounded on this bedrock high cannot be ruled out.

Several incisions can be mapped into the sand lobes indicating that a fall in the base-level of the water body into which it was deposited allowed incision into the previously deposited sand system (see Figure 7-26 to Figure 7-28) creating V-shaped erosion features. These features hint at a relatively complex depositional history for these sands. It is likely that the sands were deposited during an interglacial episode, prior to the LGM.

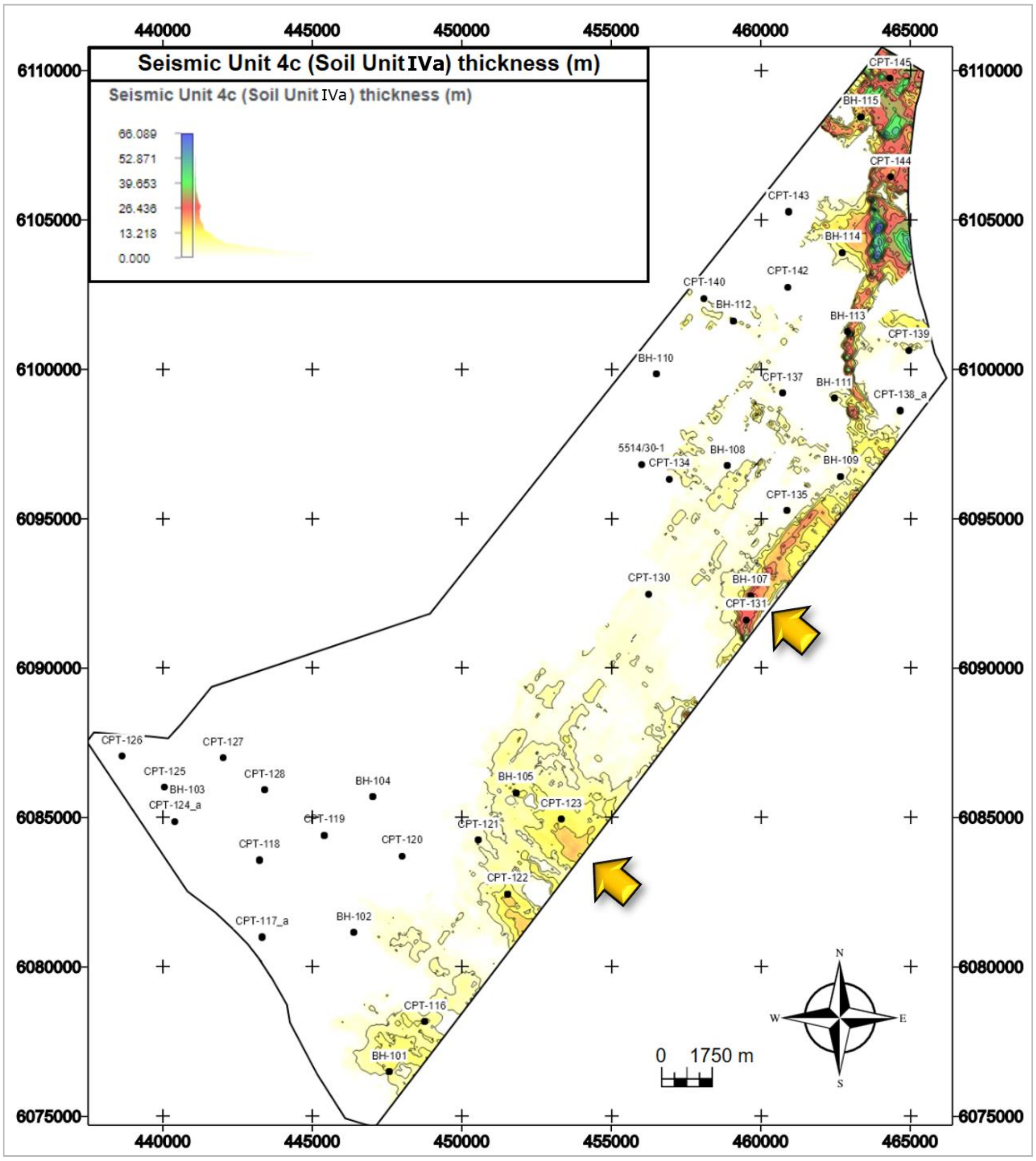


Figure 7-30. Isochore map of Unit 4c. The yellow arrows outline the two distinct sand fan-systems that have been captured in the seismic x-lines portrayed in Figure 7-26 to *Figure 7-28.*

7.6.4 Seismic Unit 4 – bedrock valley fills

Several deep valleys carved into the bedrock are mapped in the Bornholm I Site (Figure 7-31). Three of the boreholes have penetrated the sediments that plug the valleys. BH-103 recovered a thick succession of silty to sandy clay till (Soil Unit VIb) from one of the two potential tunnel valleys that have been mapped in the southwest of the Bornholm I Site (Figure 7-31). Occasional beds/lens of sand where also reported from the valley fill that BH-103 penetrated but otherwise the valley appears to have been plugged by relatively fine-grained sediment.

BH-107 and BH-113 penetrated bedrock palaeovalleys in the western part of the Bornholm I Site. Here both boreholes retrieved cores of sand (Geotechnical Soil Unit IVa) with only BH-107 encountering bedrock (Figure 7-27), in this case chalk. The sands encountered in these eastern valleys have been incorporated into Seismic Unit 4c in terms of the velocity model.

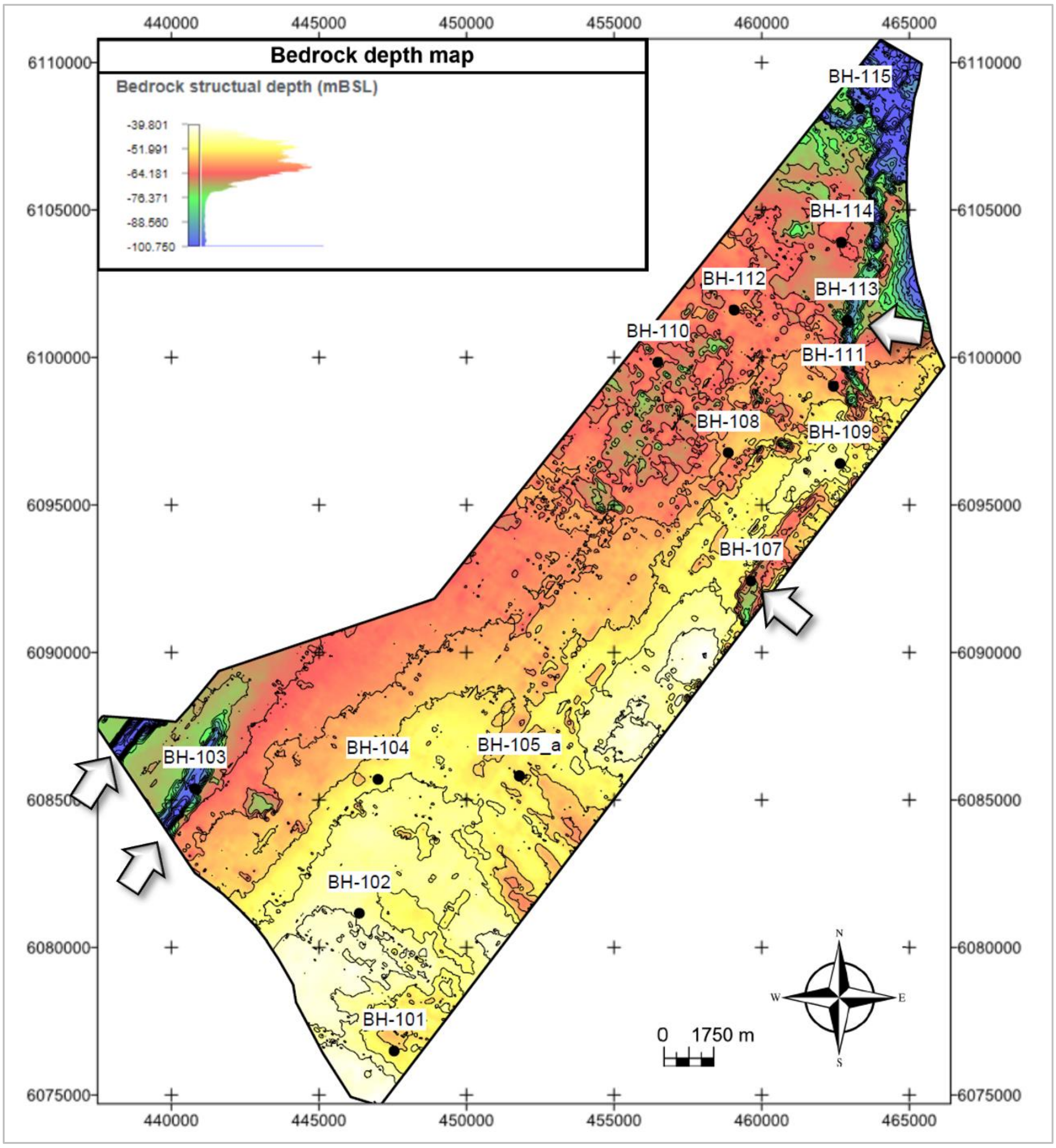


Figure 7-31. Structural map of the bed rock illustrating the prominent palaeovalleys that have been mapped. BH-103 penetrated the valley in the Southwest part of the site and encountered a thick unit of sandy-clay (Geotechnical Soil Unit IVb) whereas boreholes in the north and east drilled into palaeovalleys (BH-107 & BH-113) encountered thick sand fills (Geotechnical Unit IVa).

7.6.5 Seismic Unit 4 ridges

There are two distinct ridges developed within Seismic Unit 4. The first and most pronounced is present in the northern part Bornholm I. The second is a linear feature in the far south with only the northern side being imaged on the Bornholm I seismic dataset. It is not known if this is a true ridge *per se* since the southern margin is not imaged, though it certainly forms a distinctive bench (see Figure 7-16 & Figure 7-17) that has partly controlled the sediments in Seismic Unit 3 (see the discussion in Section 7.5.8 above).

North Ridge

This feature is responsible for the bathymetric high that was discussed in Section 5.1 and it is depicted in Figure 5-1 and Figure 7-36. Drill-core from the flank of the high in borehole BH-114 recovered an 8.73 m thick succession of chalk from an interval that corresponds to the flank of the ridge. On first impression, the presence of chalk would support an interpretation of this feature being a bed-rock high. The chalk was recovered from an interval with level bedded seismic reflectivity that sits almost directly on folded bedrock (see Figure 7-32 & Figure 7-33). If the chalk is in situ, it must represent an outlier of Upper Cretaceous sediment sitting above folded strata of probable Lower Jurassic age. Unfortunately, there is no ground information from the centre of the ridge that can confirm the presence of bedrock at very shallow depths, though a borehole does exist on a similar feature in Bornholm II (BH-220, see discussion below) and no bedrock was encountered before BH-220 reached its terminal depth at 62.5 m below the seabed. Even though the Bornholm I ridge is somewhat poorly imaged on seismic the visible geometries do not have a bedrock character.

Cross-sections through the North ridge show that it has an asymmetrical character with dips along the northern edge being steeper than those along the southern margin (Figure 7-36). The clear asymmetry decreases to the northwest as the ridge thins (compare Figure 7-36 with Figure 7-37). Internal imaging of the ridge is variable and can be very poor. However, in places there is clear evidence of internal deformation with folded strata imaged (Figure 7-35). These folds are clearly disharmonic to the underlying folded bedrock and are at a completely different scale. There must have been a dislocation plane close to the bedrock–sediment interface with the sediments of Seismic Unit 4 having been translocated from north to south. The ridge appears to have partly formed through this deformation, folding of the sediments structurally thickening the unit and at least partly developing its topography. How then does the chalk interval recovered from BH-114 (Figure 7-32 & Figure 7-33) fit with the observations of internal deformation? It hypothesised that the chalk core was recovered from a large glacial raft that was incorporated into the front of what is most likely a large moraine ridge. Geotechnical analysis of the chalk in Borehole BH-114 indicates that it has a severely damaged character that would be consistent with glacial re-working. From a seismic perspective the chalk has been recovered from an interval that has parallel reflection pattern. However, the bedded reflectors can only be traced laterally for a relatively short distance (Figure 7-32) before all visual indication of bedding and reflector coherency is lost. These observations are consistent with the chalk core in BH-114 having been recovered from a reworked raft of semi-coherent bedrock.

Interestingly, a similar bathymetric high, associated with sediments considered to be time-equivalent to Seismic Unit 4 in the Bornholm I Site, is developed in the northern part of the Bornholm II site (Figure 7-34). Whilst no borehole has penetrated the centre of the ridge-like Seismic Unit 4 thick in Bornholm I, the bathymetric ridge in Bornholm II was penetrated by Borehole BH-220. With the exception of a few thin layers of clay close to the seafloor, BH-220 recovered a succession of dense to very dense sands (Geotechnical Soil Unit IVa) to a depth of 62.5 m. It is interesting to speculate that these two ridges, both developed in northern part of their respective sites might have a common origin. Both developed sufficient topography for them to still have an impact on the modern-day bathymetry. Both the Bornholm I and Bornholm II ridges are aligned somewhat oblique to the basement high that separates the two sites (Figure 7-34) and together they lie on a NW to SE trend.

In conclusion, the ridge present in Seismic Unit 4 sediment of Bornholm I and that noted in Bornholm II most likely developed through a glacial advance that was sufficient to bulldoze and deform previously deposited sediments, likely sand-dominated sediments, to create a large-scale, ridge-shaped moraines.

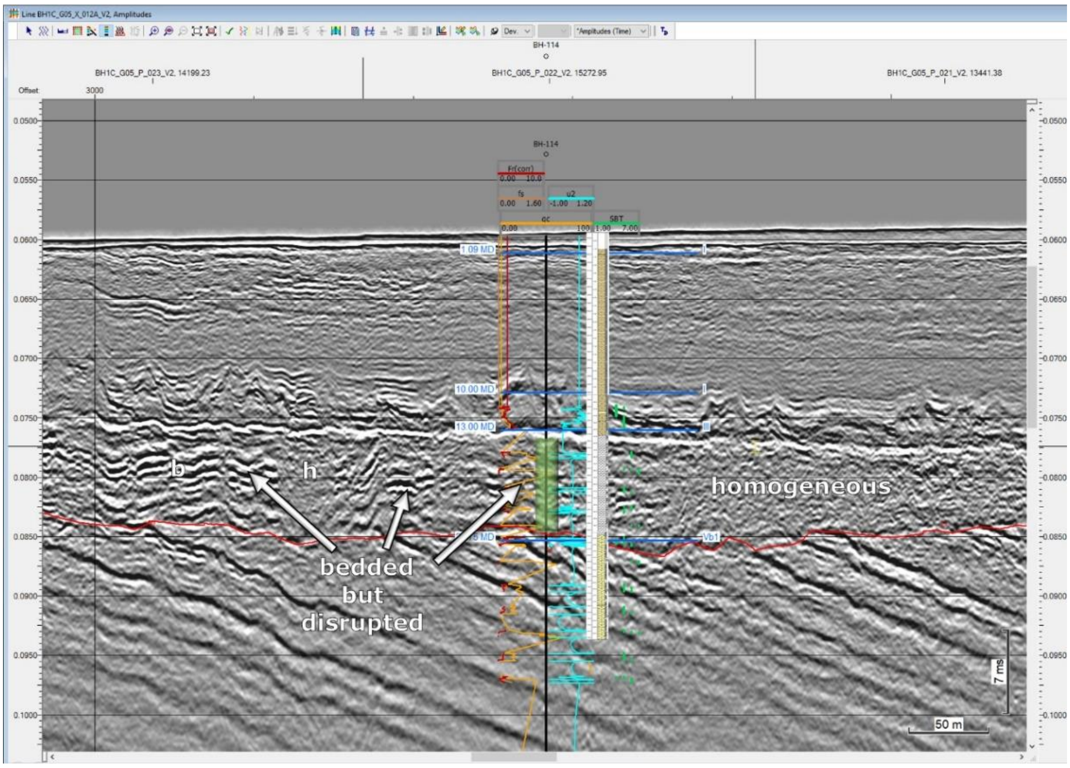


Figure 7-32. Illustration of the BH-114 borehole as it intersects the G05_X_012A_V2 Seismic X-line. The green flag illustrates where damaged chalk has been recovered in cores. Note that the borehole has penetrated a somewhat chaotic interval on the flank of the Seismic Unit 4 ridge that comprises disrupted bedded reflectors (b) that pass laterally into strata with homogenous seismic facies (h).

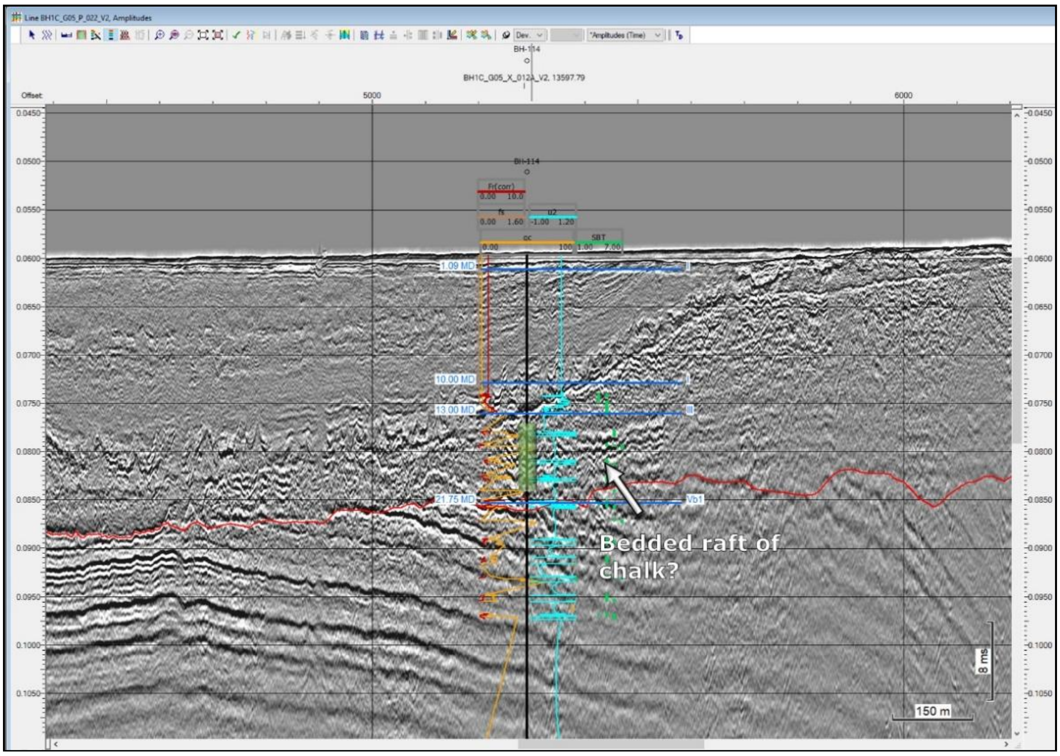


Figure 7-33. Borehole BH-114 located on the flank of the Unit IV Ridge; the green flag indicates where damaged chalk was penetrated. The chalk was recovered from a bedded interval (green flag) that has somewhat limited lateral extent; it is believed to be a raft of chalk.

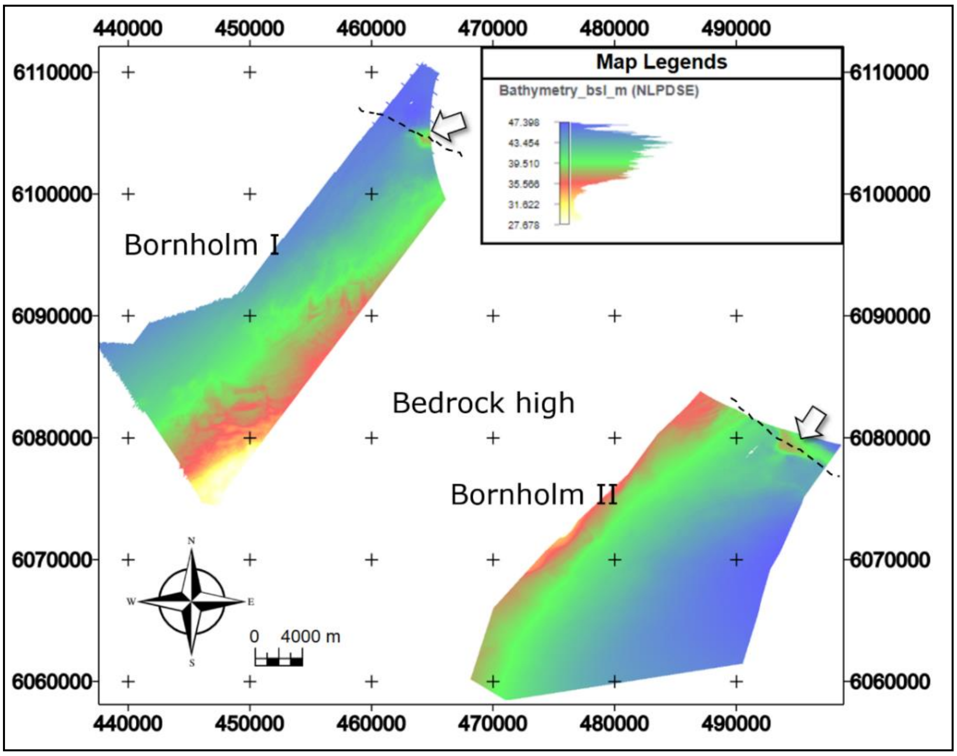


Figure 7-34. Bathymetry maps of Bornholm I and II illustrating the respective positions of bathymetric highs. These highs have a similar character and are aligned in NW to SE of each other. In both cases the highs are the result of pronounced thicks in Seismic Unit 4, although the bathymetric high in Bornholm II has been modified through the deposition of a wedge of likely Holocene sediments along its southern margin. Approximate trends to the Seismic Unit 4 ridges have been added to the map.

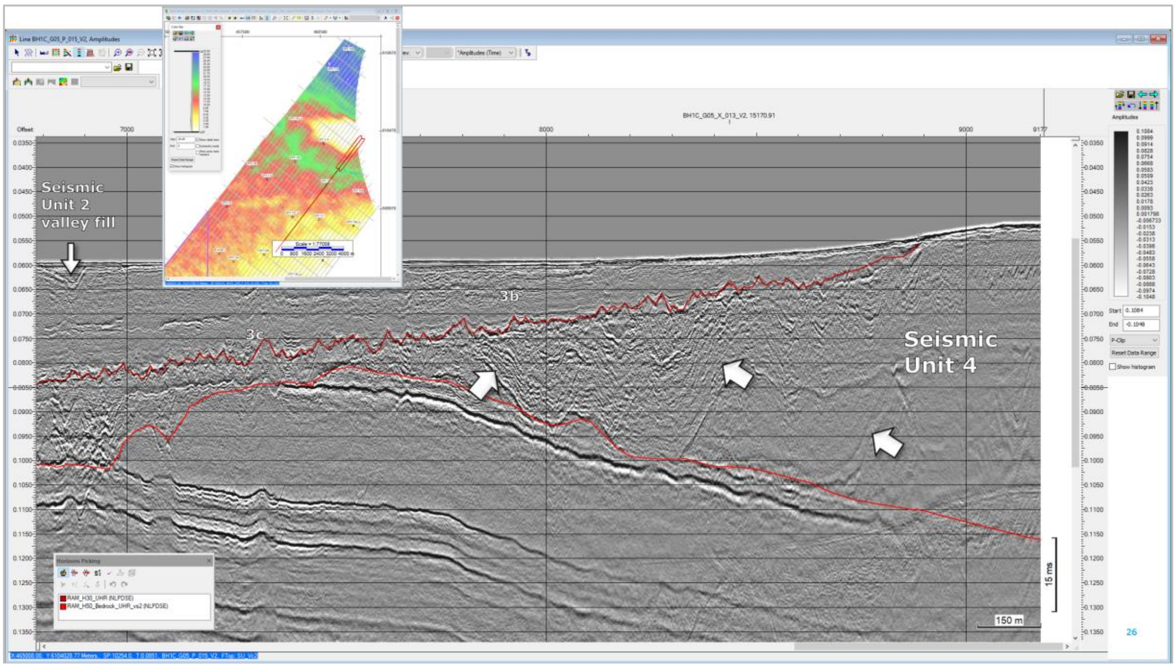


Figure 7-35. Cross-section through the Unit 4 thick on the northern part of Bornholm I illustrate internally deformed strata (white arrows). Note how image quality decreases into the ridge. Seismic in-Line G05_P_015_V2. Inset map displays the combined thickness of Seismic Units to 3 and illustrates clearly how topography across the Unit 4 ridge has affected the preserved thickness of these younger units.

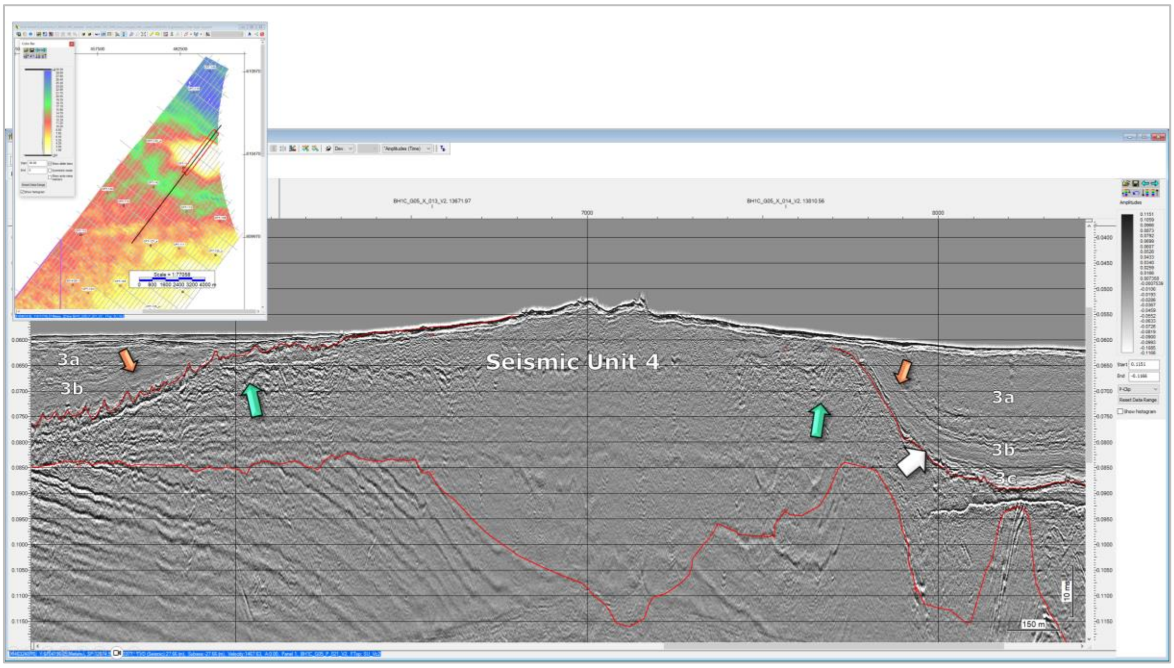


Figure 7-36. In-Line G05_P_021_V2 that crosses through the ridge of Seismic Unit 4 sediment developed in the northern part of the Bornholm I Site. The seismic has been exaggerated in the vertical to emphasise the asymmetry of the ridge, which has a steeper northern margin (right-hand side). The earliest Seismic Unit 3 sediments (subunit 3c) onlap the flanks of the high (white arrow) whereas Seismic Subunit 3b sediments thin and drape the structure (orange arrows), though they appear to have been planned off just below the seabed. The irregular topography developed at the seabed over the crest of the ridge can be viewed on the bathymetry map displayed in Figure 5-1. There is some evidence of internal deformation within the ridge (green arrows) with the presence of contorted bedding but imaging of the inner part of the ridge is not especially good. Location map displays the combined thickness of Seismic Units 1 to 3 and illustrates clearly how topography across the Unit 4 ridge has affected the preserved thickness of these units.

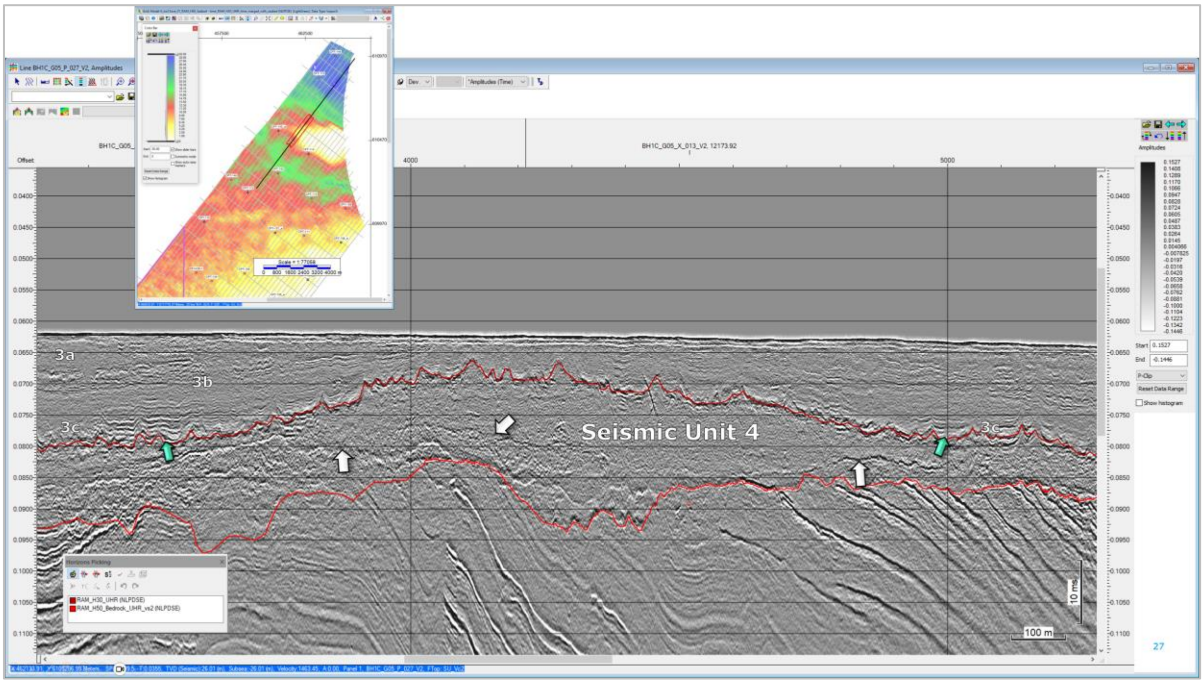


Figure 7-37. Stepping towards the Northwest the relief of the ridge gradually decreases. Here Seismic Unit 3 sediments can be seen to thin and drape completely across the ridge with the basal sub-unit 3c locally onlapping the hummocky moraines (green arrows) mapped out by the H30 (H35) Seismic Horizon. Note the highly folded bedrock below the ridge. Within the ridge there are several seismic events that appear that suggest that the ridge is composed of several stacked sediment packages (white arrows). Inset map displays the combined thickness of Seismic Units 1 to 3 and illustrates clearly how topography across the Unit 4 ridge has affected the preserved thickness of these units.

7.7 Seismic Unit 5 Bedrock

The Bornholm I Site has a rather complicated bedrock with a variety of rock-types having been recovered in cores (see Section 8.6 below and Table 8.22). In places the bedrock is very weakly cemented so that cores have returned sand samples even though the cores were cut from bedrock successions. The bedrock unconformity dips gradually towards the east and north, though several large palaeovalleys have been cut into (Figure 7-38).

7.7.1 Bedrock seismic pick

The top of bedrock in the Bornholm I site has been mapped as the H50 Seismic Horizon. This horizon has been picked on a variety of features; in some parts of the Bornholm I site H50 has been mapped on a high-amplitude soft seismic event (trough) whereas an amplitude peak (hard event) may have been used to map the bed rock in other parts of the site. Elsewhere it has simply been picked at the termination of dipping bedrock strata. Here the top bedrock has been picked at the point where all visage of bedding is lost with the assumption being that the breakdown of clear bedding likely marks the transition from in situ beds of rock to a soil that could represent either a weathered rock regolith or a glacial till (Figure 7-39).

One of the challenges in picking the top of bedrock is that the lithology of the sub-cropping bedrock is highly variable; it ranges from limestone, to chalk, to siltstone, to sandstone or even mudstone/claystone in places. Indeed, to make matters worse, several of the boreholes have encountered probable Lower Jurassic clastic sediments that are extremely weakly cemented, possibly even uncemented. Cores cut from these intervals have recovered sand. Borehole description logs have reported long intervals of sand (Gardline, 2023), that have been classified as till, even when there is little doubt that the boreholes have drilled into folded bedrock strata (Figure 7-40).

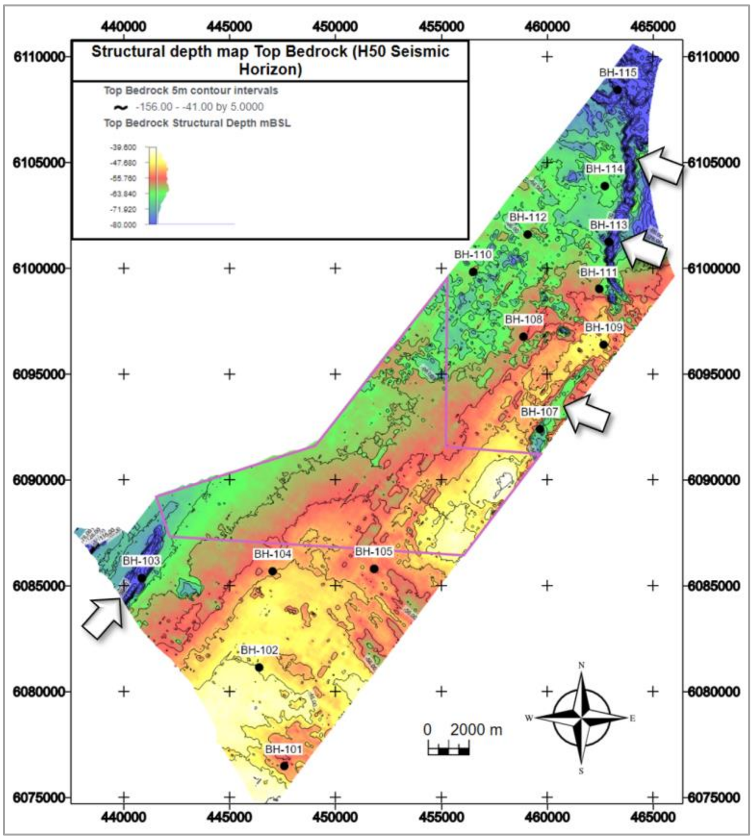


Figure 7-38. Structural Depth Map of the top of the Bedrock, illustrating the deep palaeovalleys that have been carved into bedrock (arrowed).

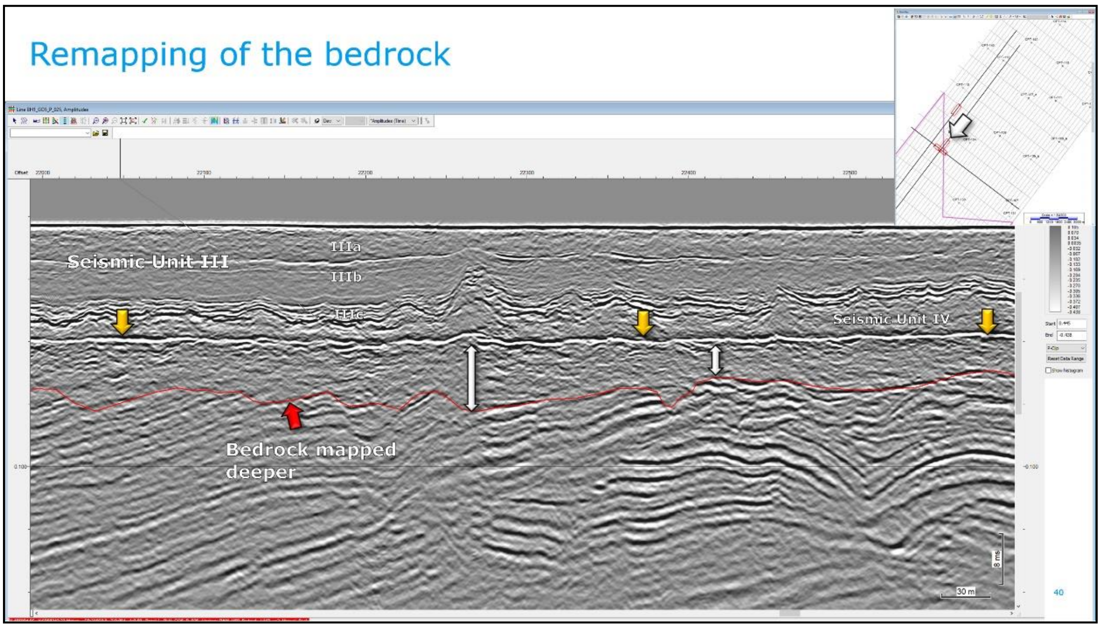


Figure 7-39. Seismic in-line G05_P_025 illustrating how the top of the bedrock has been picked. The original pick lay along the soft reflector (yellow arrows). Ramboll has moved the pick deeper to the point at which all definition of bedrock strata disappears. The zone in between defined by the white arrows should be viewed as a zone of uncertainty; this could simply represent bedrock regolith, or it might be part of the Pleistocene sediment cover.

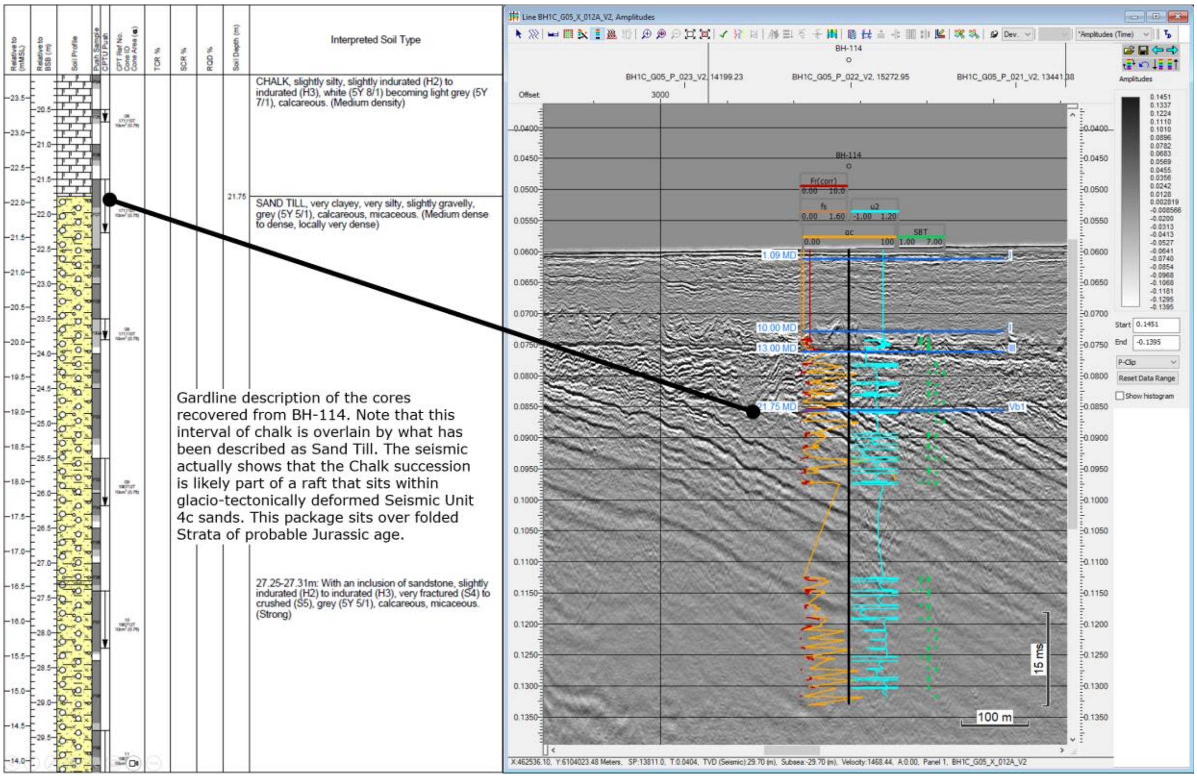


Figure 7-40. BH-114 with the transition between the Chalk and Sands marked on the seismic. The cored interval described as Sand Till comes from relatively steeply dipping bedrock strata that are of probable Jurassic age.

7.7.2 Bedrock character

The Bornholm I Site contains a surprisingly complex bedrock succession below the Pleistocene sediments. Of the 14 boreholes that were drilled on the site all but one, BH-113, have encountered bedrock of various lithologies; chalk, limestone, sandstone, siltstone and mudstone have all been encountered. Perhaps the greatest resource is the deep Pernille (5514/3-1) Exploration well that was drilled to test the hydrocarbon potential of strata at several levels in the Rønne Graben. This well proved a thick succession of Upper Cretaceous limestones and chalks that lie above marlstones of Late Cenomanian age. These Cretaceous sediments sit unconformably over a heterolithic package of Lower Jurassic sandstones and shales that can be so poorly cemented that sand and clay were recorded in mud circulated to the drill deck. This note in the Final Well Report of 5514/3-1 is pertinent to the current project in that long intervals of sand have been recovered from several of the Bornholm I Boreholes, particularly in BH-114 but also in BH-115, were there can be little doubt that the cores have been recovered from bedrock strata (Figure 7-40).

7.7.3 Bedrock structure

Two structural provinces can be defined for the Bornholm I site on the basis of the observed structural deformation. These provinces are demarked by a large monocline that strikes NW to SE across the Bornholm I Site (Figure 7-41). To the south of the structure the bedrock largely comprises relatively gently to moderately dipping strata with Cretaceous limestones, marls and chalk that subcrop beneath the Pleistocene sediment cover. There is evidence of syn-sedimentary faulting and internal slumping of sediments within these strata, but structural deformation is low compared to that North of the monocline. This area has been designated Bedrock Province 1 (Figure 7-42).

By contrast, North of the monocline bedrock strata are considerably more structurally deformed with a series of synclines and anticlines developed. Bedrock penetrations north of the monocline have encountered clastic sediments that consist primarily of sandstones, shales, siltstones and coals. Paleontological studies of a sample in BH-115 provided a likely Middle Jurassic age (Network Stratigrpahic Consulting Limited, 2023), though most of the taxa had long ranges. The area North of the monocline has been designated Bedrock Province 3 (Figure 7-42), with the band of vertical strata along the southern limb of the monocline being Bedrock Province 2.

Some measure of the scale of the monocline can be taken from the 5514/3-1 well that is located several kilometres south of the monocline. Here the unconformity between the Upper Cretaceous and Lower Jurassic strata encountered in the well sits at a structural depth of ca. 860 m below the seabed. The monocline turns the bedrock strata vertical, and it is this structural element that has brought the deeply buried Jurassic strata to shallow burial depths such that they subcrop beneath the Pleistocene strata to north of the synclinal axis to the monocline (Figure 7-41).

7.7.4 Bedrock geomorphology

Although the bedrock shows an overall structural deepening to the West and the North the top of the bedrock is not a simple peneplaned surface; it has significant topography and geomorphological elements. Several deep valleys have eroded down into the bedrock prior to being filled with sediments that are assumed to be of Pleistocene age. Two valleys have been mapped in the Southwest corner of Bornholm I (see Figure 7-38), of which one has been penetrated by BH-103 which recovered a thick succession of dense clay-rich sediments (Soil Type IVb) before encountering chalk bedrock. This valley shallows towards the Northeast with the valley head having been mapped (see Figure 5-10). The valley is oriented perpendicular to the general slope of the top bedrock surface indicating either (i) that the present-day westwards dip to the bedrock is a more recent development, or (ii) that another mechanism was responsible for directing water to flow along the strike, rather than the dip of the bedrock. The most obvious solution is that these valleys developed as tunnel systems beneath an ice sheet and were carved by meltwater streams developed at the base of the ice sheet.

Conversely, there are several broad bedrock valleys on the eastern side of the Bornholm I that broaden and become gentler towards the northwest (Figure 7-43). These valleys gradually deepen and narrow towards the structural high, that separates the Bornholm I and II sites, and they are considered to have been carved by water shedding off this topographic high. It is into these valleys that the sand systems of Seismic Subunit 4c, i.e. the H45 sand systems were deposited (see Figure 7-42 & Section 7.6.3 above).

Borehole BH-113 has been drilled into a broadly north-south valley (Figure 7-38) that can be traced northwards under the Bathymetric high and into the northern part of the Bornholm I Site (Figure 7-44). It is possible that this palaeovalley links southwards across a ‘sill’ into a northeast to southwest aligned valley that runs along the very eastern side of the Bornholm I Site, and which sits beneath the H45 sand systems.

In summary there are several deep topographic features that have been carved into the bedrock that are likely to be the result of glacial activity, particularly the southwest to northeast orientated palaeovalleys. Gentler and broader valleys may have been formed during interstadial periods by erosion from drainage off the flanks of the high that separates Bornholm I and II.

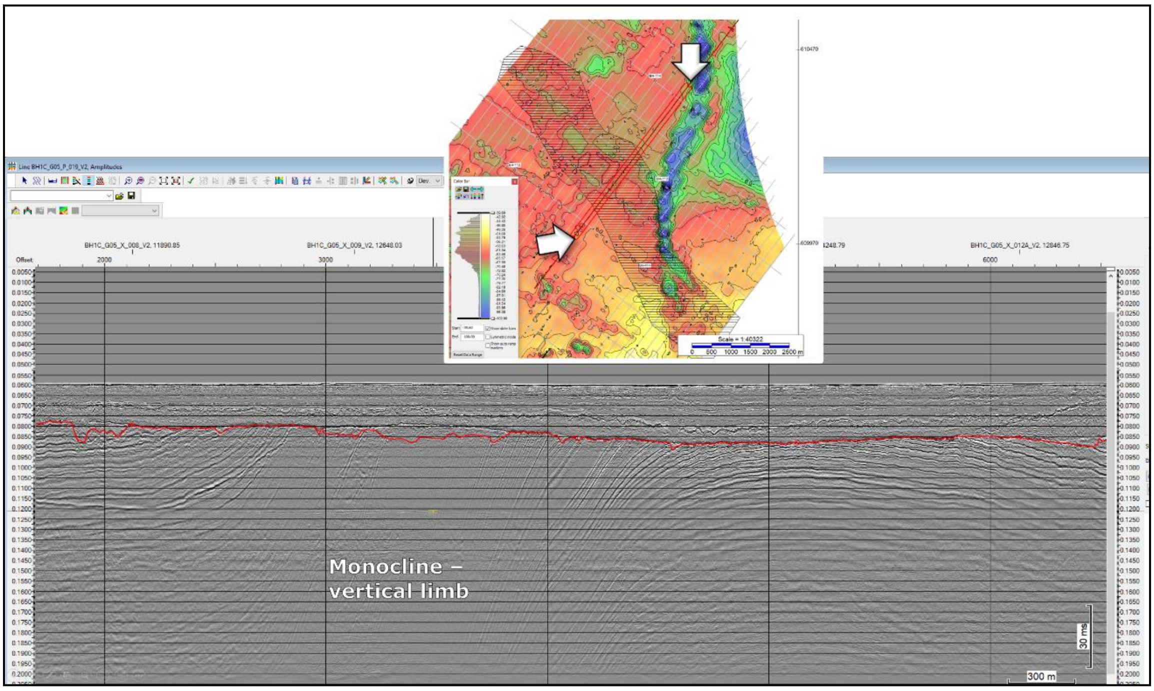


Figure 7-41. Seismic line illustrating the monocline with the vertical beds that are outlined by the shaded area on the inset map which illustrates the structural depth of the top bedrock Seismic Horizon.

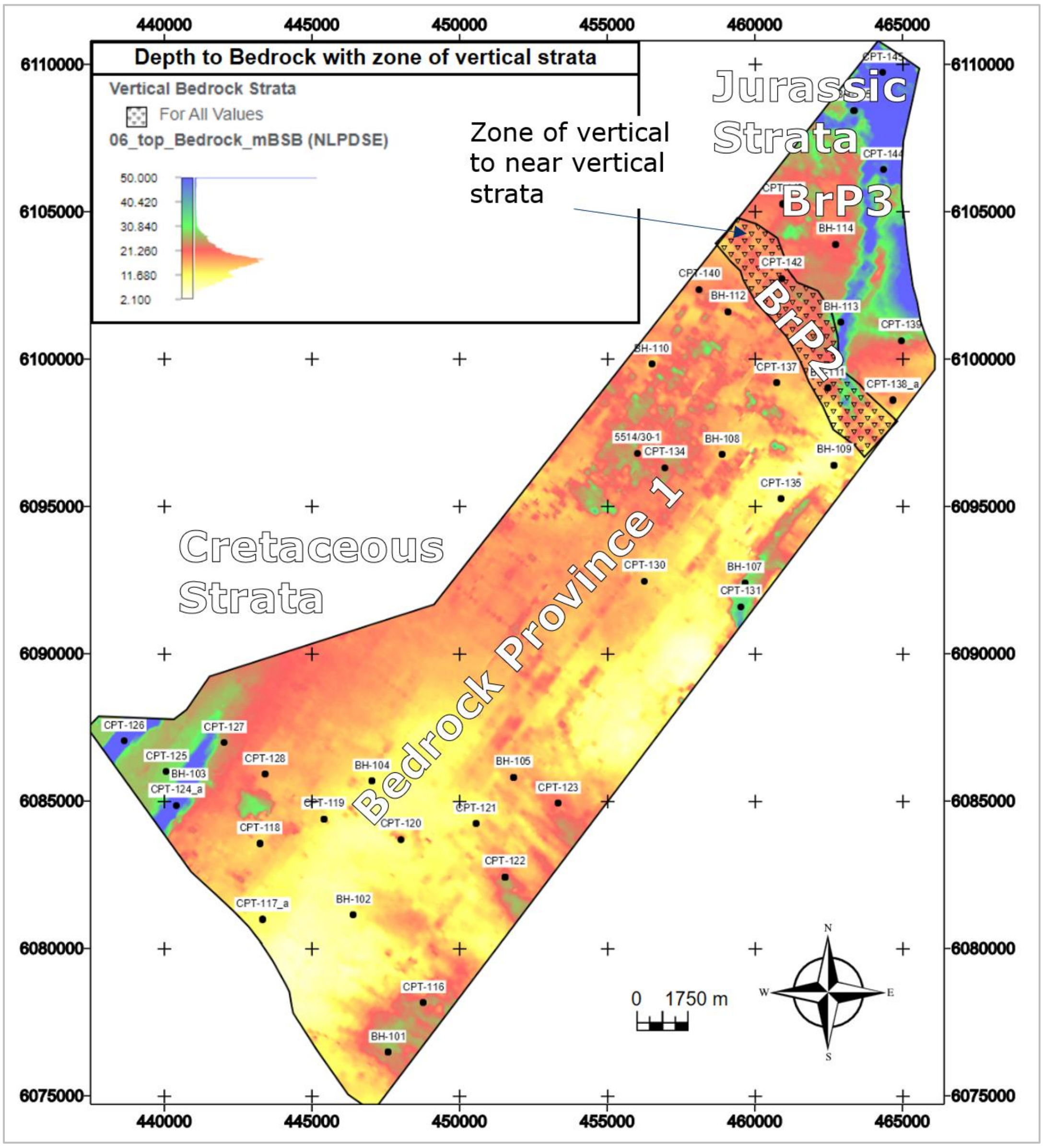


Figure 7-42. Map illustrating the structural depth map for the top of the bedrock. Note the hatched zone that depicts the vertical to near vertical strata of the monocline that separates the Bornholm I Site into a northern Structural Province (BrP2) dominated by large open folded strata of probable Lower Jurassic age from a southern zone of more gently dipping to flat-lying strata dominated by limestone, chalk and mudstone lithologies of Cretaceous age. Boreholes BH-112 and BH-109 penetrate thick intervals of siltstones and mudstones that could belong to the Late Cenomanian marlstone succession that was penetrated in the 5514/30-1 well.

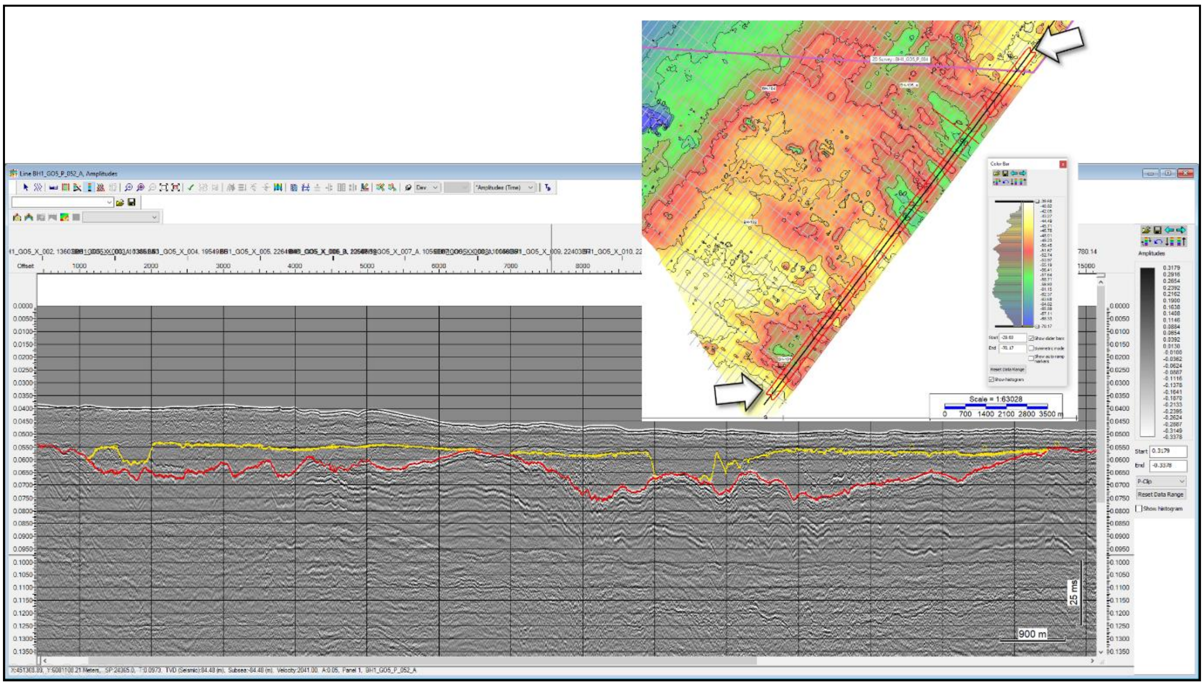


Figure 7-43. Seismic in-line G05_P_052_A illustrating the gentle open valleys developed in the south-eastern part of the Bornholm I Site. The yellow H45 Seismic Horizon marks the mapped top of the sand system that plugs these gentle valleys (see Section 7.6.3).

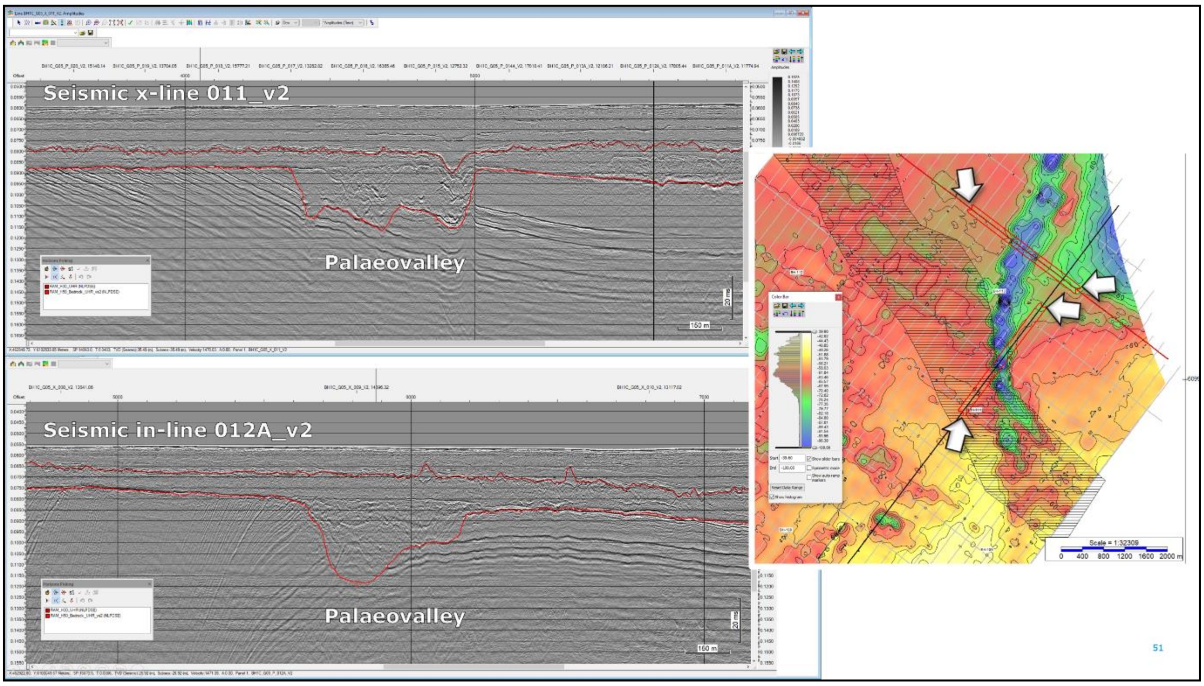


Figure 7-44. Seismic in- and cross-lines through the large sand-filled palaeovalley located in the north of the Bornholm I Site. BH-113 penetrated the flank of the palaeovalley highlighted here and recovered a thick succession of sand (Soil Type IVa).

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 Bornholm I and Bornholm II OWF areas. A summary of the geotechnical investigation for Bornholm I is provided below in Table 8.1. A total number of 14 boreholes and 44 shallow CPTs 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 Bornholm I area are presented in this report.

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

Location	Maximum Depth	North	East	Location	Maximum Depth	North	East
[-]	[m]	[-]	[-]	[-]	[m]	[-]	[-]
BH-101	69.96	6076482.8	447550	CPT-117_a	9.02	6080991.6	443300.1
BH-102	70.45	6081152.9	446372.4	CPT-117_b	9.02	6080986.2	443305.1
BH-103	69.65	6085377.3	440799.5	CPT-118	1.04	6083563.2	443202
BH-104	70.07	6085690.4	447004.9	CPT-118_a	1.16	6083567.5	443201.6
BH-104_a	59.5	6085695.2	447000.6	CPT-119	1.06	6084398	445375.4
BH-105	29.1	6085814.1	451798.2	CPT-119_a	0.89	6084402.7	445375
BH-105_a	69.48	6085803.8	451798.1	CPT-119_b	0.95	6084398.2	445379.4
BH-107	69.28	6092414.9	459637.8	CPT-120	16.73	6083699.2	447981
BH-108	58	6096768.5	458871.2	CPT-121	6.7	6084239.2	450534.8
BH-109	69.72	6096398.6	462662.1	CPT-121_a	8.56	6084244.1	450535.2
BH-109_a	3.86	6096393.9	462667	CPT-122	6.73	6082430.4	451507.4
BH-110	37	6099836	456485.8	CPT-122_a	1.09	6082436.3	451508.1
BH-111	50.05	6099019.1	462438.8	CPT-122_b	1.22	6082430.7	451512.8
BH-112	50	6101604.8	459076.3	CPT-122_c	8.48	6082425.9	451508
BH-113	70.02	6101250.5	462890	CPT-122_d	1.08	6082431.4	451503.2
BH-113_a	9.91	6101245.1	462895.2	CPT-123	5.42	6084928.1	453312.8
BH-114	69.75	6103901	462707.4	CPT-123_a	4.98	6084933.2	453312.8
BH-115	70	6108439.9	463327.6	CPT-124_a	8.22	6084864.3	440389.9
CPT-101	1.92	6076483.2	447546.1	CPT-125	11.23	6086010.9	440039.9
CPT-101_a	3.88	6076487.9	447546	CPT-126	7.86	6087042	438603.9
CPT-102	7.68	6081148.4	446372.1	CPT-127	10.27	6086986	442001.8
CPT-103	8.88	6085374	440796	CPT-128	8.78	6085910	443391.9

Location	Maximum Depth	North	East	Location	Maximum Depth	North	East
[-]	[m]	[-]	[-]	[-]	[m]	[-]	[-]
CPT-103_a	8.11	6085379	440796.1	CPT-128_a	8.62	6085914.7	443392.1
CPT-104	3.02	6085695.1	447004.9	CPT-130	11.02	6092470.1	456242.9
CPT-104_a	10.13	6085700	447005.2	CPT-131	6.52	6091598	459494
CPT-105	7.08	6085808.8	451798.1	CPT-134	10.89	6096317.9	456925.6
CPT-107	7.36	6092410	459637.7	CPT-135	3.14	6095256.9	460858.2
CPT-108	11.32	6096768.1	458866.9	CPT-135_a	4.67	6095262	460858
CPT-109	3.8	6096394	462662	CPT-137	10.09	6099193.7	460710.6
CPT-109_a	5.74	6096388.9	462661.9	CPT-137_a	8.51	6099196.8	460710
CPT-110	9.64	6099836.5	456481.9	CPT-138_a	6.24	6098611.4	464643.2
CPT-111	13.09	6099015.4	462439	CPT-138_b	13.47	6098607.1	464647.6
CPT-112	9.99	6101601.1	459077.5	CPT-139	10.8	6100626.2	464932.5
CPT-113	13.66	6101243.9	462889.8	CPT-140	11.41	6102359.5	458096.5
CPT-114	11.95	6103896.8	462707.5	CPT-142	12.72	6102742	460884.5
CPT-115	19.51	6108440.6	463333.2	CPT-143	15.2	6105260.6	460919.9
CPT-116	3.76	6078164.9	448744	CPT-143_a	16.43	6105266.2	460919.7
CPT-116_a	4.3	6078169.8	448743.9	CPT-144	16.98	6106433.2	464322.2
CPT-117	8.16	6080986	443300.2	CPT-145	19.69	6109727.3	464309.9

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

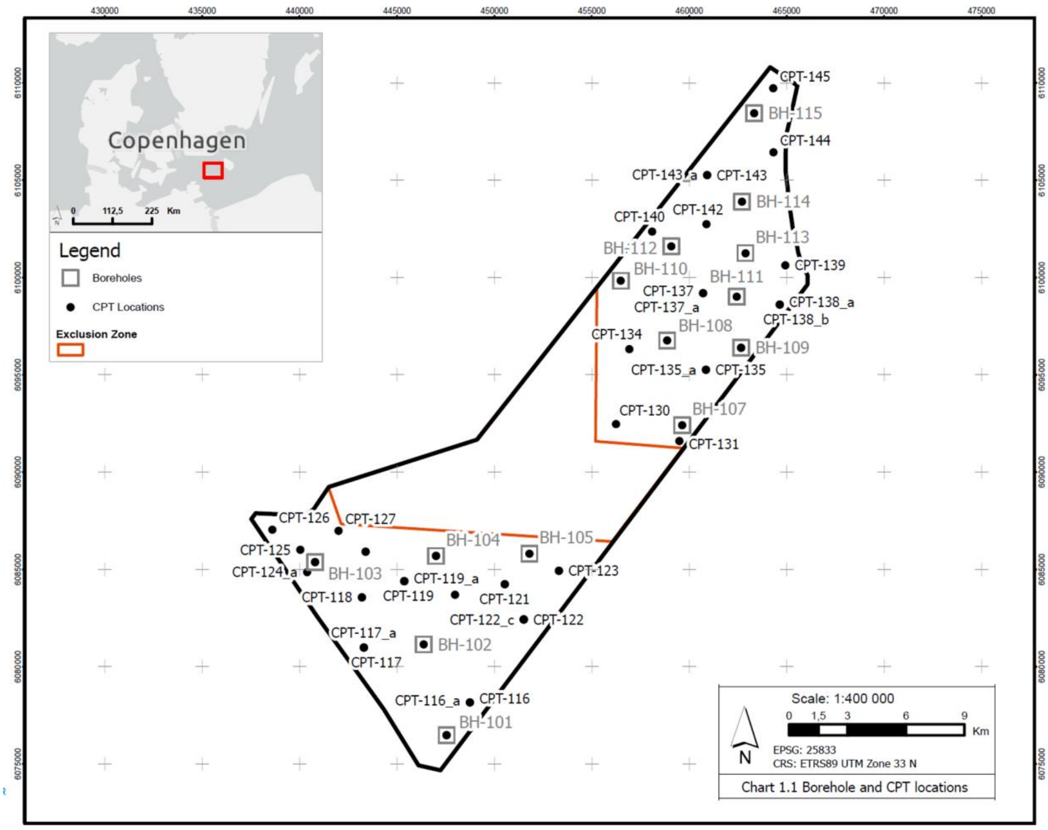


Figure 8-1. Geotechnical data available at Bornholm I.

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.

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 normalized 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 Holocene age. Similarly, soil unit Ib, encountered in the top layers, consists of very soft clay, organic silty material with high plasticity, also from the 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 Holocene age, while soil unit III consists of firm to stiff clay material also from the Holocene age. Beyond the Holocene soils, soil units IVa and IVb emerge with a 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 Units and their relationship to the Geophysical Seismic Units.

Table 8.2. Geotechnical soil units at Bornholm OWF areas.

Soil Unit	Soil Type	Description	Seismic Units and Geological age	Colour
Ia	Sand	Loose to medium dense sand	Seismic Unit 2 (east) Holocene/Latest Pleistocene (Post glacial)	
Ib	Clay and /or Gyttja	Very soft organic clay and/or gyttja	Seismic Units 1, 2 (west) and 3 Holocene/Pleistocene (Post glacial)	
II	Clay	Transition layer of clay with soft to firm strength	Seismic Unit 3 – but rare in Bornholm I Pleistocene (Post glacial)	
III	Clay	Firm to stiff clay	Seismic Unit 4 locally at the base of Unit 3 Pleistocene (Glacial)	
IVa	Sand	Medium dense to dense sand	Seismic Unit 4c – and Seismic Unit 3d Pleistocene (Glacial)	
IVb	Clay Till	Very stiff to very hard clay till	Seismic Unit 4a, 4b and 4c Pleistocene (Glacial)	

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 8.3. Geotechnical rock units at Bornholm OWF areas.

Rock Unit	Rock Type	Description	Age and Structural Province (SP)	Colour
Va1	Limestone/Mudstone	Soft, very weak to medium weak, Limestone/Mudstone	Cretaceous - SP 1	
Va2	Limestone/Mudstone	Hard, weak to extremely strong, Limestone/Mudstone	Cretaceous - SP 1	
Vb1	Chalk	Soft	Cretaceous - SP 1	
Vb2	Chalk	Hard	Cretaceous - SP 1	
Vc1	Sandstone	Soft, extremely weak to weak	Jurassic – SP 3	
Vc2	Sandstone	Hard, medium strong to strong	Jurassic – SP 3	

There are differences between Gardline's (Gardline, 2023) and Ramboll'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 10. 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 I. Four 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.

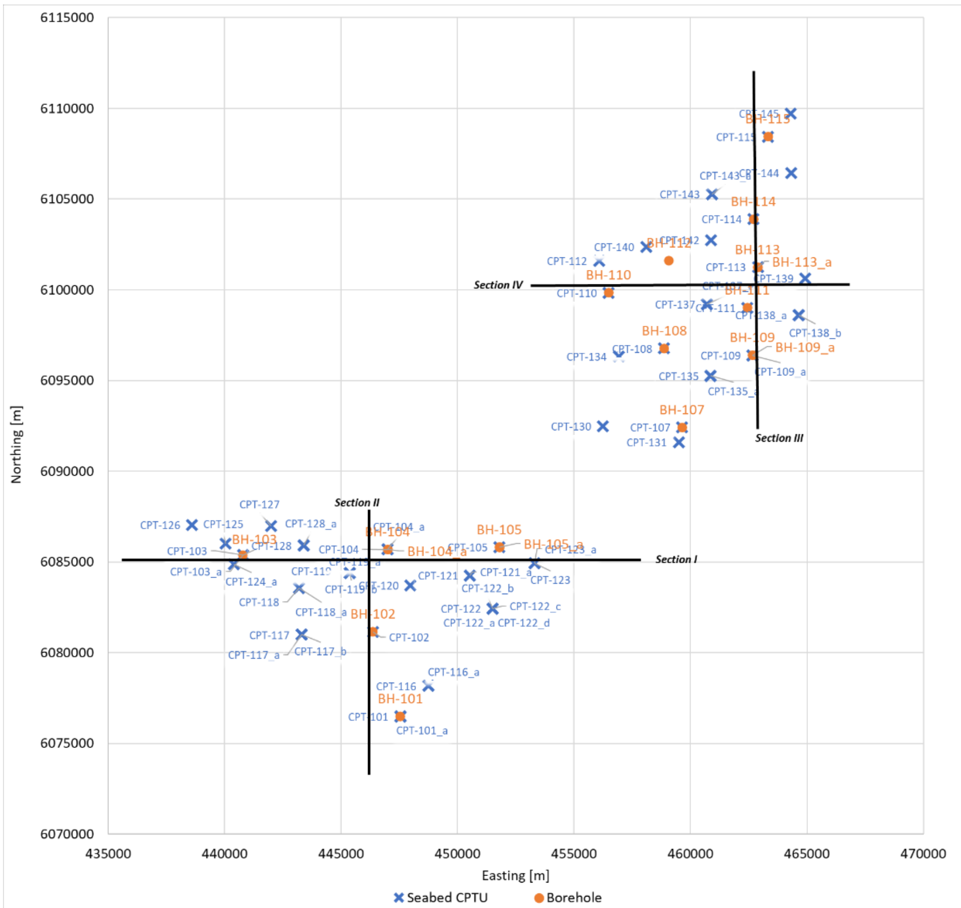


Figure 8-2. Geotechnical cross sections locations.

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 classification 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.

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, slightly sandy
III	Clay, 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

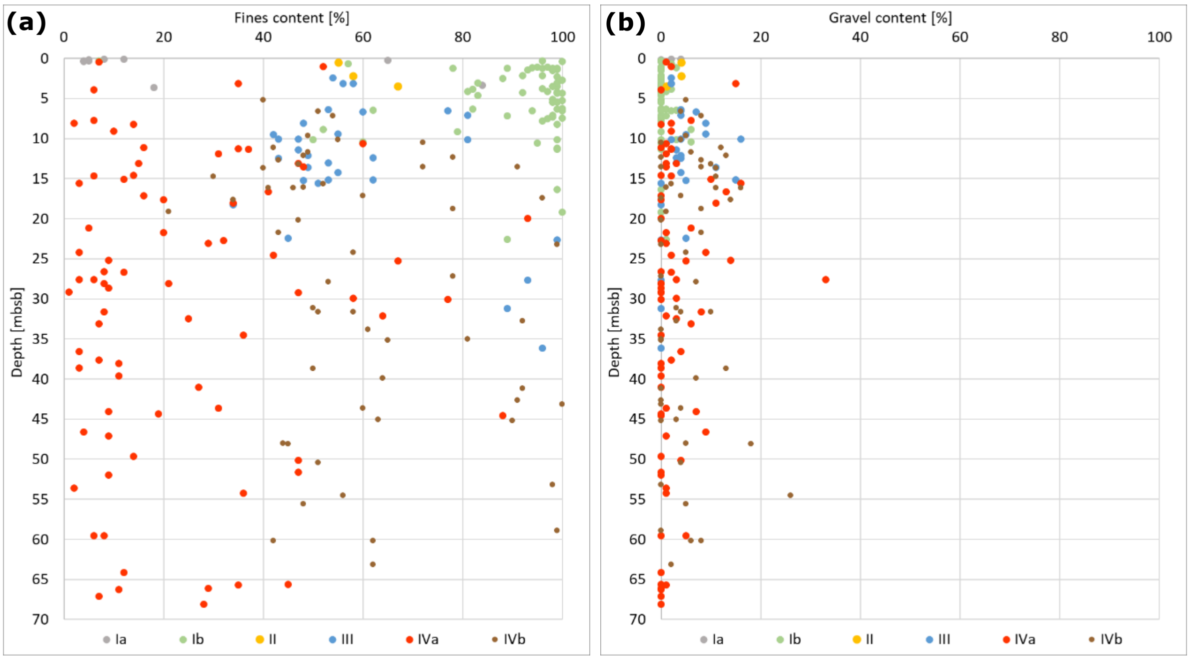


Figure 8-3. Fines (a) and gravel (b) content.

8.5.2 Maximum and Minimum Dry Unit Weight

A total of 3 maximum and minimum dry unit weight 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/m³]	$\gamma_{d,min}$ [kN/m³]
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 has been determined from a total of 197 tests that have been performed (including outliers). The results are depicted in Figure 8-4-Figure 8-9.

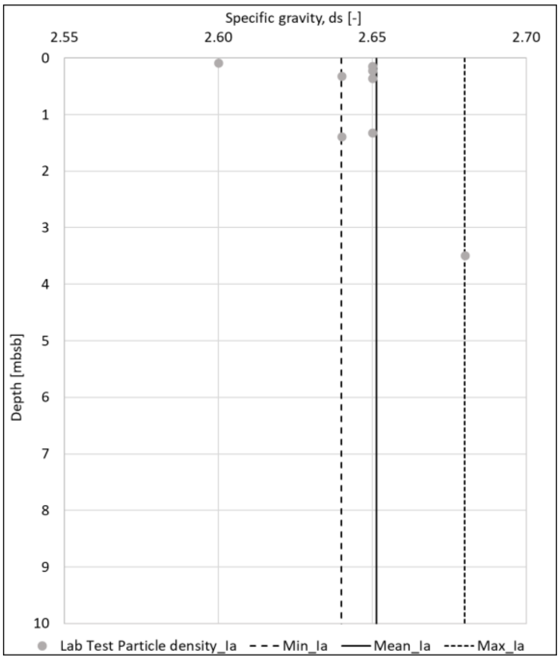


Figure 8-4. Specific gravity for unit Ia.

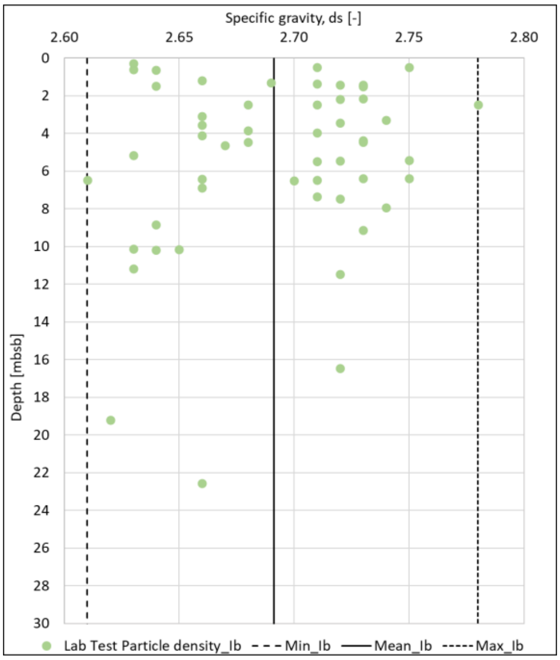


Figure 8-5. Specific gravity for unit Ib.

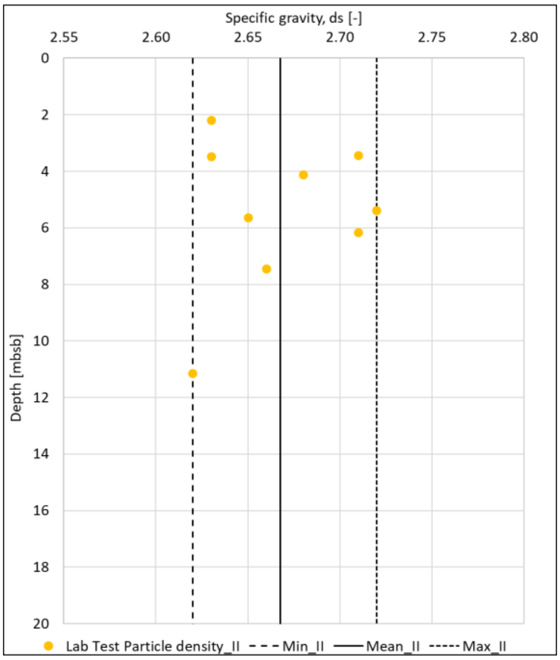


Figure 8-6. Specific gravity for unit II.

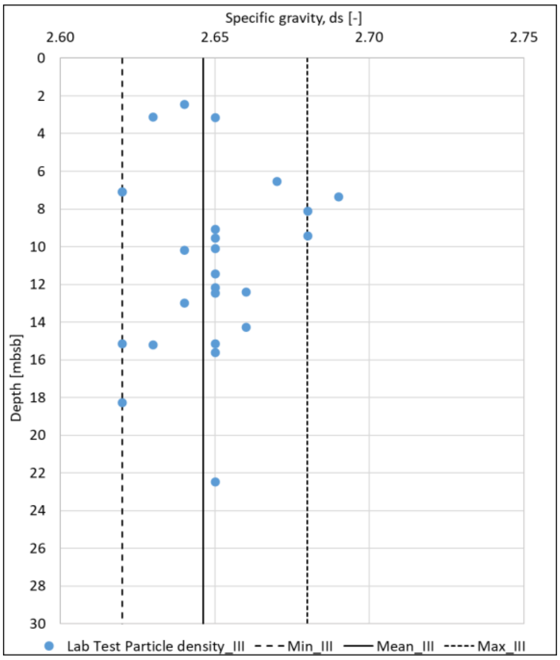


Figure 8-7. Specific gravity for unit III.

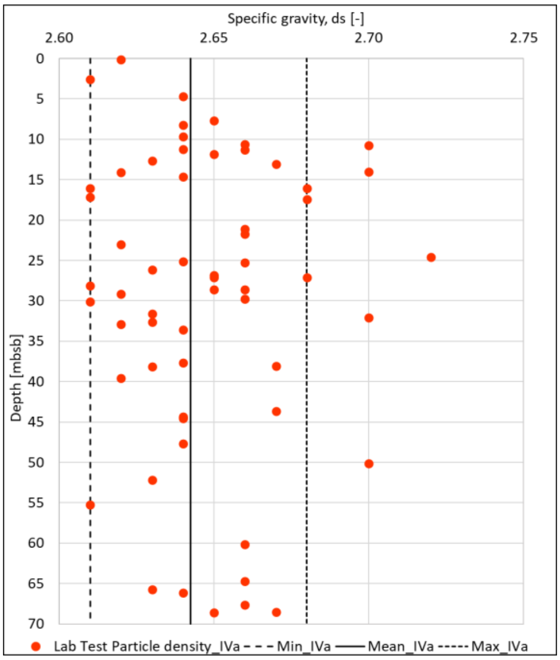


Figure 8-8. Specific gravity for unit IVa.

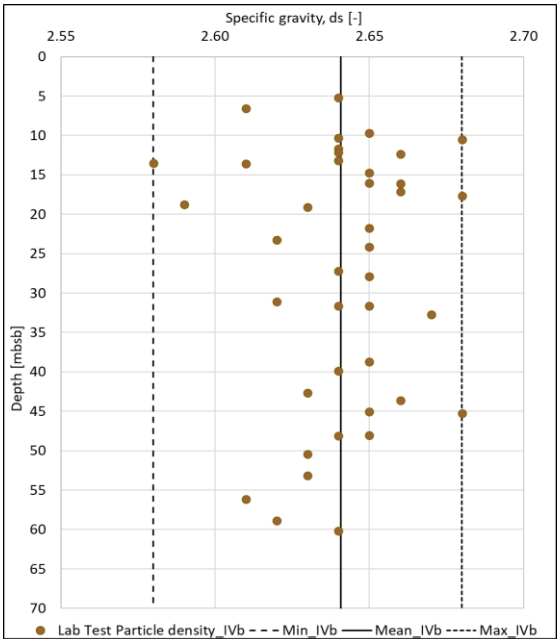


Figure 8-9. Specific gravity for unit IVb.

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 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

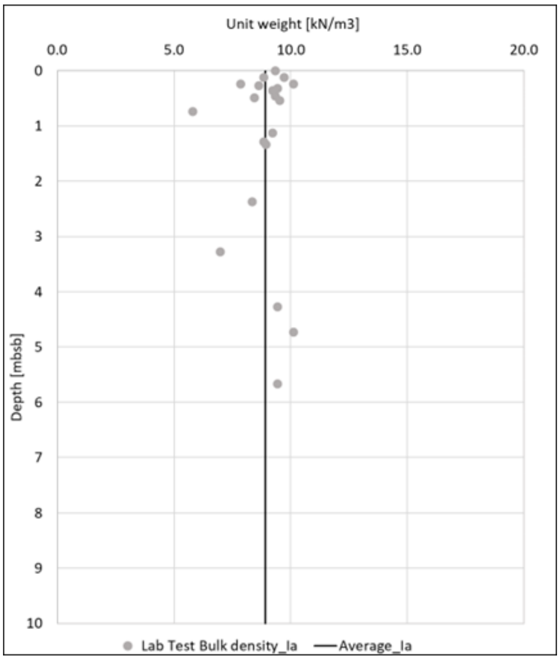


Figure 8-10. Submerged unit weight for unit Ia.

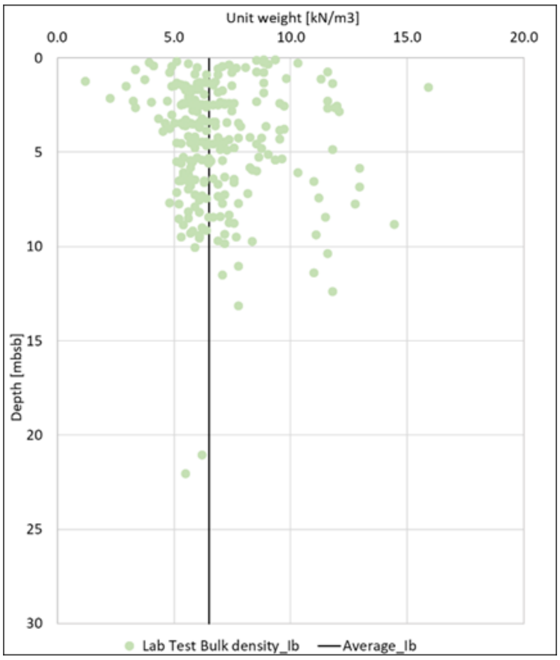


Figure 8-11. Submerged unit weight for unit Ib.

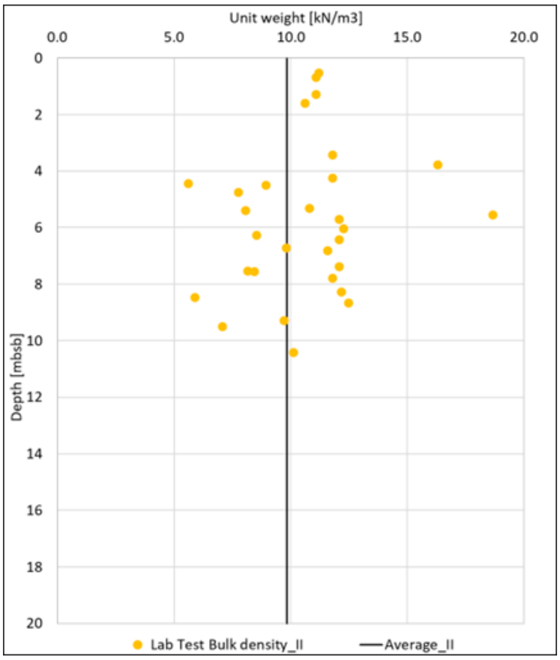


Figure 8-12. Submerged unit weight for unit II.

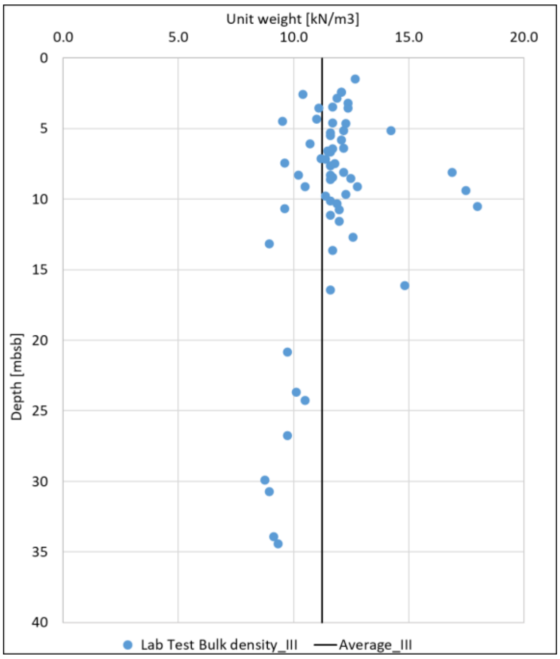


Figure 8-13. Submerged unit weight for unit III.

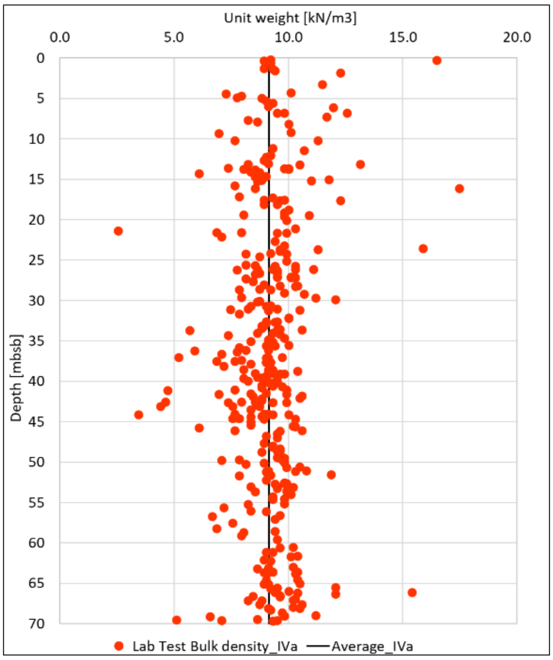


Figure 8-14. Submerged unit weight for unit IVa.

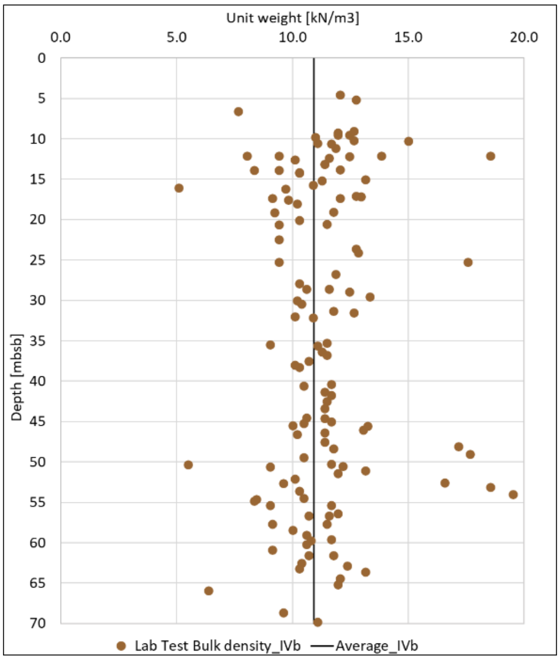


Figure 8-15. Submerged unit weight for unit IVb.

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 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	58
IVa	27.7	42	12	27.3	165
IVb	17.3	37	4	16.8	132

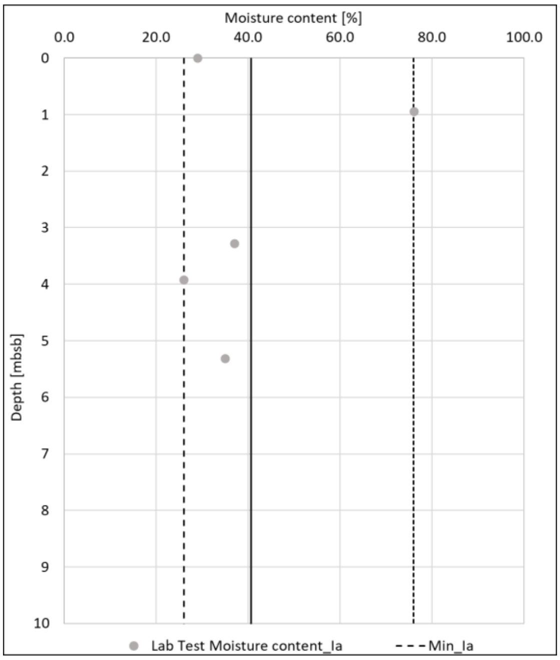


Figure 8-16. Moisture content for unit Ia.

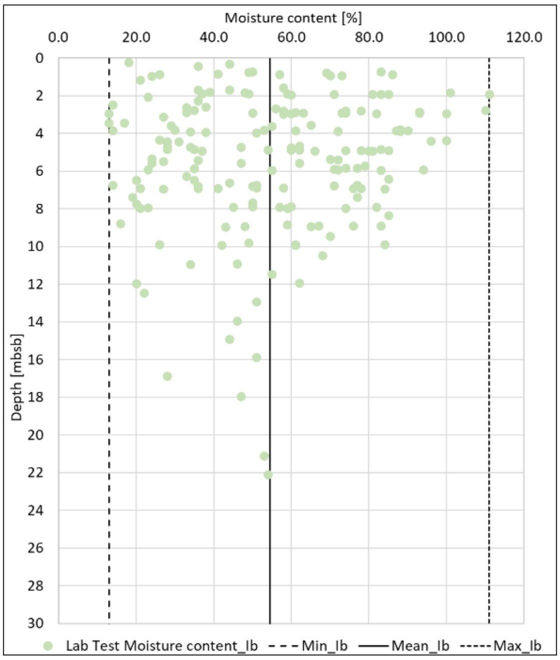


Figure 8-17. Moisture content for unit Ib.

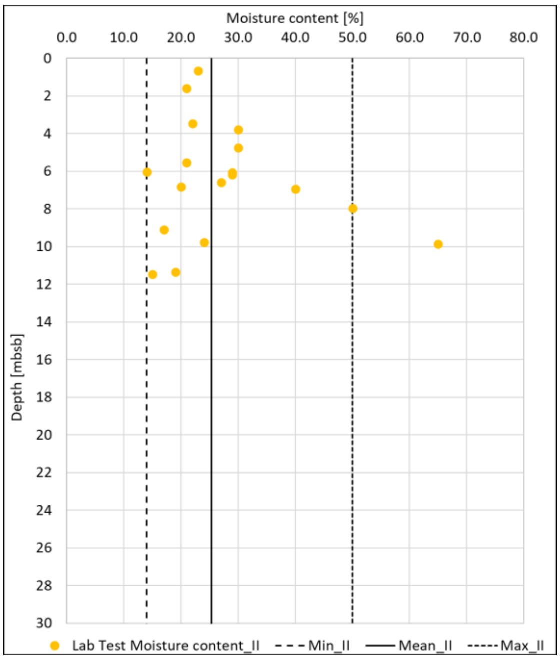


Figure 8-18. Moisture content for unit II.

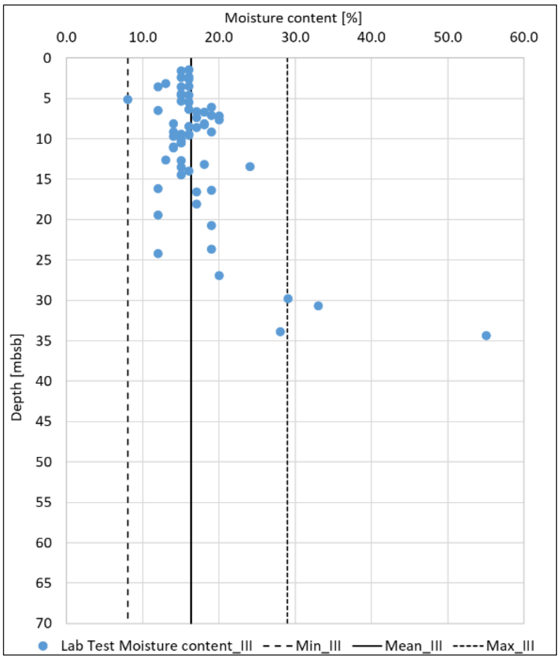


Figure 8-19. Moisture content for unit III.

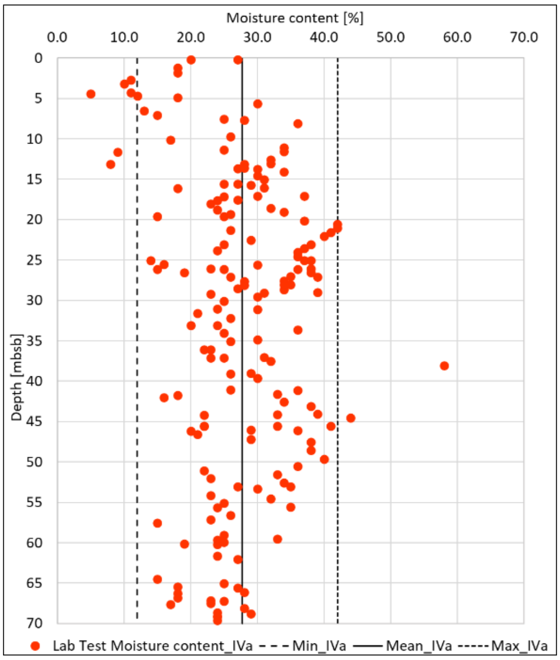


Figure 8-20. Moisture content for unit IVa.

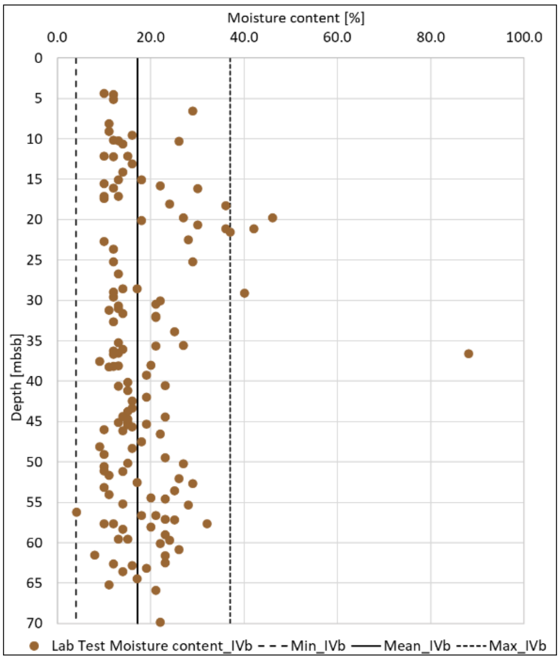


Figure 8-21. Moisture content for unit IVb.

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.

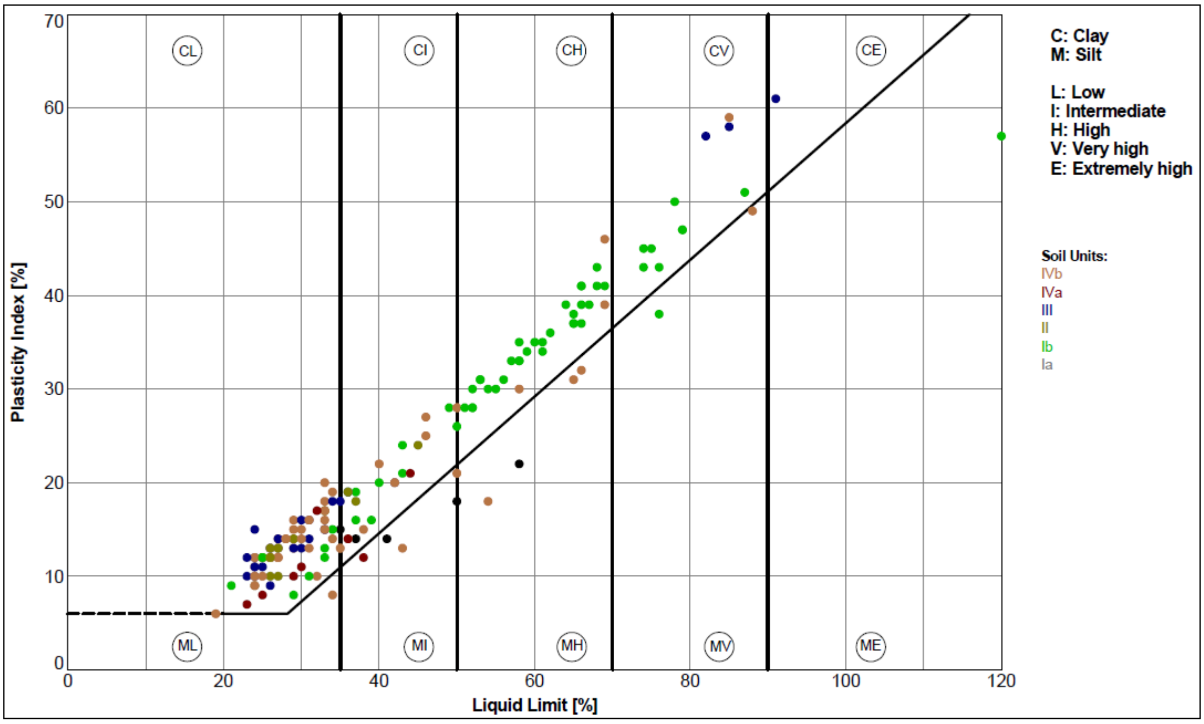


Figure 8-22. Plasticity chart of the soil units.

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. Soil Unit Ib is the most organic-rich material.

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 OCR determined, see Figure 8-23.

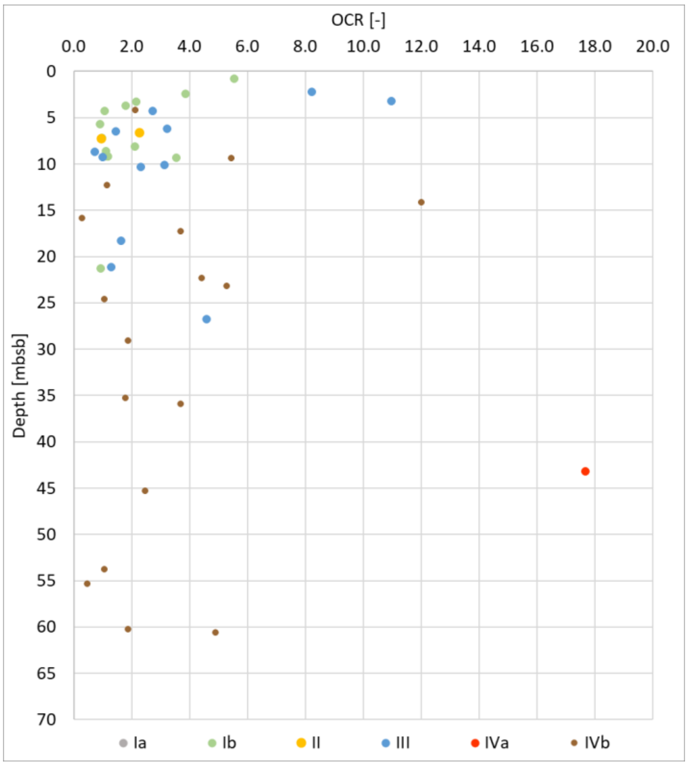


Figure 8-23. OCR from IL.

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:

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

φ is peak angle of internal friction.

The horizontal effective stress is used in the calculation of the relative density, Dr. 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.

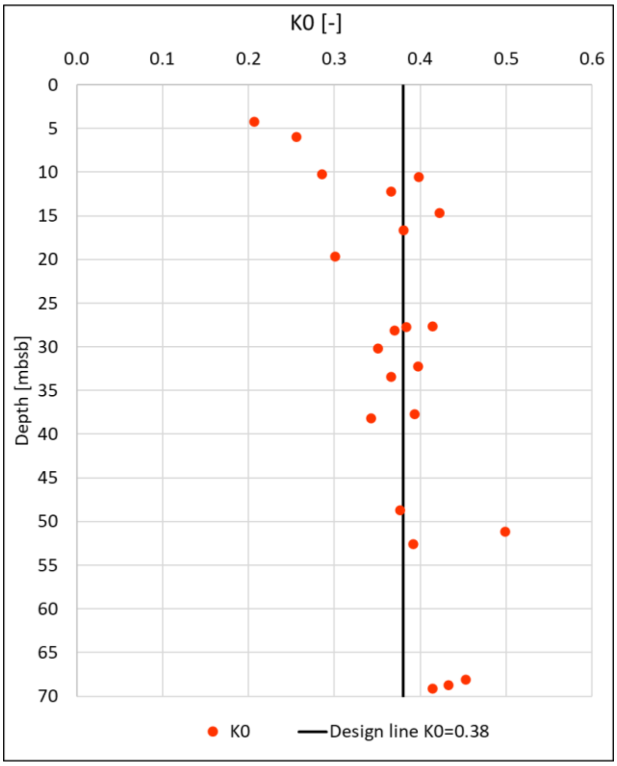


Figure 8-24. K_0 values.

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 andFigure 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

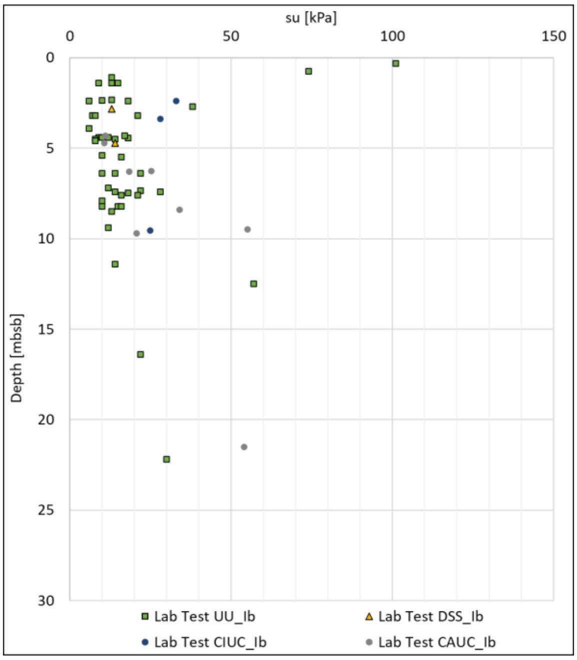


Figure 8-25. Undrained shear strength tests for unit Ib.

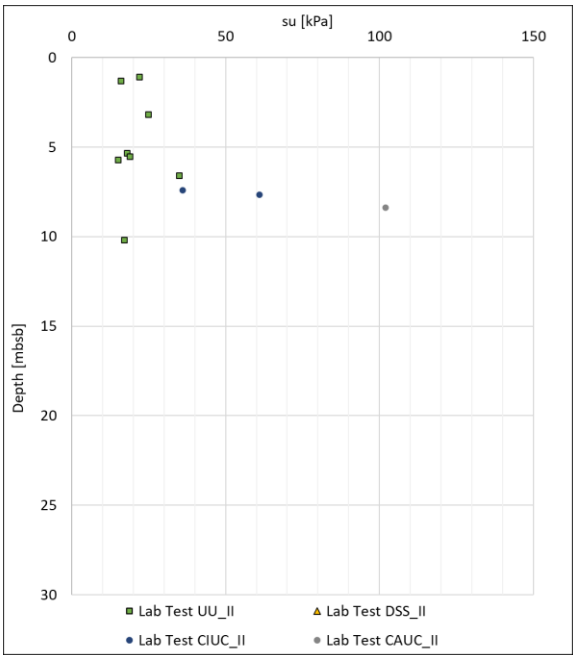


Figure 8-26. Undrained shear strength tests for unit II.

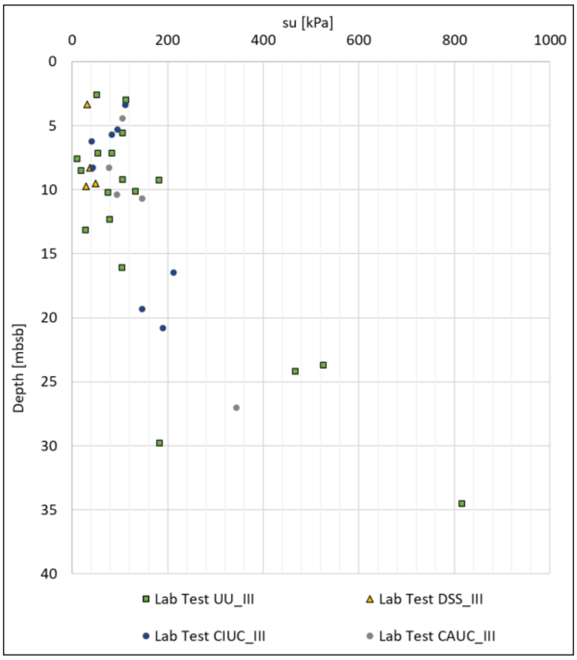


Figure 8-27. Undrained shear strength tests for unit III.

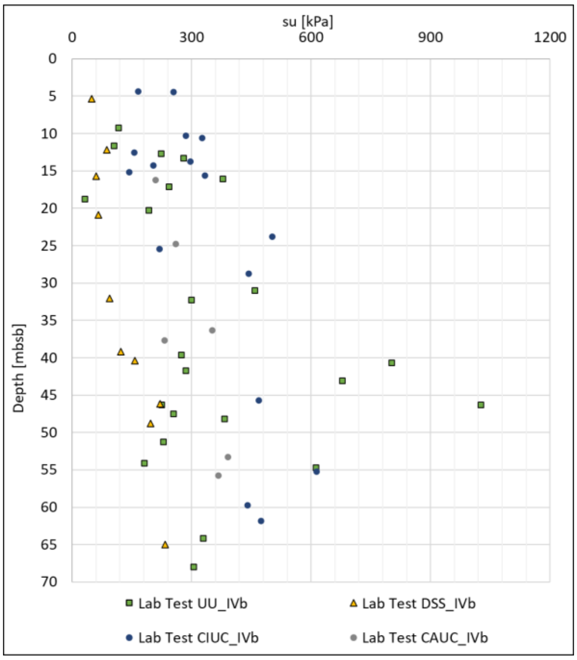


Figure 8-28. Undrained shear strength tests for unit IVb.

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.

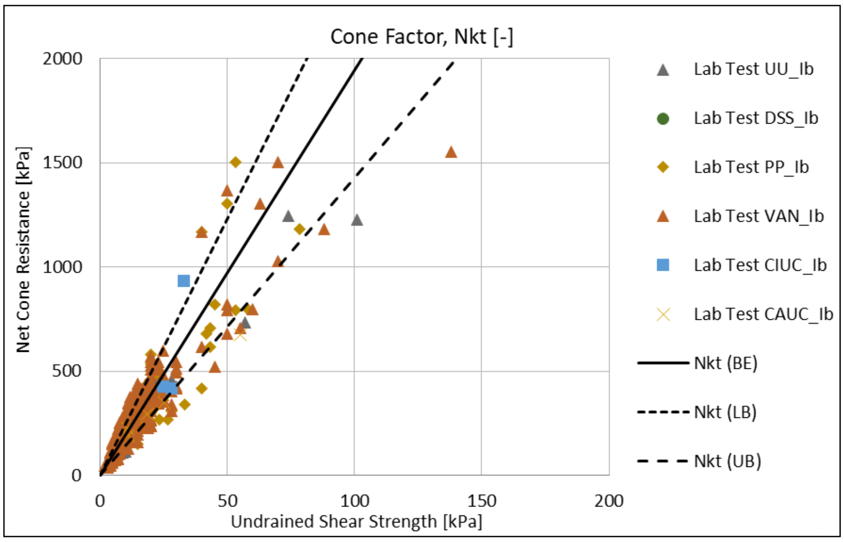


Figure 8-29. Cone factor estimation for soil unit Ib.

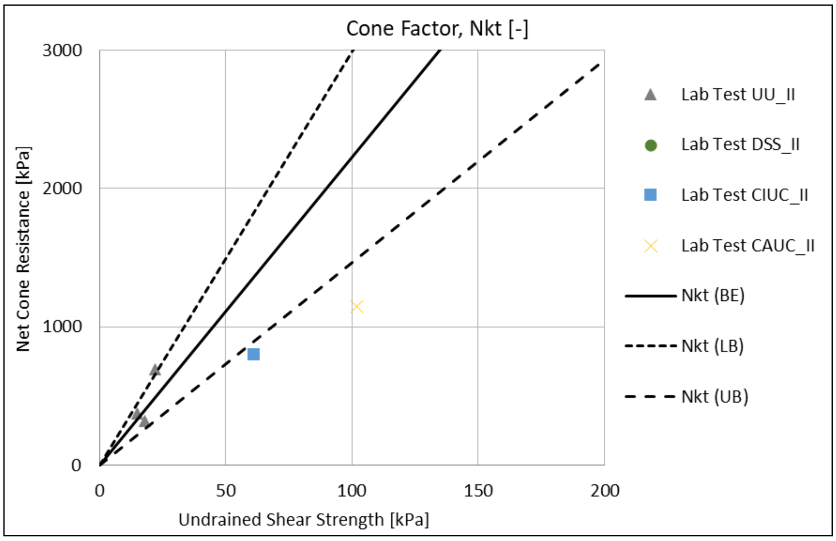


Figure 8-30. Cone factor estimation for soil unit II.

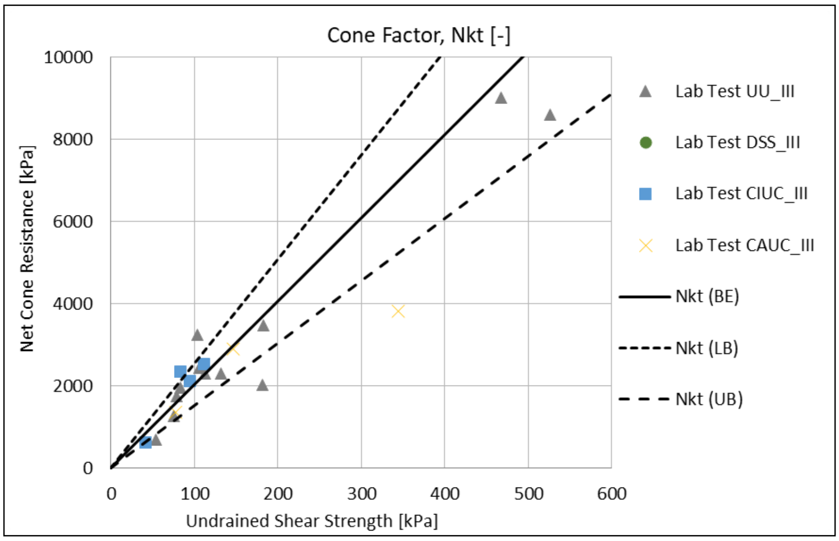


Figure 8-31. Cone factor estimation for soil unit III.

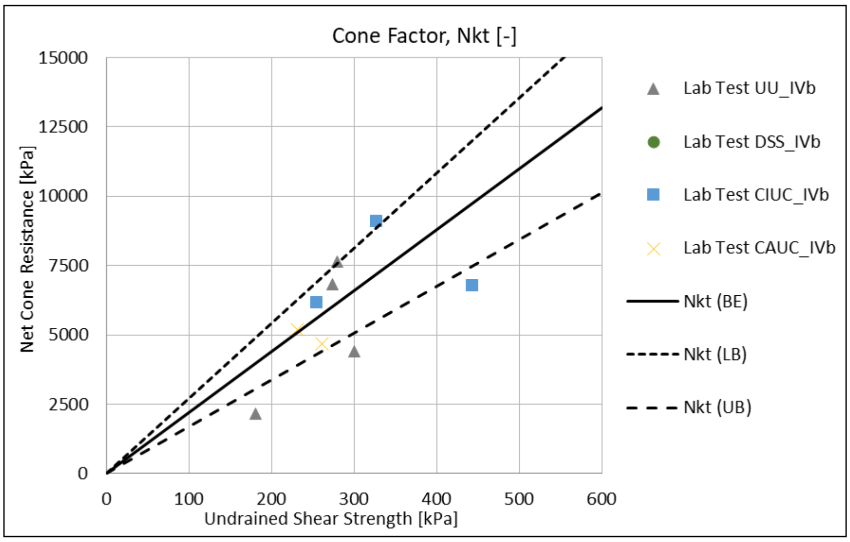


Figure 8-32. Cone factor estimation for soil unit IVb.

8.5.9.3 Effective Strength Properties

For coarse-grained soil, the 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, Dr, can be determined from the laboratory test based on the below equation:

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

$\gamma_{d,max}$ 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. 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.

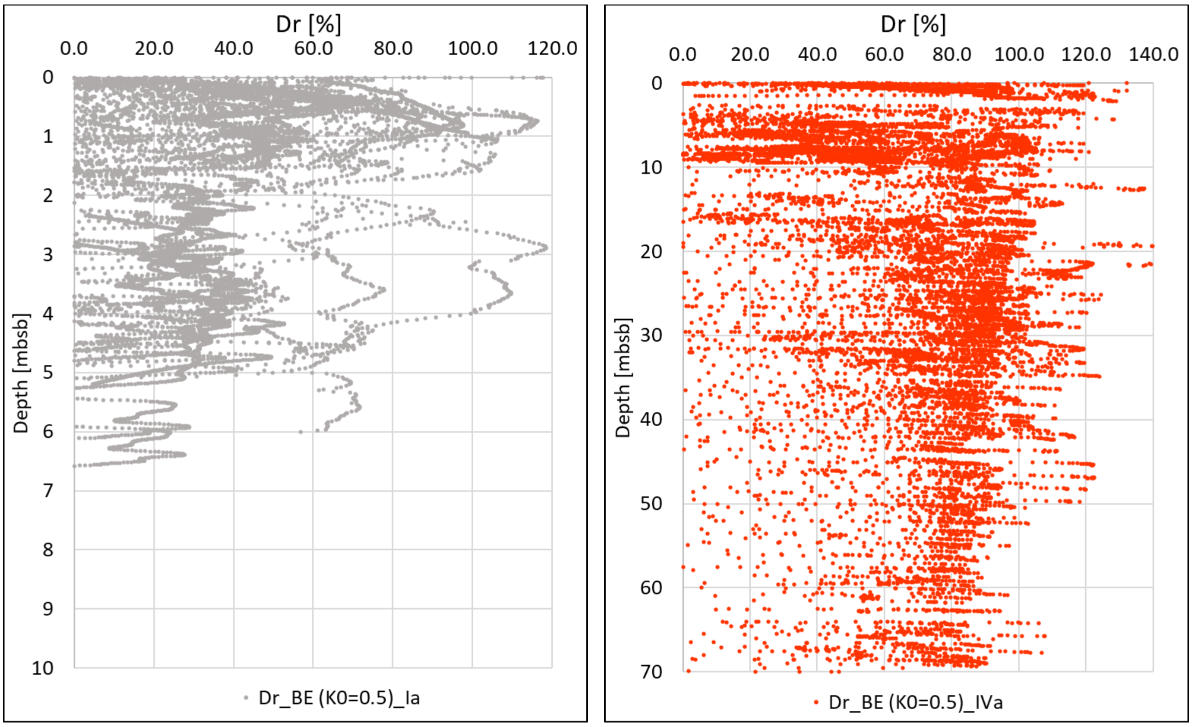


Figure 8-33. CPT correlation of Relative density for the non-cohesive soil units.

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 D_r and 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 both Ia and IVa soil units.

$$\varphi = 0.14D_r + 28 \quad (8.7)$$

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

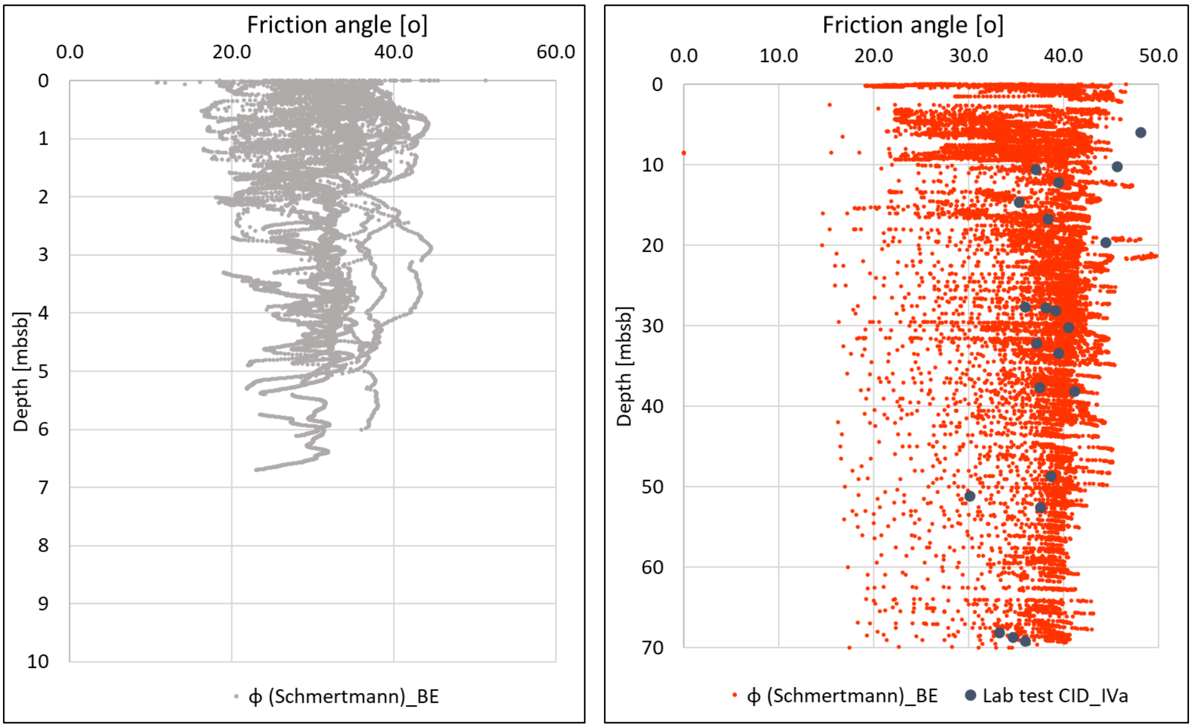


Figure 8-34. Angle of internal friction and CID tests for the non-cohesive soil units.

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:

$$G_0 = \rho {v_s}^2 \quad (8.8)$$

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

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

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 utilised 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.

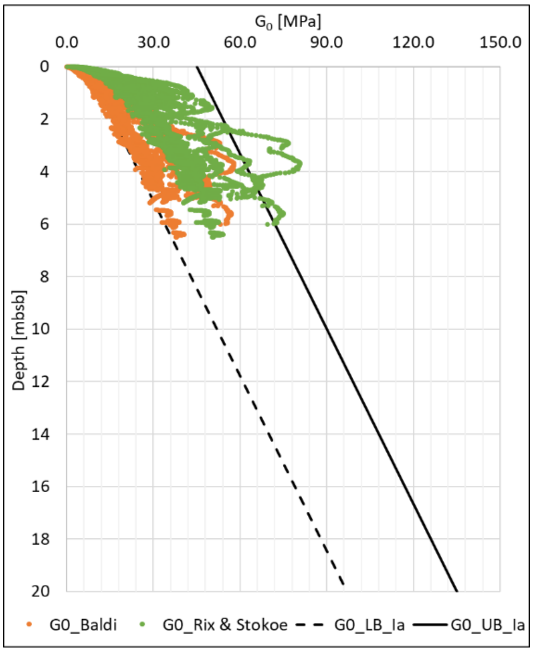


Figure 8-35. G_0 for Soil Unit Ia.

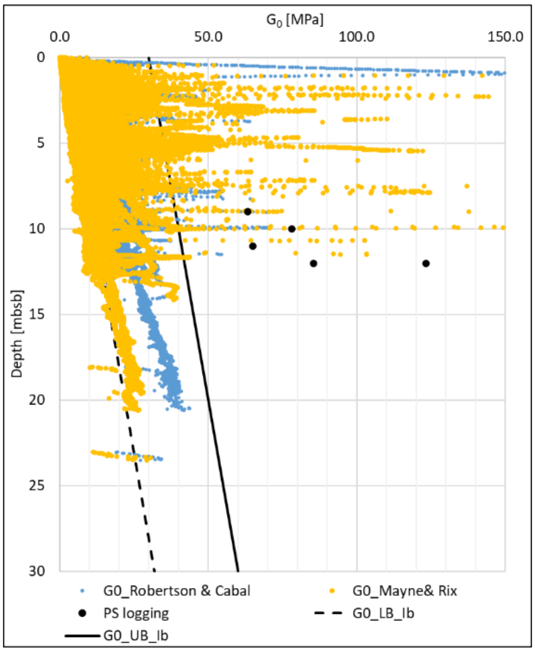


Figure 8-36. G_0 for Soil Unit Ib.

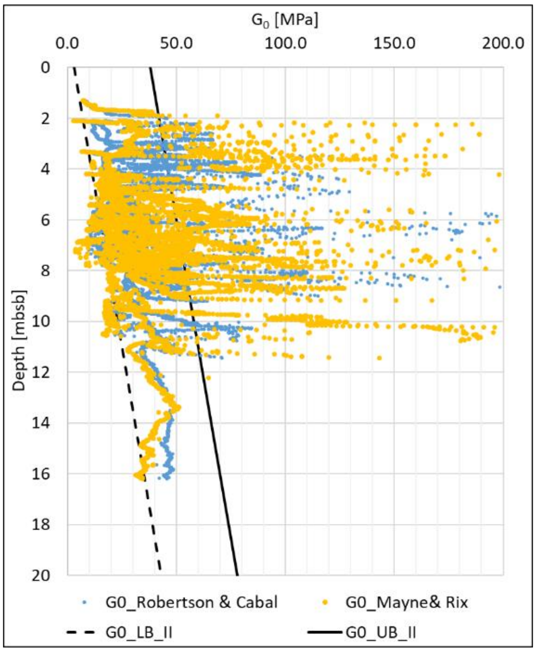


Figure 8-37. G_0 for Soil Unit II.

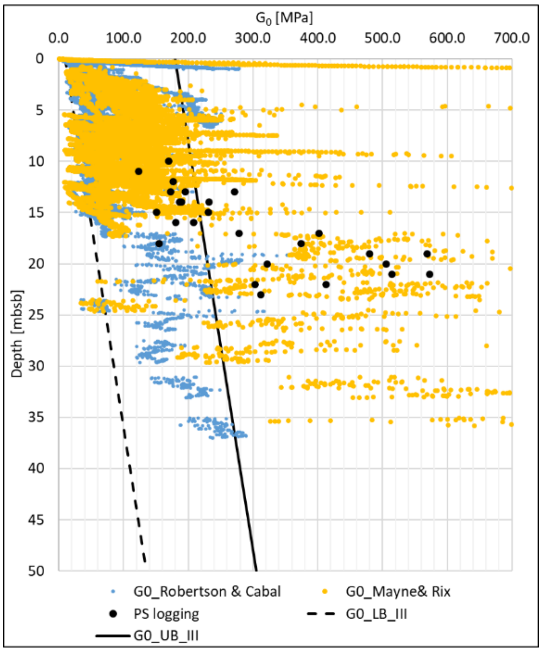


Figure 8-38. G_0 for Soil Unit III.

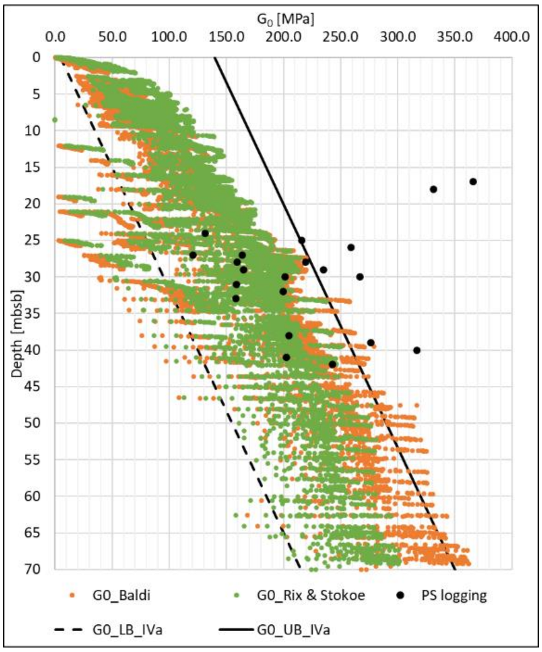


Figure 8-39. G₀ for Soil Unit IVa.

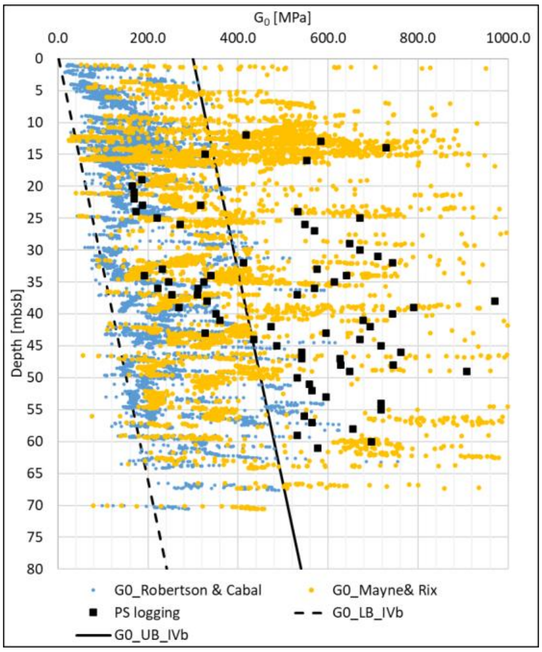


Figure 8-40. G₀ for Soil Unit IVb.

Table 8.20. G₀ values for design.

Soil Unit	G_0_LB	G_0_UB
	[MPa]	[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 UU, CIUc and CAUc tests. In Table 8.21, the results are shown.

Figure 8-41-Figure 8-44 presents 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

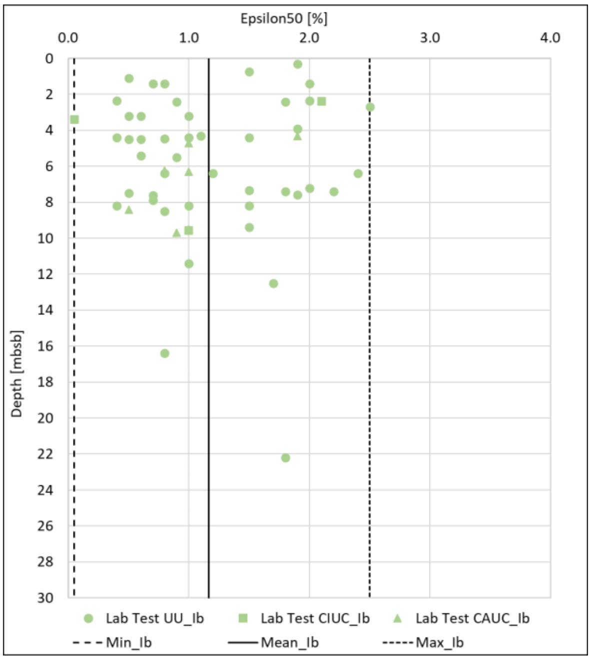


Figure 8-41. Epsilon50 values for unit Ib.

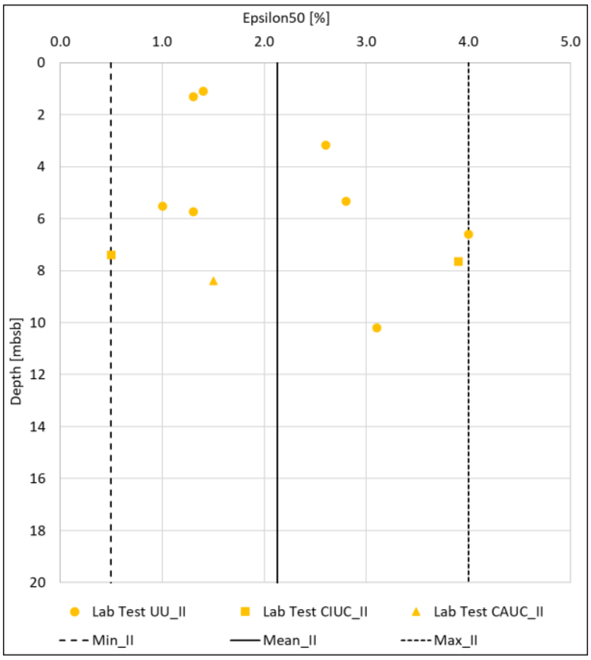


Figure 8-42. Epsilon50 values for unit II.

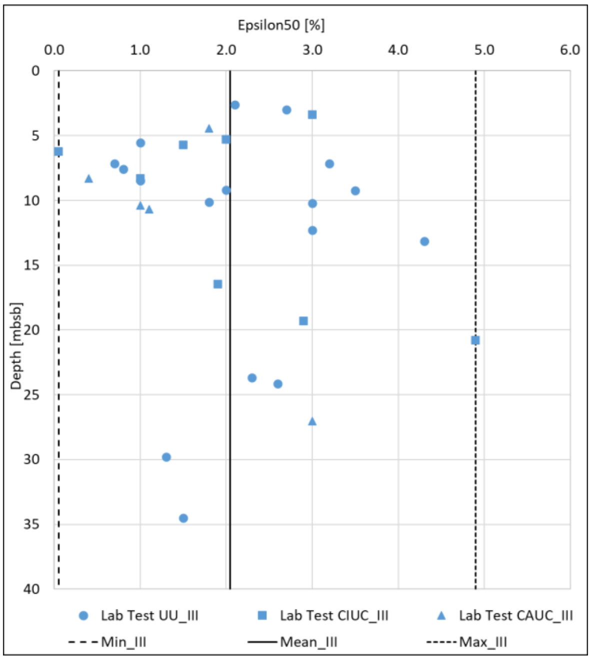


Figure 8-43. Epsilon50 values for unit III.

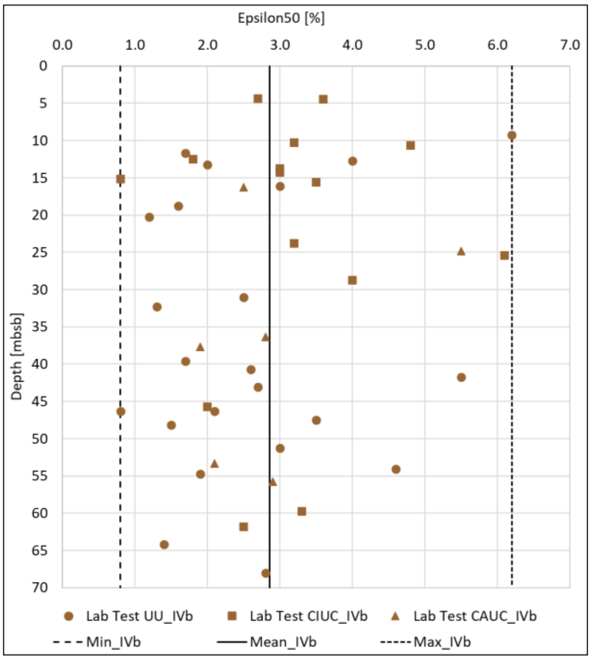


Figure 8-44. Epsilon50 values for unit IVb.

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 Structural Province (SP)
Va1	Limestone//Mudstone	Soft, very weak to medium weak, Limestone/Mudstone	Cretaceous - SP 1
Va2	Limestone//Mudstone	Hard, weak to extremely strong, Limestone/Mudstone	Cretaceous - SP 1
Vb1	Chalk	Soft Chalk	Cretaceous - SP 1
Vb2	Chalk	Hard Chalk	Cretaceous - SP 1
Vc1	Sandstone	Soft, extremely weak to weak, Sandstone	Jurassic – SP 2
Vc2	Sandstone	Hard, medium strong to strong Sandstone	Jurassic – SP 2

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.

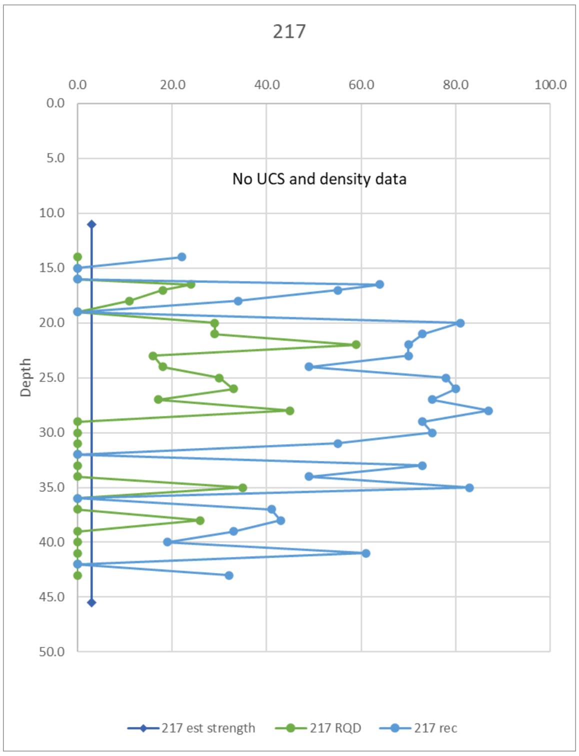


Figure 8-46. BH-217 TCR and RQD values in H2 chalk.

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.

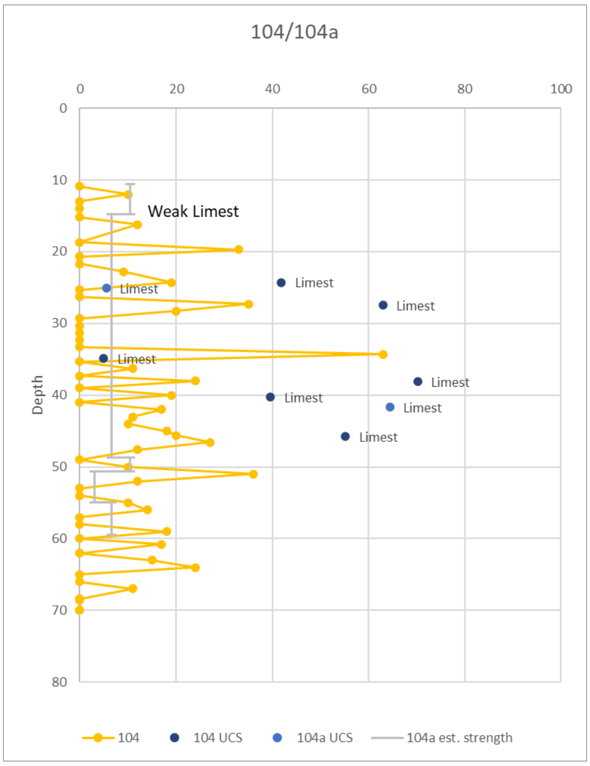


Figure 8-47. Example of weak limestone with very low RQD but showing high UCS strength.

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.

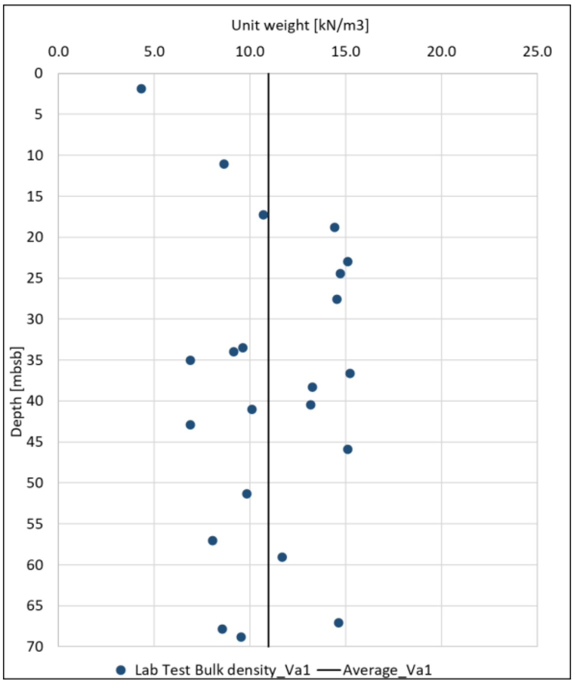


Figure 8-48. Submerged unit weight for unit Va1.

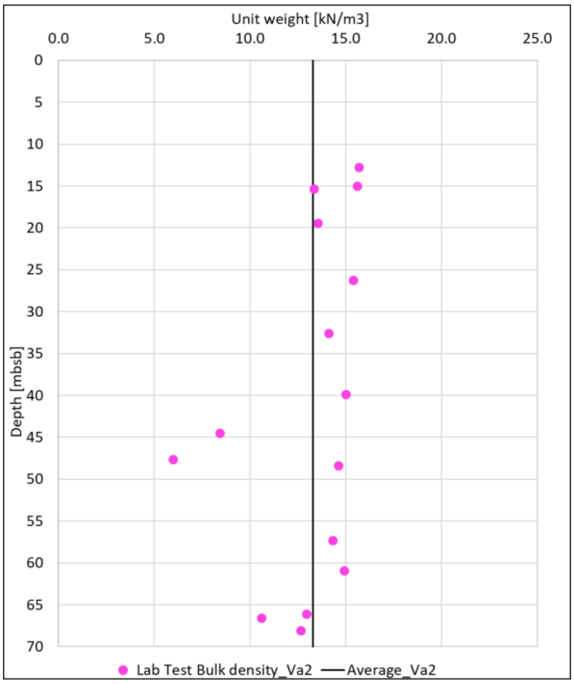


Figure 8-49. Submerged unit weight for unit Va2.

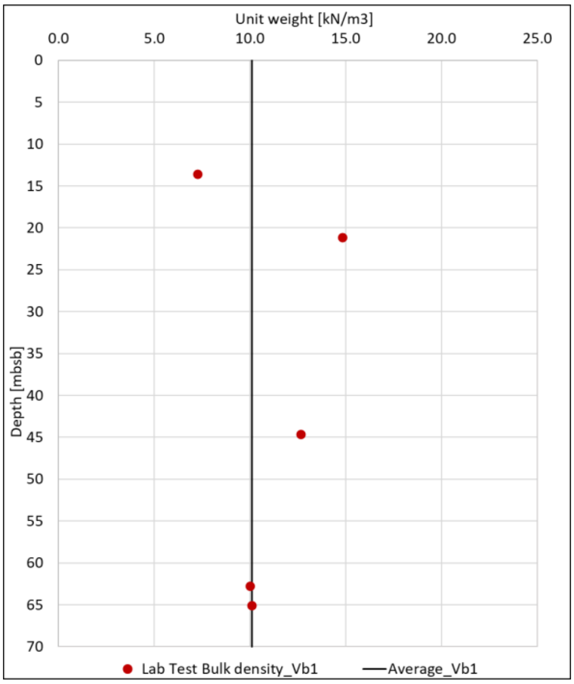


Figure 8-50. Submerged unit weight for unit Vb1.

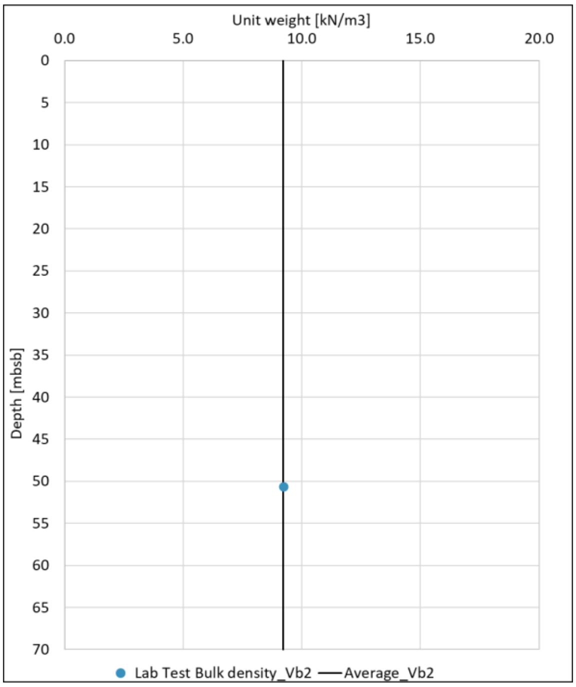


Figure 8-51. Submerged unit weight for unit Vb2.

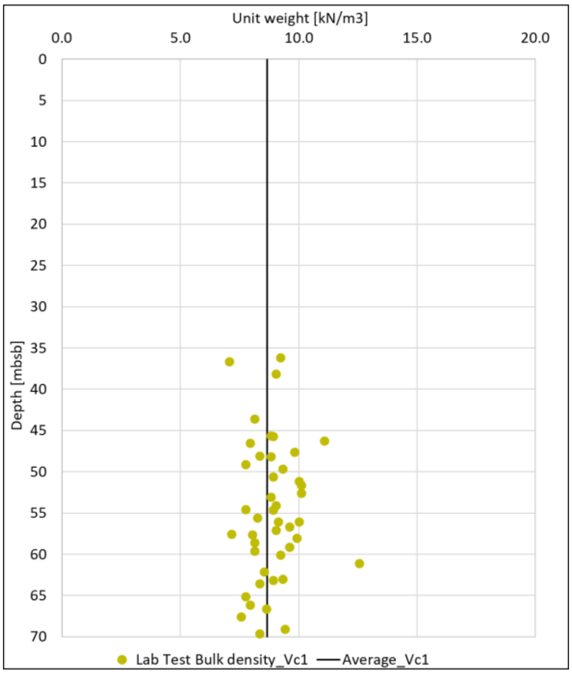


Figure 8-52. Submerged unit weight for unit Vc1.

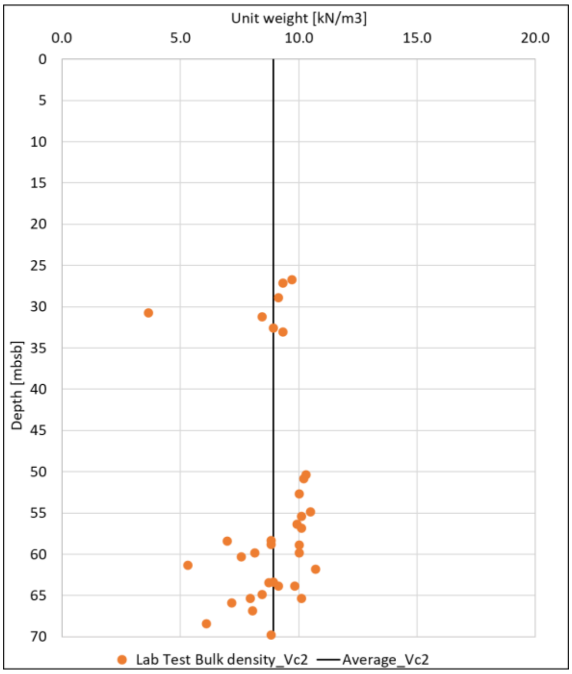


Figure 8-53. Submerged unit weight for unit Vc2.

Table 8.25. Submerged unit weight for each rock unit.

Rock Unit	γsub [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.

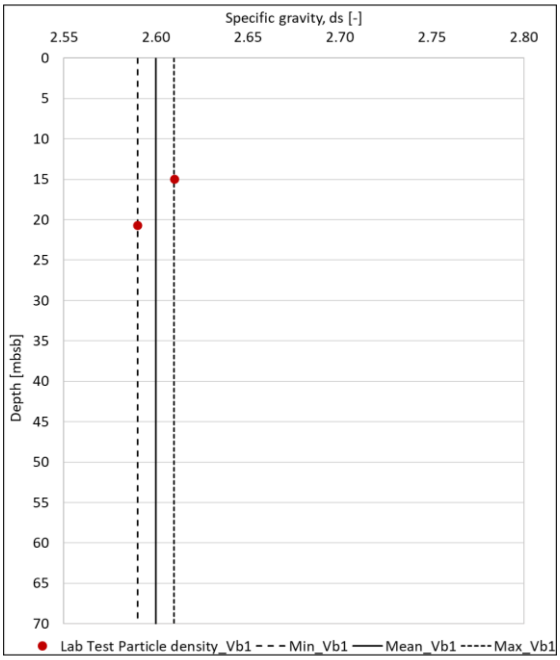


Figure 8-54. Specific gravity for unit Vb1.

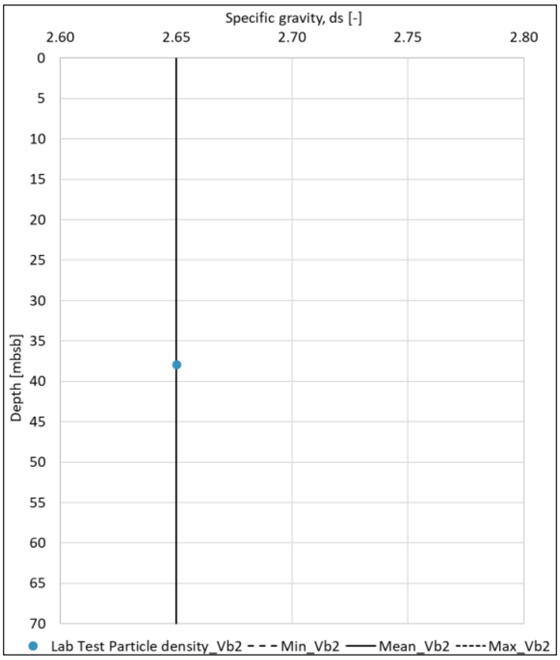


Figure 8-55. Specific gravity for unit Vb2.

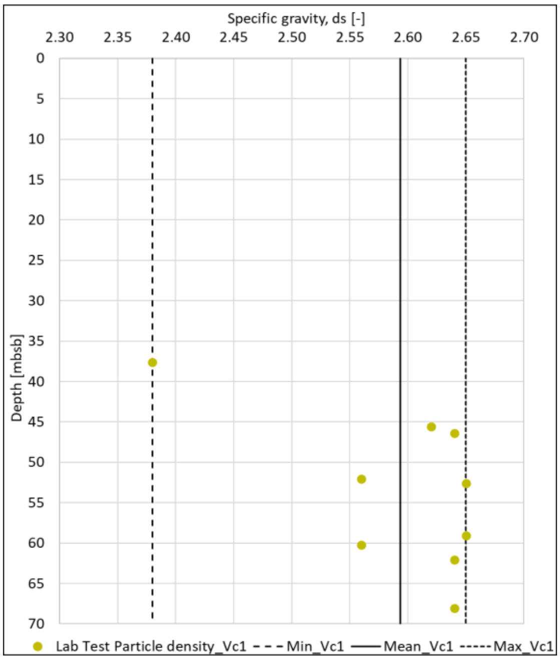


Figure 8-56. Specific gravity for unit Vc1.

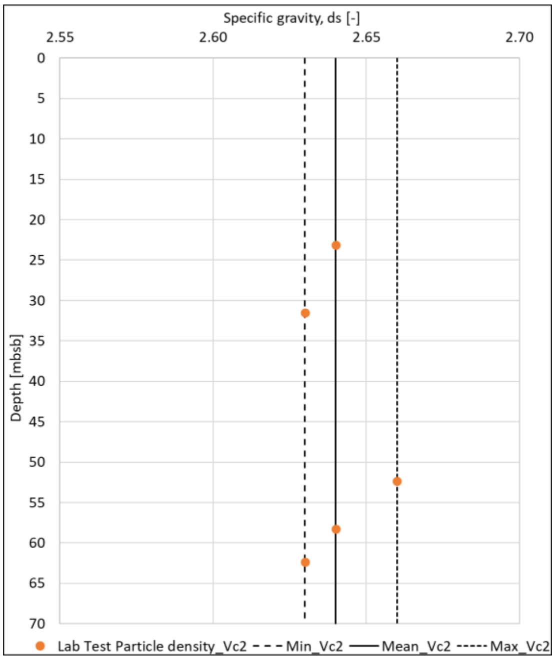


Figure 8-57. Specific gravity for unit Vc2.

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, where “EW” is for Extremely Weak, “VW” is for Very Weak, “W” is for Weak, “MW” is for Medium Weak, “ES” is for Extremely Strong, “VS” is for Very Strong, “S” is for Strong and “MS” is for 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.

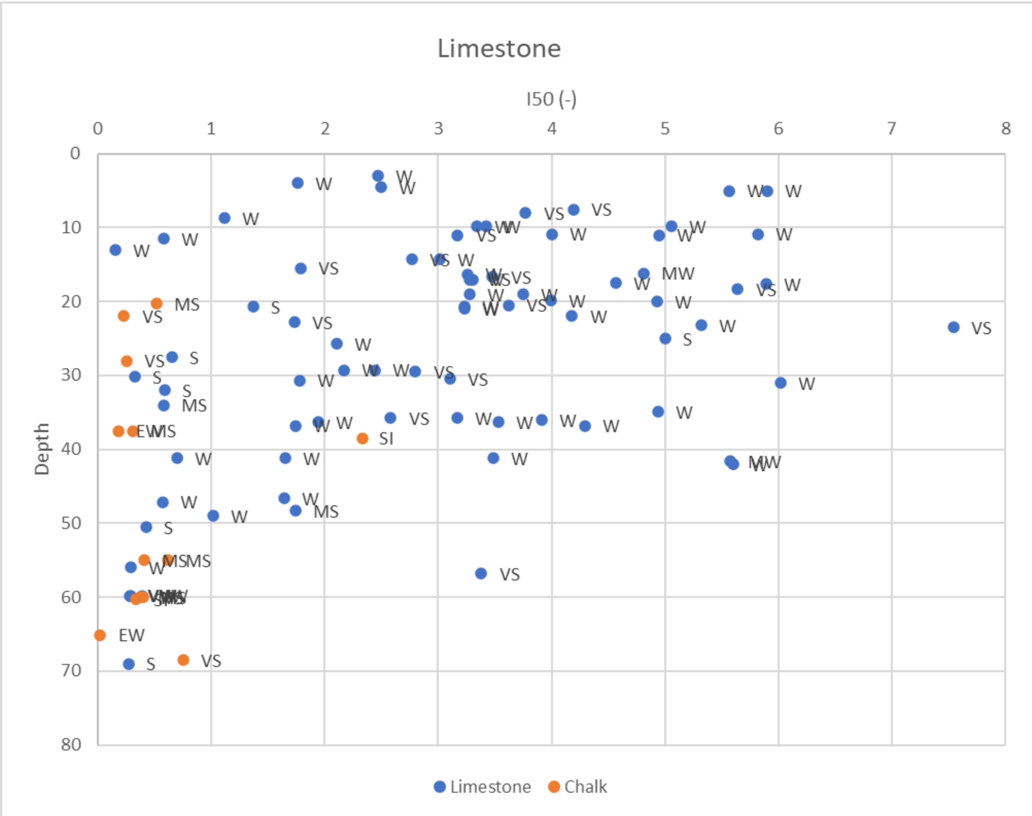


Figure 8-58. I_{50} index strength versus depth, limestone and chalk.

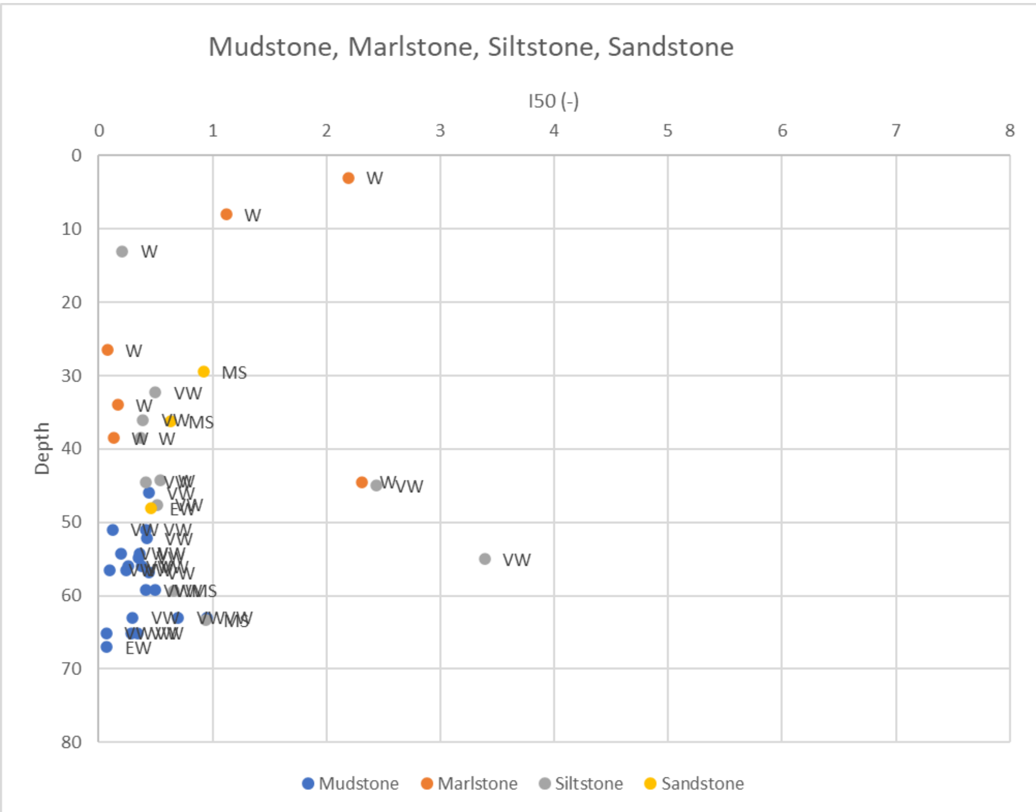


Figure 8-59. I_{50} index strength versus depth, mudstone, marlstone siltstone and sandstone.

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 value

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	
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*	
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*	

*Estimated values

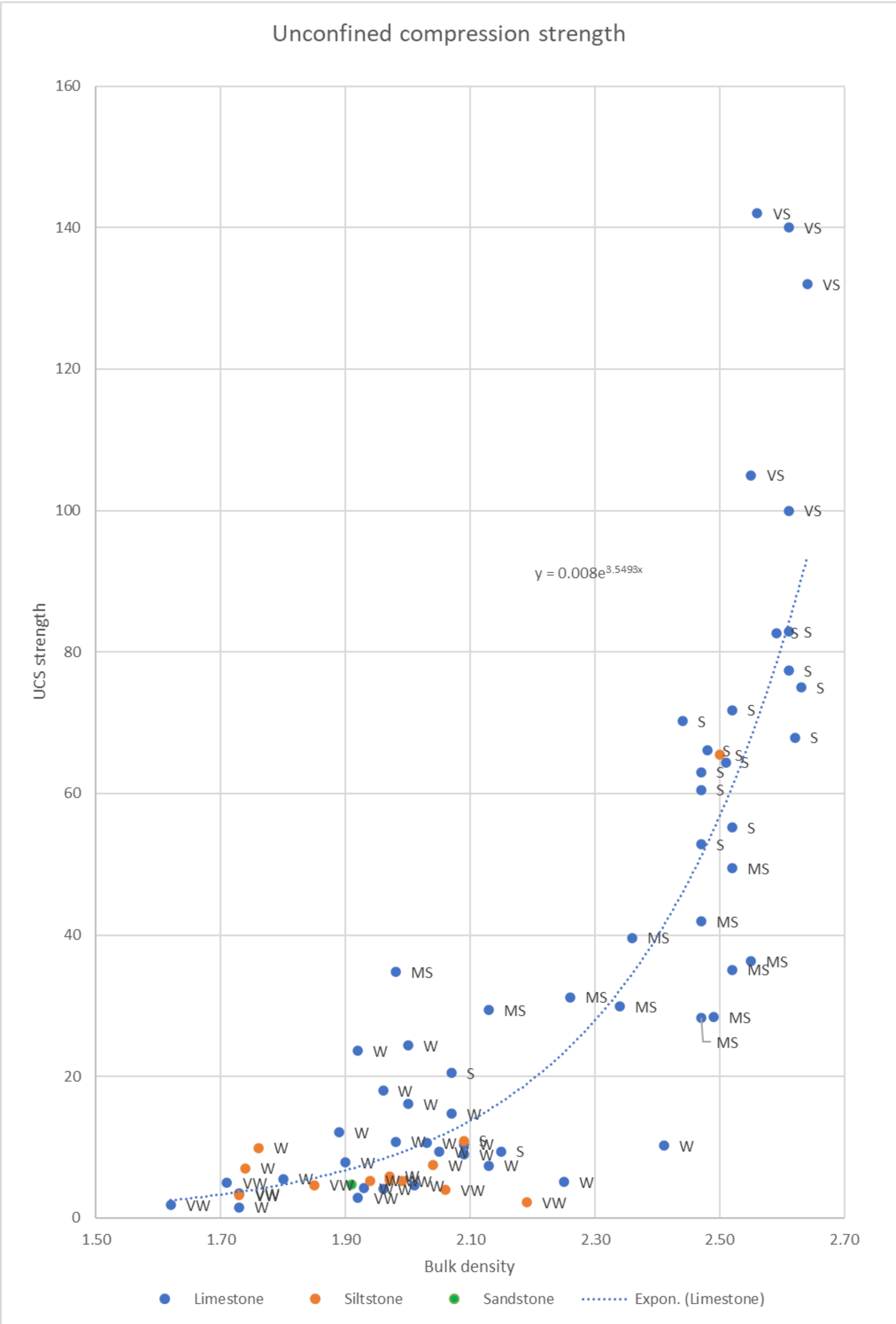


Figure 8-60. Unconfined compressive strength versus bulk density.

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 Vb1 and Vb2, 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

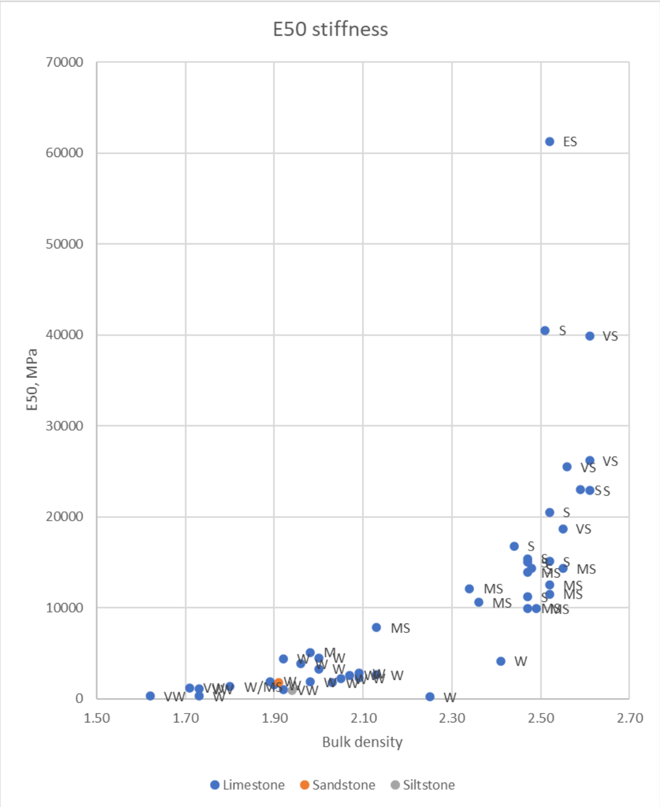


Figure 8-61. E50 stiffness from UCS tests, versus bulk density.

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 I.

Borehole	Picked "bedrock"	Rock type
BH-101	25.3	Weak limestone/weak marlstone
BH-102	9.1	Weak limestone/mudstone w. 2 MS limestone layers
BH-103	54.0	Chalk H2
BH-104	10.9	Weak limestone w. single MS limestone
BH-105	17.5	Weak limestone and strong siltstone w. single ES limestone layer
BH-107	30.5	Chalk H2 with H3/H4 layers. Bedrock picked at Dm chalk at 30.58
BH-108	14.5	Weak marlstone/limestone
BH-109	7.5	Very weak and weak siltstone
BH-110	14.0	Weak mudstone
BH-111	21.5	Very weak siltstone
BH-112	21.0	Extremely weak siltstone

BH-114	22.2	Chalk at 13 m followed by sand and sandstone from 34.7m. Bedrock picked in dense sand
BH-115	35.0	Weak sandstone

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 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 installation risks into account and estimate 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 is shown in Figure 9-1. For a circular footing at depth, the conventional analysis involves determining the ultimate bearing capacity, at that depth and then calculating the vertical displacement, 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.

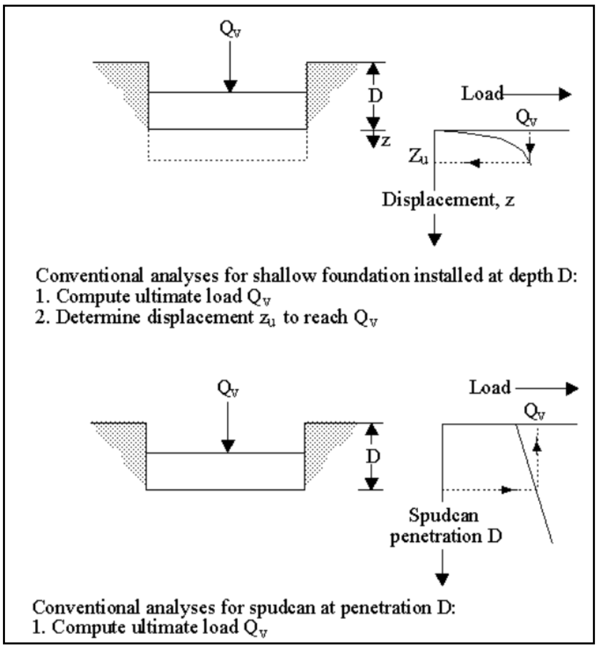


Figure 9-1. Conventional bearing capacity vs spudcan leg penetration (The Society of Naval Architects and Marine Engineers (SNAME)., August 2008).

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.

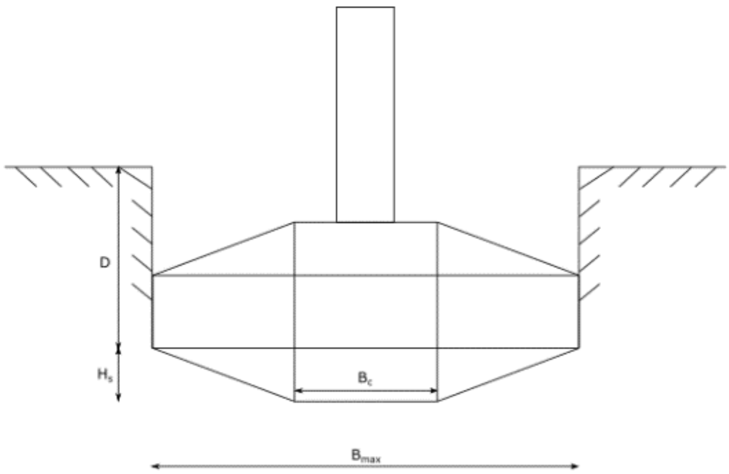


Figure 9-2. A common design of a spudcan.

The geometric and mechanical properties are given below:

Base area at	95.4 m^2
Base diameter,	11.02 m
Volume of the spudcan	266.7 m^3
Tip to base distance,	1.0 m
Base of tip [m]	3.1 m
Preload bearing pressure	89.5 t/m^2

The preload footing reaction is set to 8,538.3 tonnes and the stillwater 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,
submerged unit weight,
CLAY: Undrained shear strength,
submerged unit weight,
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-101/BH-101.
- Group 2 consists of location CPT-102/BH-102, CPT-103/BH-103, CPT-104/BH-104, CPT-105/BH-105, CPT-107/BH-107, CPT-108/BH-108, CPT-109/BH-109, CPT-110/BH-110, CPT-111/BH-111, CPT-112/BH-112 and CPT-114/BH-114. CPT-102/BH-102 and CPT-104/BH-104 have a small layer of sand at the top, which is less than 0.5 m and very loose, therefore they have been added in Group 2.
- Group 3 consists of location CPT-113/BH-113 where 1 meter of sand is found over clay. There is a large penetration in CPT-115/BH-115 and although it consists of clay soil from the seabed and it could be included in Group 2, it has been added in Group 3 as it is the only location with such a deep penetration combined with large water depth. From a first estimation a jackup with at least 70 m of minimum leg of length will be required.

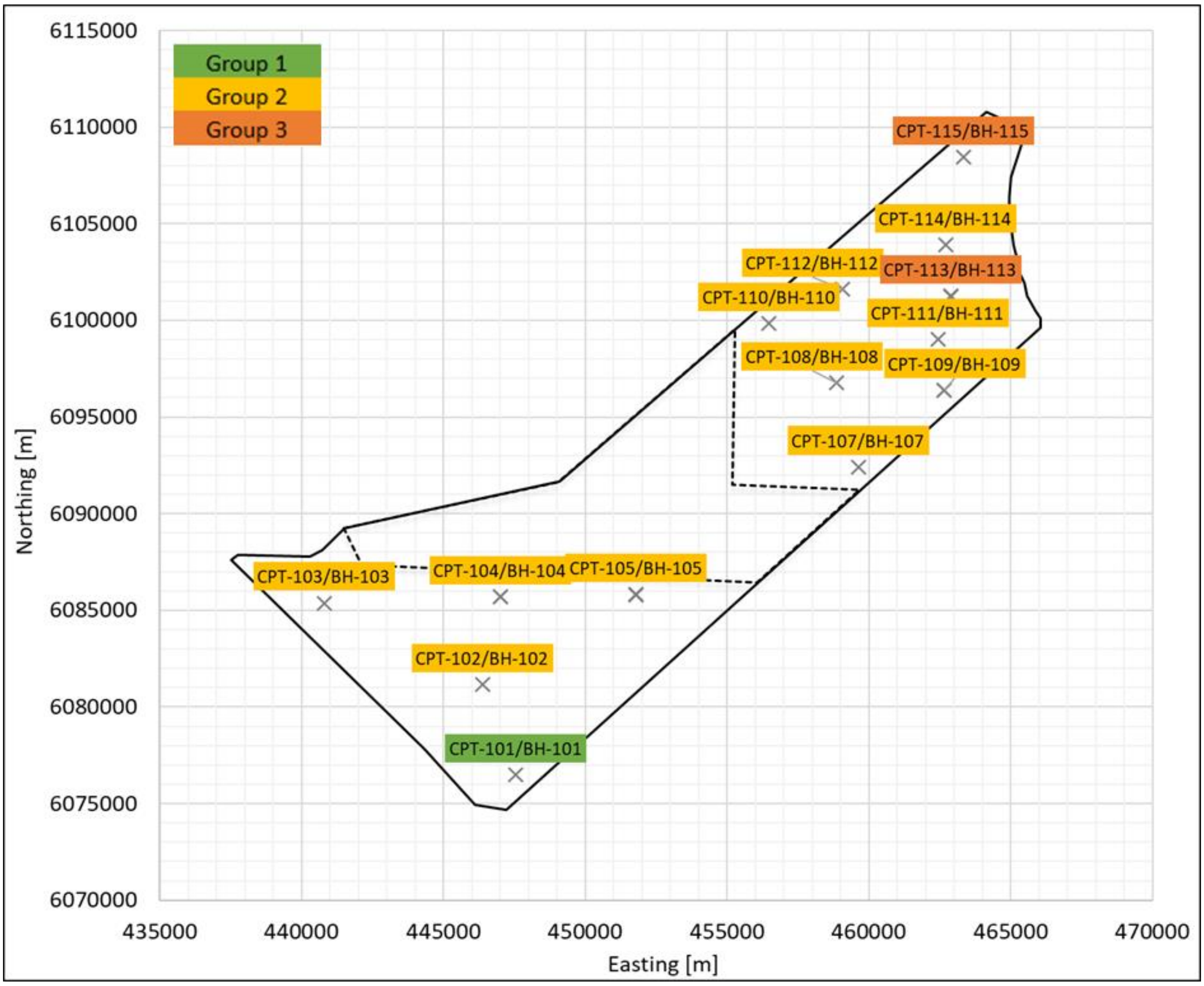


Figure 9-3. Group divided borehole with combined CPT locations.

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

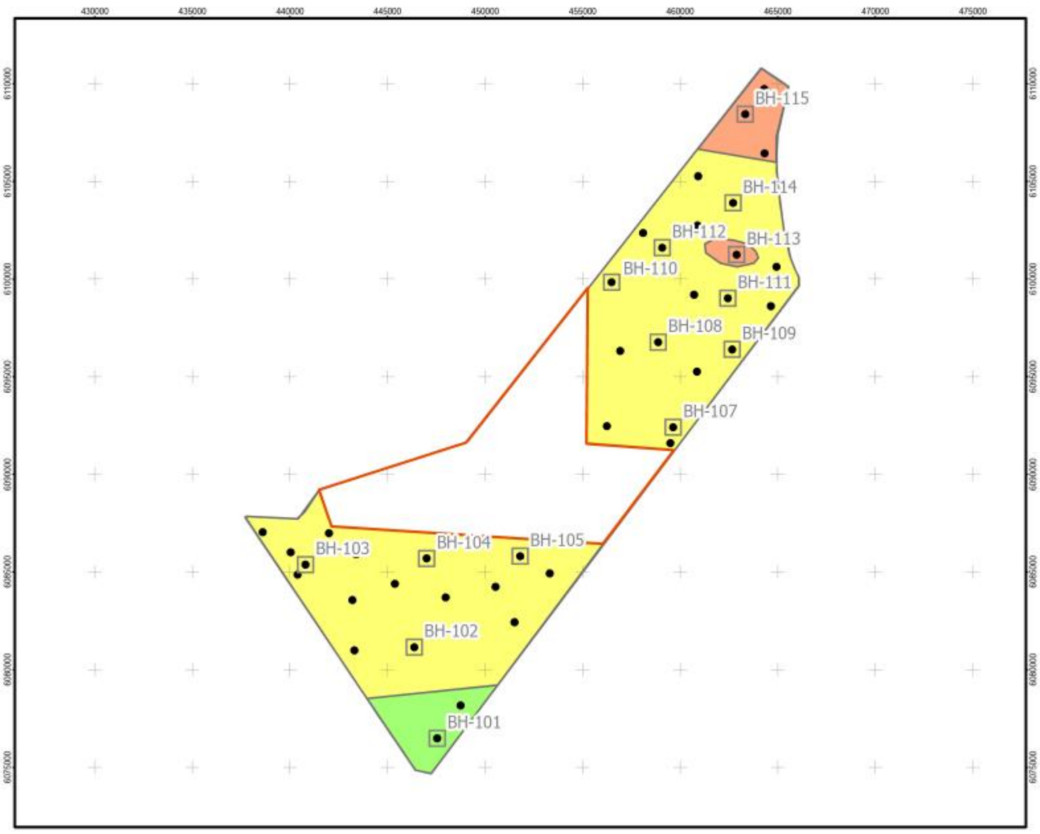


Figure 9-4. Group divided map showing polygons of the 3 groups. Group 1 is related to the green area, group 2 to yellow area and group 3 in the red area.

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-101/BH-101, which will be the representative soil profile of the group. The predicted spudcan resistance of Group 1 can be seen in Figure 9-5.

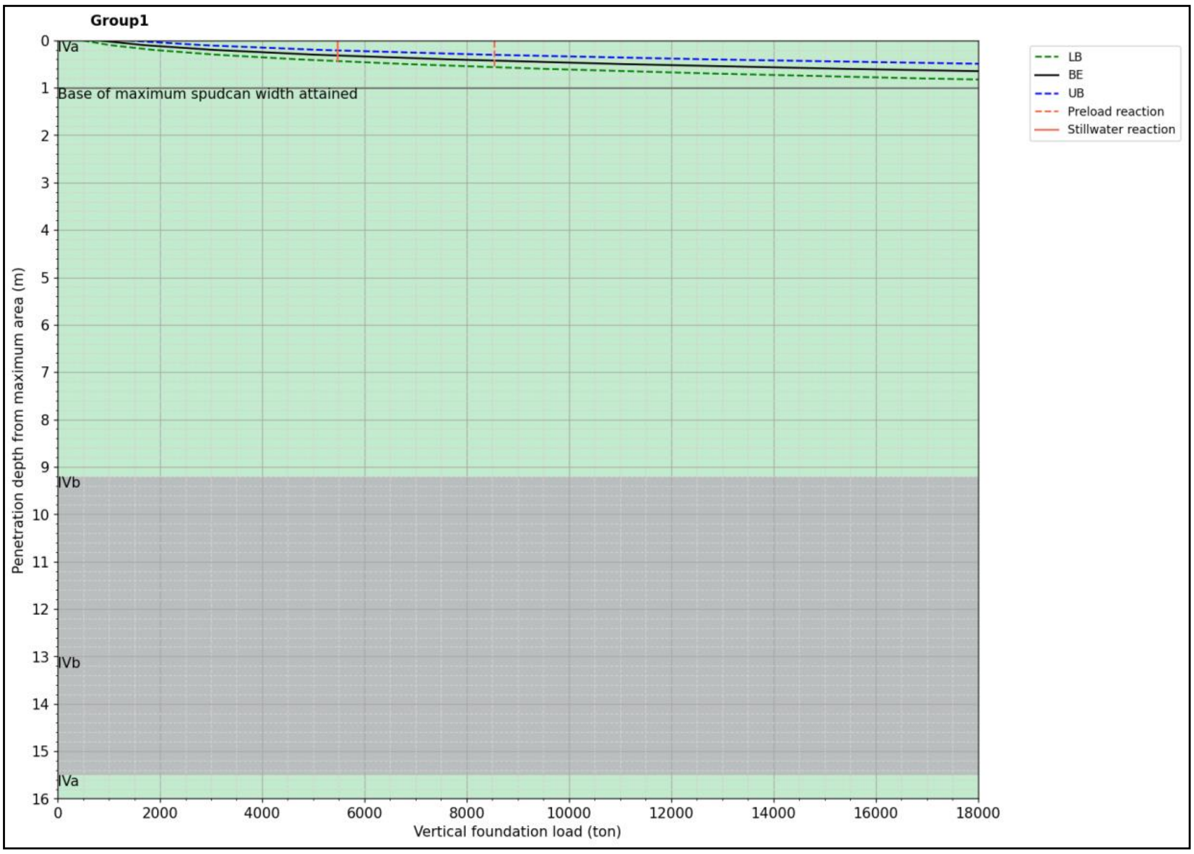


Figure 9-5. Predicted spudcan resistance of Group 1.

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	0.32	0.42
UB	0.21	0.30

9.7 Group 2

The representative location of Group 2 is CPT-112/BH-112, where the soil profile consists of 10.4 m soft clay, underlain by a stiffer clay down to 15.5m below seabed. This is then followed by hard and stiff sand and clay layers. The predicted spudcan resistance of Group 2 can be seen in Figure 9-6.

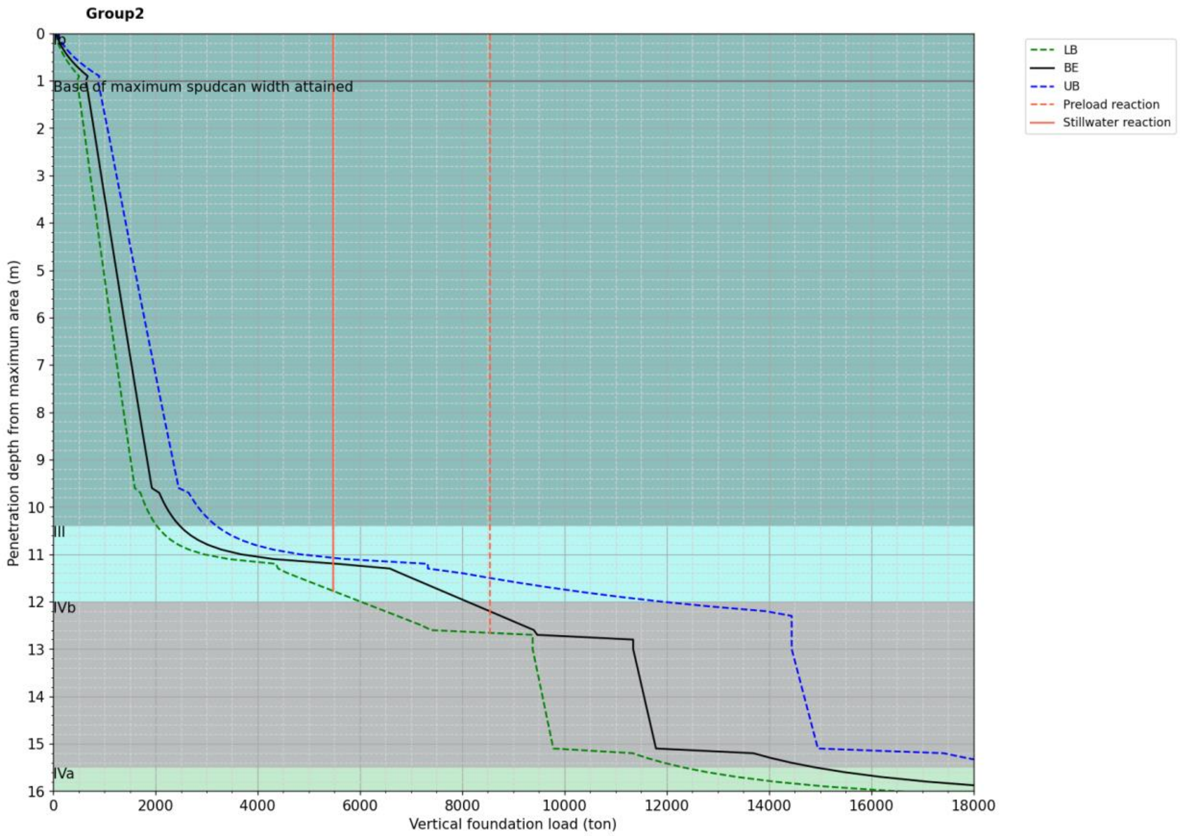


Figure 9-6. Predicted spudcan resistance of Group 2.

Table 9.3 gives the predicted penetration depths for stillwater and preload reaction. It can be observed that the predicted penetration depths are around 11.1m below seabed to 12.7m below seabed. From 0 to 9.7m the penetration happens in the soft clay layer, where after 9.7m the clay gets squeezed down to around 11.3m. From around 11.3 to 12.7m punch-through clay over clay interchanged with squeezed clay. Depending on the boundary (LB, BE or UB) this range changes. Subsequently, the clay in this depth is getting penetrated.

Table 9.3. Predicted penetration depth for Group 2.

Boundary	Depth for stillwater reaction [m]	Depth for preload reaction [m]
LB	11.8	12.7
BE	11.2	12.2
UB	11.1	11.5

9.8 Group 3

The representative location of Group 3 is CPT-113/BH-113, where the soil profile consists of 1.0 m loose sand, underlying by soft clay down to 12.8m below seabed. This is then followed by interchanging hard and stiff sand and clay layers. The predicted spudcan resistance of Group 3 for CPT-113/BH-113 location can be seen in Figure 9-7.

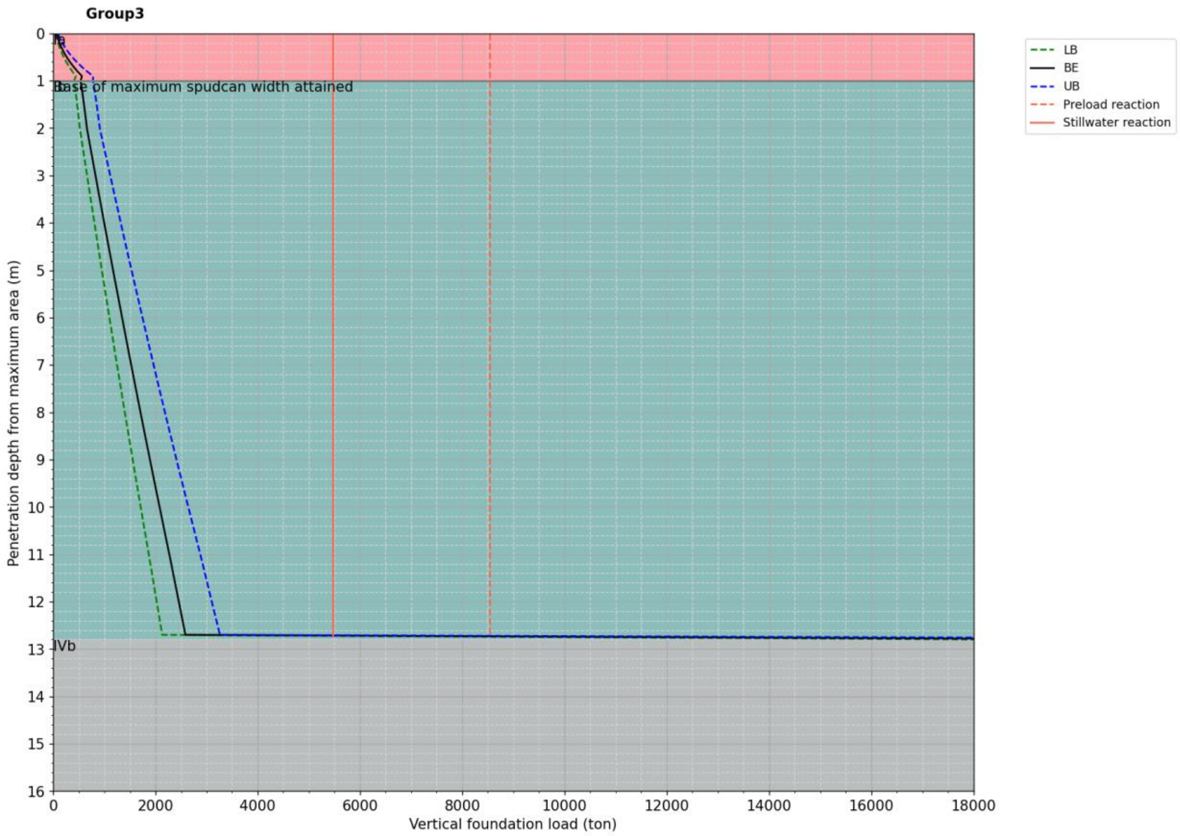


Figure 9-7. Predicted spudcan resistance of Group 3 for CPT-113/BH-113.

Table 9.4 gives the predicted penetration depths for stillwater and preload reaction. It can be observed that the predicted penetration depths are at 12.7 m below seabed. The 1 m of sand overlying around 12 m soft clay results in punch-through down to 12.7 m below seabed followed. This risk of rapid penetration is high at this location.

Table 9.4. Predicted penetration depth of Group 3 for CPT-113/BH-113.

Boundary	Depth for stillwater reaction [m]	Depth for preload reaction [m]
LB	12.7	12.7
BE	12.7	12.7
UB	12.7	12.7

Further information regarding the presence of sand over clay is described in section 11.2.3.

The location CPT-115/BH-115 is investigated also in Group 3 since it is the only location found with such a deep penetration. The soil profile consists of 23.5m of soft clay, underlain by a stiffer clay down to 24.7m below seabed. The predicted spudcan resistance of this location can be seen in Figure 9-8.

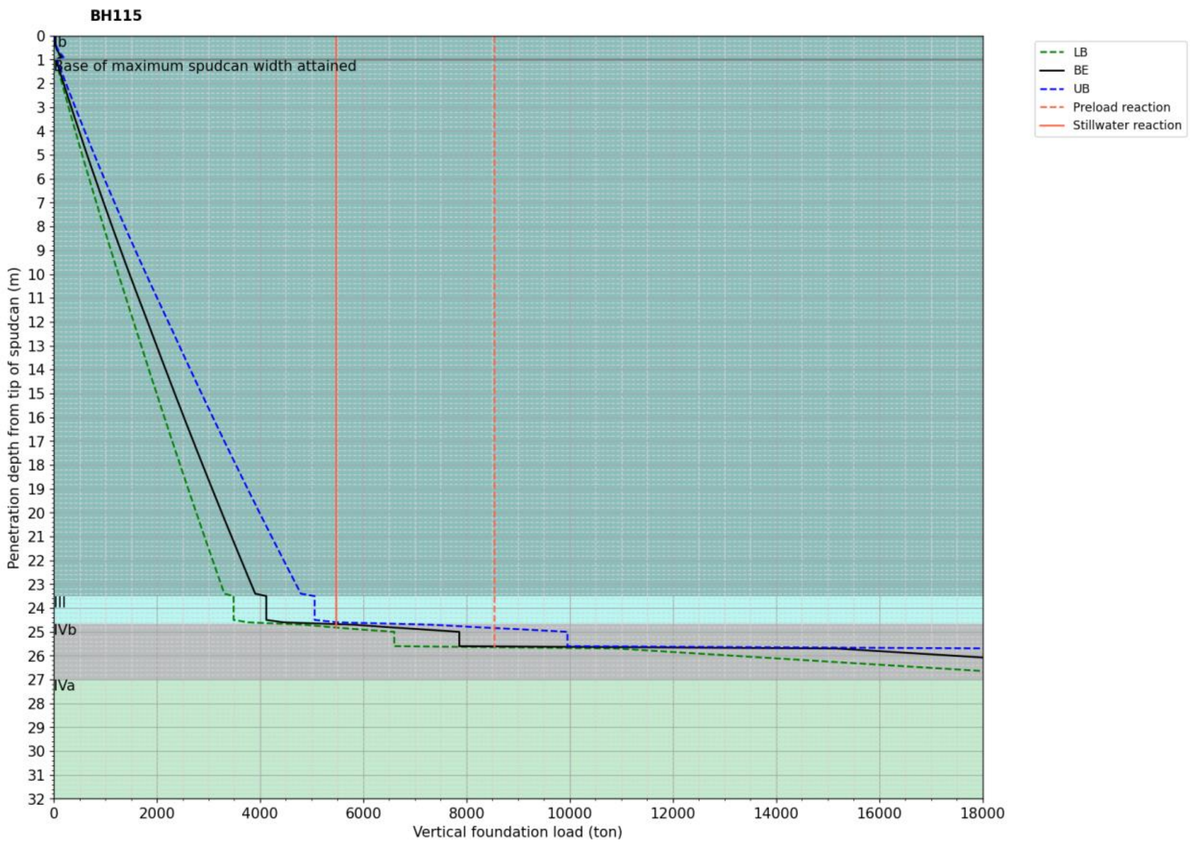


Figure 9-8 Predicted spudcan resistance of Group 3 for CPT-115/BH-115.

Table 9.5 gives the predicted penetration depths for stillwater and preload reaction. It can be observed that the predicted penetration depths are around 24.6m below seabed to 25.6m below seabed due to the soft soils in this location.

Table 9.5 Predicted penetration depth of Group 3 for CPT-115/BH-115.

Boundary	Depth for stillwater reaction [m]	Depth for preload reaction [m]
LB	24.8	25.6
BE	24.7	25.6
UB	24.6	24.8

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 given investigated location and the soil profile itself. 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. 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. 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

10.1 Introduction

This section describes the Bornholm I Ground Model. Six Ground Model Units have been defined based on integration of the Seismic and Geotechnical Units and they have been mapped across the Bornholm I Site. Where possible the Ground Model Units have been tied to the Seismic Units that are described in Chapter 7 deviations from this are described below.

It must be noted that not all the Geotechnical Soil Units have been incorporated into the Ground Model; Soil Unit II has only been defined in a few of the Boreholes and CPTs in the Bornholm I dataset and no attempt has been made to map it across the Bornholm I Site. The Bornholm I Ground Model comprises the following Units, stratigraphically from top to bottom they are:

1. GMU1 – Soil Unit Ia (loose to medium dense sand).
2. GMU2 – Soil Unit Ib (soft, organic-rich clays).
3. GMU3 – Soil Unit III (firm to stiff, sandy clay).
4. GMU4 – Soil Unit IVb (very stiff to very hard clay till).
5. GMU5 – Soil Unit IVa (medium-dense to dense sand).
6. GMU6 – Bedrock: Soil Unit V (variable lithologies).

The relationship of these GMUs to the Geotechnical Soil Units to the mapped Seismic Units is summarised in Table 10.1.

Table 10.1. Table summarising how the defined seismic, sediment and geotechnical units correlate to the integrated Ground Model Units.

Integrated Ground Model Units	Top Seismic Horizon	Bottom Seismic Horizon	Geotechnical Soil Unit	Seismic Unit(s)	Lithology	Depositional Environment	Age
GMU1	H00 Seabed	H15	Soil Unit Ia	Seismic Unit 2a	Loose Sand	Shoreface, shallow marine	Latest Pleistocene to Holocene
GMU2	H00 Seabed/H15	H30	Soil Unit Ib	Seismic Unit 1 Seismic Unit 2b Seismic Unit 3	Soft, Organic-rich Clay	Marine and lacustrine clays	Late Pleistocene (Baltic-Lake/Sea)
GMU3	H30 (H35)	H40 or interpolated from CPT/BH picks	Soil Unit III	Seismic Unit 4	Transitional to Stiff Clay (Silty Clay)	Glacial Till and/or Moraine	Pleistocene
GMU4	H40 or interpolated from CPT/BH picks	H50 (Bedrock) or H45	Soil Unit IVb	Seismic Unit 4	Stiff Clays	Glacial Till and ice-front distal subaqueous fan or distal delta front	Pleistocene
GMU5	H45	H50 (Bedrock)	Soil Unit IVa	Seismic Subunit 4c	Dense sand	Sandy delta or ice-front subaqueous plume fan	Pleistocene
GMU6	H50 (Bedrock)		Soil Unit V	Bedrock	Limestones, chalk, sandstone, marls and locally coal	Deltaic to marine	Jurassic & Cretaceous

In some instances it has proved impossible to define a perfect match between the mapped Seismic Horizons and the Geotechnical Soil Units that define the various Ground Model Units. In such instances the depth picks of the Soil Units in the CPTs and Boreholes have been gridded with the resulting grid being adjusted to existing Seismic Horizons (see discussions below).

Each Ground Model Unit is described below with the relationship of the Ground Model units to the Bornholm I Site geology being demonstrated in Figure 10-1 and Figure 10-2. Charts depicting the depth below the Seabed to top of the Ground Model Units are illustrated in Appendix 8 and their thicknesses are illustrated 9. A set of cross sections are depicted in Appendix 10.

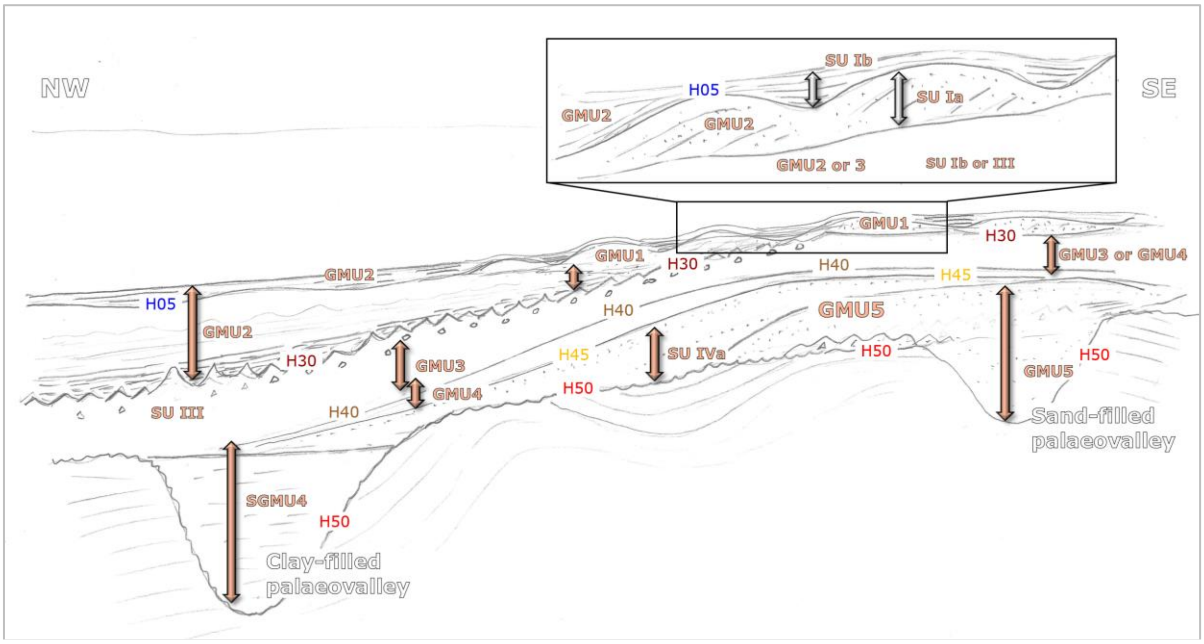


Figure 10-1 Conceptual sketch orientated broadly SW to NE across the Bornholm I Site, favouring the eastern side where the sand bodies that comprise Seismic Subunit 4c are located. The sketch illustrates the how the mapped seismic horizons, the geology and the Geotechnical Soil Units correlate. For a section sitting at right-angles to this model see Figure 10-2. See text for discussion.

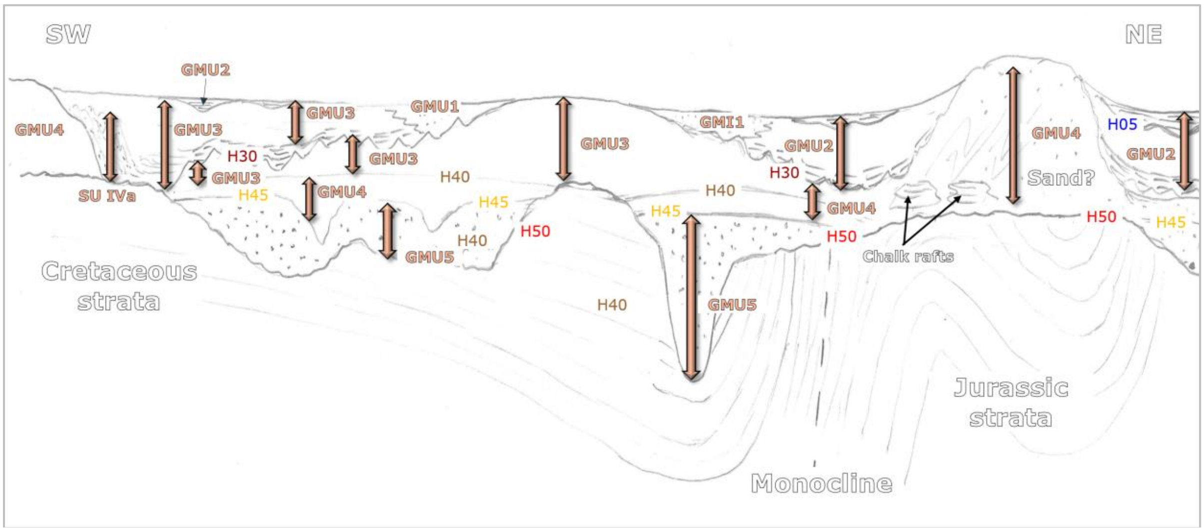


Figure 10-2. Conceptual sketch orientated in NW to SE orientation across the Bornholm I Site, orientated at right angles to that illustrated in Figure 10-1. No CPTs nor Boreholes have penetrated the large moraine like feature that forms a bathymetric high in the northern part of the Bornholm I site, but a borehole has penetrated a similar feature in Bornholm II where stiff sands of Geotechnical Soil Unit IVa were encountered. As a result, the sediments that comprise the thick moraine ridge have been assigned to Geotechnical Soil Unit IVa pending future geotechnical investigations.

10.2 GMU1 – Geotechnical Soil Unit Ia (loose to medium dense sand)

Loose, low to medium strength sands, as defined by the Geotechnical Soil Unit Ia have been encountered in few locations along the south-eastern part of the Bornholm I Site and, in a strip, south of the Bathymetric High. These sands comprise Ground Model Unit 1 (GMU1). Where present, the soft sands appear to correspond to the mapped H15 Seismic Horizon and the mounded facies of Seismic Unit 2a (see Section 7.4 and Figure 7-5). Given this correlation the distribution of the mounded facies in Seismic Unit 2a has been used to populate this Soil Unit/Zone in the Ground Model, with the H15 Seismic Horizon having been used to define the base of the Soil Unit Ia sands and thus GMU1. The resulting distribution of the GMU1, represented by Soil Unit Ia, is shown in Figure 7-5 and Chart 2.2 with the thickness of GMU1 illustrated in Chart 3.1. Cross sections through this Soil Unit depicted in Appendix 10.

The loose, low to medium strength sands of Soil Unit Ia are expected to occur at the very top of the sediment succession. It remains possible that thin layers of soft, organic clays (Soil Unit Ib) may overlie the Soil Unit Ia sands, or even intercalate with the sand.

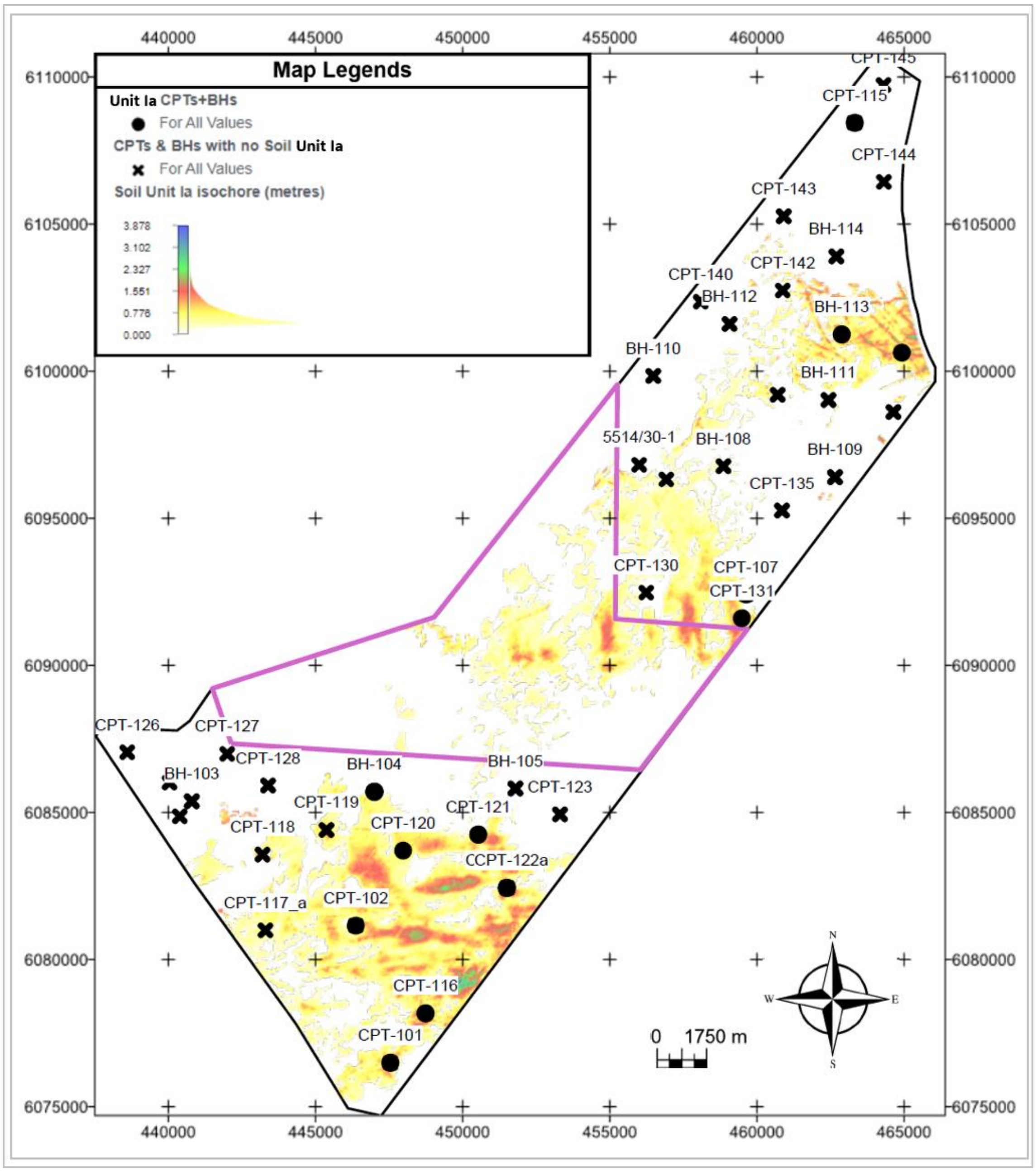


Figure 10-3. GMU1 (Geotechnical Soil Unit Ia) isochore based on the mapped Seismic Unit 2a mounded facies, illustrating both the distribution and the thickness of this Geotechnical Soil Unit across the Bornholm I Site.

10.3 GMU2 – Geotechnical Soil Unit Ib (soft, organic-rich clays)

The soft, organic-rich clays that define Soil Unit Ib and which characterise GMU2 make up most of the Holocene and Baltic Lake succession at the Bornholm I Site. This Ground Model Unit comprises the Bulk of Seismic Units 1 and 3 and they its soft, organic-rich clays also fill the channel features of Seismic Unit 2b. In the Ground Model the top of Unit 2 is defined over much of the area by the modern-day seabed or, where present, the base of GMU1 (loose sands of Soil Unit Ia). GMU2 wedges out against the Glacial sediments whose top is defined by the H30 Seismic Horizon such that this Ground Model Unit is absent as a continuous sheet over much of the eastern part of the Bornholm I Site (Figure 10-4). Although not present as a continuous sheet in the eastern part of the Bornholm I Site, GMU2 (Soil Unit Ib), is locally preserved in small pockets between the sand mounds of GMU1, or in hollows between the eroded moraine ridges that define the top of the glacial successions of Seismic Unit 4a (see patchy distribution in Figure 11-6 and discussion in Section 11.2.1 below).

GMU2 (Soil Unit Ib) thickens towards the East and the North and it reaches its maximum thickness of just over 30 m in the northern part of the Bornholm I Site around the location of CPT-145 (Figure 10-4). Figure 10-4 and Chart 2.3 illustrate the depth at which GMU2 (Soil Unit Ib) is likely to be encountered beneath the seabed whilst its thickness across the site is shown in Chart 3.2.

Given the weak nature of soft organic-rich clays that comprise GMU2 any structure of significant weight is likely to be subject to self-weight penetration (SWP) into this Ground Model Unit and this soil is unlikely to offer any significant support for foundations. This issue is discussed in Sections 8 and 9 above. When creating the Soil Province map (see Figure 12-3 & Chart 4.3) a critical depth of 5 m for GMU2 (Soil Unit Ib) soft clays was considered to be important from a Geotechnical design perspective; areas with less than 5 m thickness of Soil Unit Ib are differentiated from those areas where thickness was more than 5 m (Chart 4.2).

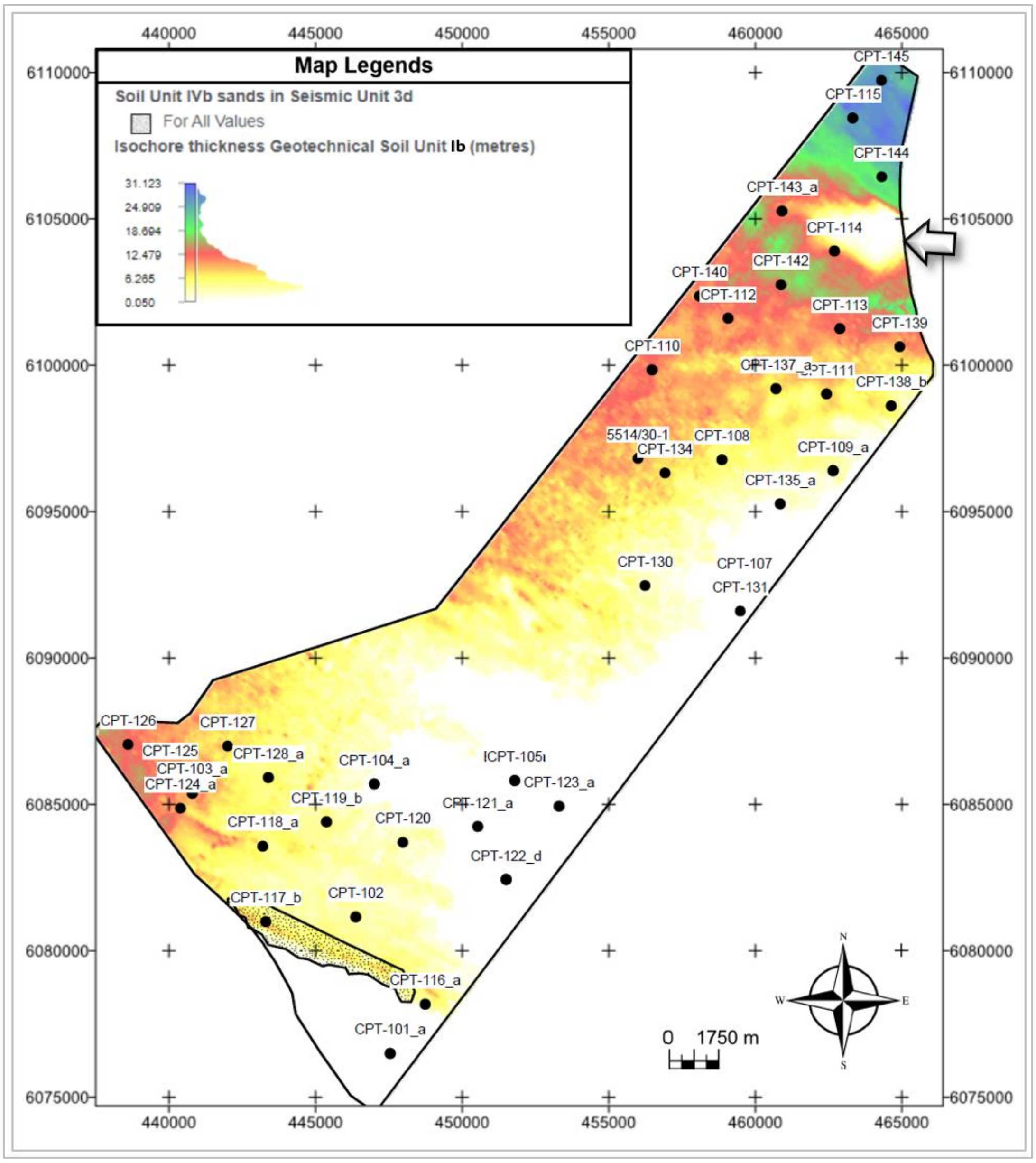


Figure 10-4. Map illustrating the distribution and thickness of the soft, organic-rich clays of Geotechnical Soil Unit Ib. Note how this unit thins onto highs developed in the Underlying Glacial Units (GMU3 & 4) in the East and South of Bornholm I as well as over the moraine-ridge developed in the North of the Site (arrowed). Also shown is a polygon where sands (assigned to Soil Unit IVa) might be present in GMU2 at relatively shallow depths. These Soil Unit IVa Sands have been encountered in the CPT-117 location, but their full distribution remains uncertain (see Section 7.5).

10.4 GMU3 – Geotechnical Soil Unit III (firm to stiff, sandy clay)

GMU3 is defined Geotechnically by Soil Unit III. This Soil Unit marks a transition from the soft, organic-rich clays of the Baltic Lake Succession (GMU2) to the firm to stiff sandy clays of the glacially influenced Bornholm I successions. Although thin intervals of Geotechnical Soil Unit III are observed at the base of GMU3, particularly in the 3c Seismic Subunit, Soil Unit III is primarily associated with Seismic Unit 4a in the Bornholm I Site. As such the top of GMU3 (Soil Unit III) is defined in the Ground Model by the highly irregular H30 Seismic Horizon (see Table 10.1).

The base of GMU3 (Soil Unit III) has been more difficult to map. In many CPTs and Boreholes the boundary between Soil Unit III and Soil Unit Ib occurs within Seismic Unit 4a; it does not coincide with a mappable seismic event. Moreover, there are areas in the Bornholm I Site where Soil

Unit III is absent, and Soil Unit Ib passes directly into the very stiff to very hard clay tills that comprise Soil Unit IVb. In these areas GMU2 is directly underlain by GMU4, GMU3 is absent.

To capture the spatial distribution of GMU3 (Geotechnical Soil Unit III) the base of the unit was constructed step-wise using the following procedures:

1. Since the base of Soil Unit III generally doesn't coincide with a mapped Seismic Horizon an initial grid was created from gridding the Geotechnical picks in the CPTs and Boreholes. Care was taken to ensure that the gridded base of GMU3 was deeper than CPTs that had reached their terminal depth within Geotechnical Soil Unit III. This was achieved by adding 'dummy' picks to those CPTs which terminated in Soil Unit III.

The base of Geotechnical Soil Unit III was then adjusted;

2. Where the initial Grid for the base of Soil Unit III sat shallower than the H30 Seismic Horizon (top of Seismic Unit 4) it was adjusted down so that it conforms with H30.
3. CPTs and Boreholes that have penetrated into Seismic Unit 4b, defined by the H40 Seismic Horizon show that this unit is characterised by Geotechnical Soil Unit IVb. Where the initial Soil Unit III base grid was deeper than H40 it was subsequently adjusted upwards to the H40 Seismic Horizon.

The final grid for the base of GMU3 (Soil Unit III) is therefore an amalgamation of an initial gridding of the CPT and Borehole Soil Unit picks that has subsequently been constrained by Seismic Horizons H30 and H40. Furthermore, GMU3 (Soil Unit III) has also been clipped out against the H30 Seismic Horizon in those areas where Soil Unit IVb sits directly below the H30 Seismic Horizon and where Soil Unit III is not recorded in the CPTs and Boreholes and Soil Unit Ib sits above Soil Unit IVb (see Figure 10-5).

The distribution and thickness of GMU3 (Soil Unit III) is illustrated in Figure 10-5, Chart 2.4 and Chart 3.3. GMU3 (Geotechnical Soil Unit III) is absent over the southern part of Bornholm I and has a limited distribution in northern areas (Figure 10-5).

Cross sections illustrating its distribution are provided in Appendix 10.

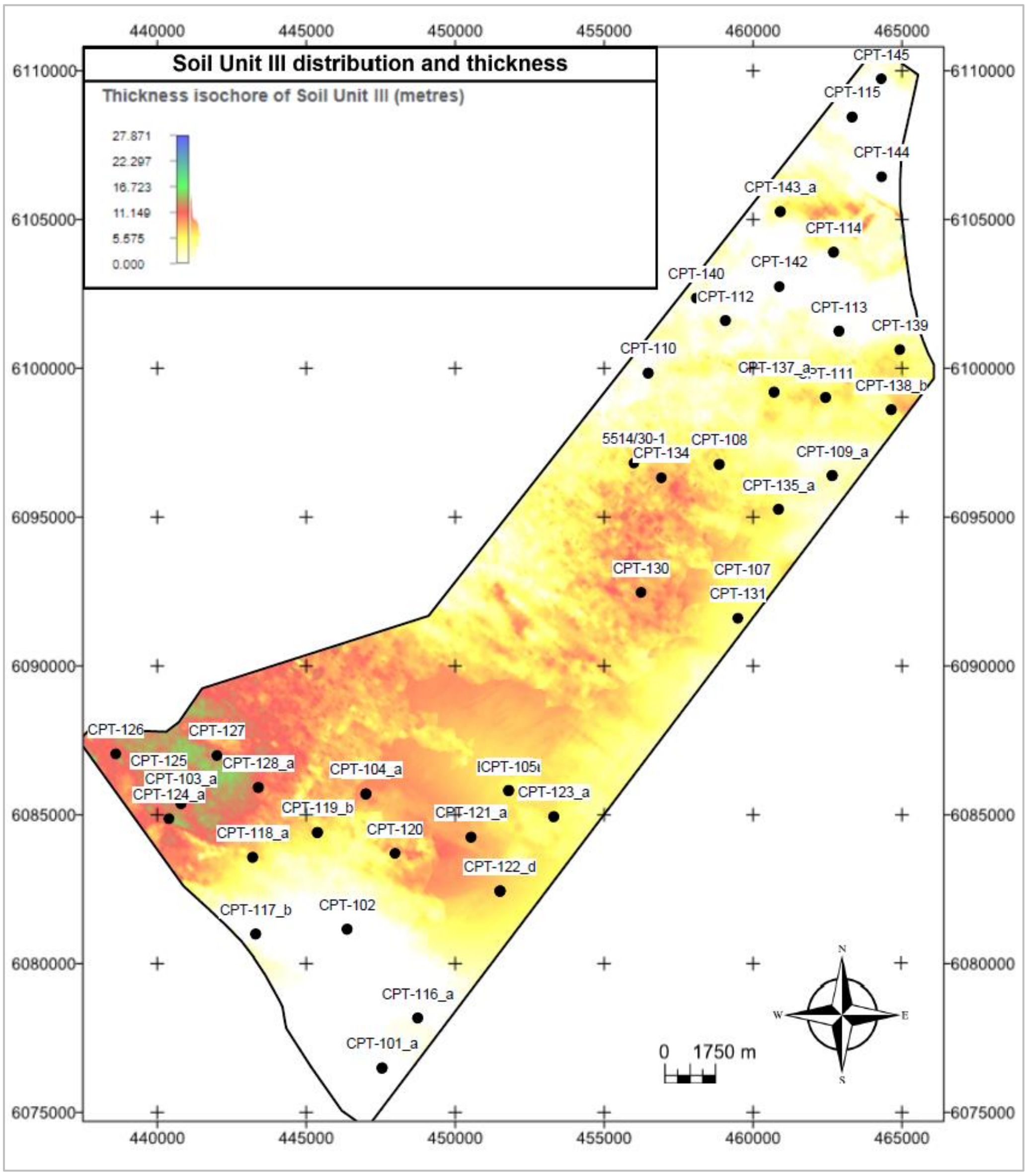


Figure 10-5. Map illustrating the distribution and thickness of GMU3 (Geotechnical Soil Unit III). Note that GMU3 is absent in the vicinity of CPT-112, 142, 113 and 139. Here the soft organic-rich clays of GMU2 directly overly GMU4.

10.5 GMU4 – Geotechnical Soil Unit IVb (very stiff to very hard clay till)

The very stiff to very hard glacial tills of Geotechnical Soil Unit IVb, which define GMU4 are confined to Seismic Unit 4 (Table 10.1). In places this GMU4 (Soil Unit IVb) can comprise the entire stratigraphic interval of Seismic Unit 4, although it normally occurs beneath an interval of Geotechnical Soil Unit III (GMU3). The top surface for GMU4 (Soil Unit IVb) is the composite surface discussed above; in places it conforms to the H30 Seismic Horizon (top of Seismic Unit 4), and in other areas it is marked by the H40 Seismic Horizon. There are areas, however, where the contact between Soil Unit III and IVb does not conform to a seismic event/pick and here the top surface has been created by simply gridding up the CPT picks themselves. Since the upper surface cannot always be defined seismically there is obviously some uncertainty to the depth at which GMU4 (Geotechnical Soil Unit IVb) will be encountered.

The base of GMU4 (Geotechnical Soil Unit IVb) is either the top bedrock Seismic Horizon, H50, or the H45 Seismic Horizon that defines the top of the sand-systems of Seismic Unit 4c. GMU4 is present throughout much of the Bornholm I Site. The thickness of GMU4 is displayed in Figure 10-6 and Chart 3.4, whilst the depth beneath the Seabed at which it is likely to be encountered is illustrated in Chart 2.5. Its geometry can be observed on the Cross-sections reproduced in Appendix 10. In the Southwestern part of Bornholm I GMU4 (Soil Unit IVb) can be very thick as it fills palaeovalleys that have been carved into the bedrock (Figure 10-6). BH-103 penetrated one of these palaeovalleys proving the thick succession of GMU4 (Soil Unit IVb).

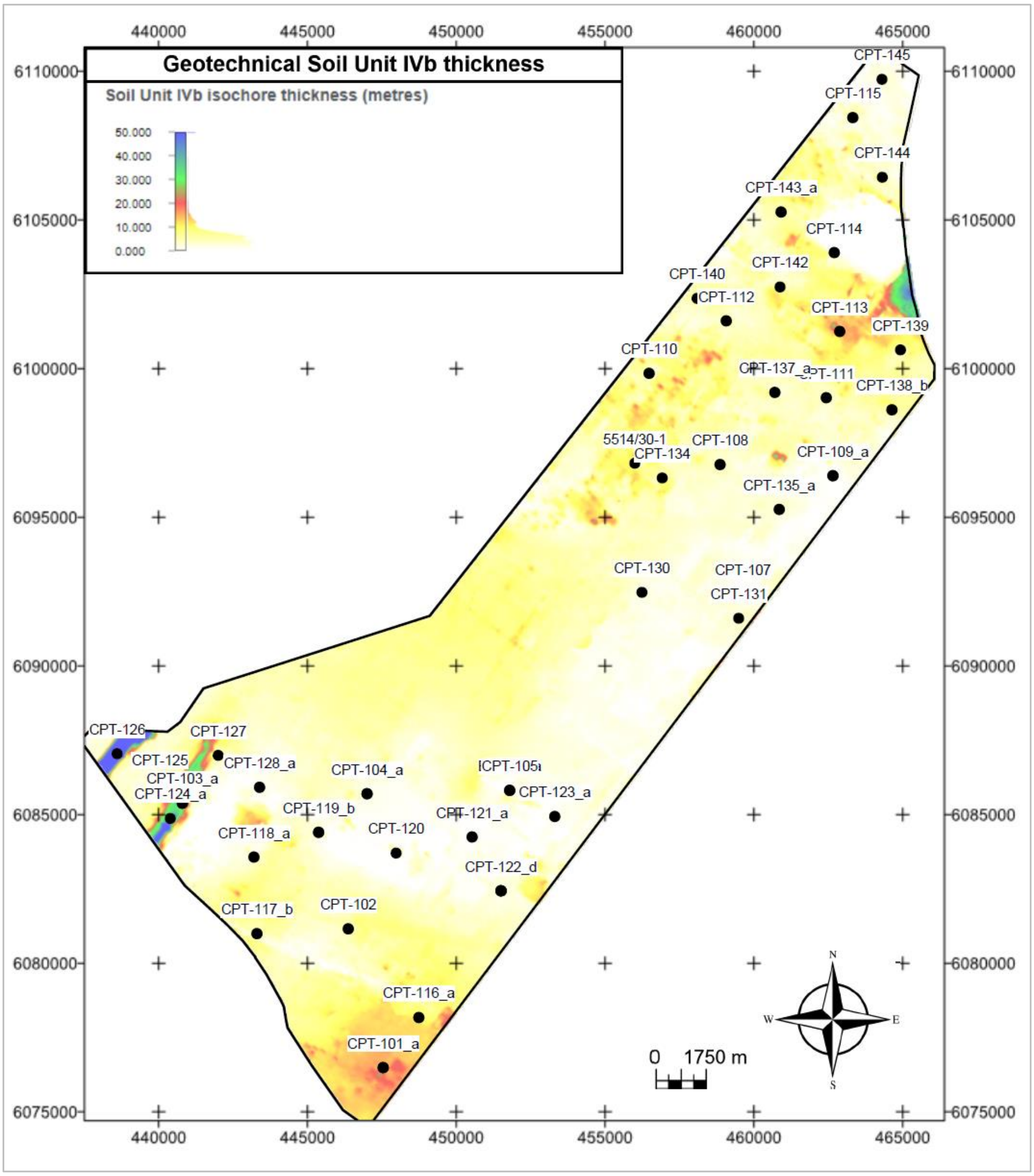


Figure 10-6. Map illustrating the distribution and thickness of GMU4 (Geotechnical Soil Unit IVb). Note how this Unit plugs deep valleys that have been carved into the bedrock in the southeast corner of the Bornholm I Site.

10.6 GMU5 – Geotechnical Soil Unit IVa (medium dense to dense sand)

The medium dense to dense sands of Geotechnical Soil Unit IVa define GMU5. These dense, stiff sands are largely confined to Seismic Unit 4c (see Section 7.6.3 above), although there is a narrow belt of Soil Unit IVa in Seismic Unit 3 (Subunit 3d) in the southern part of Bornholm I (see Section 7.5.7 above). In the Ground model Geotechnical Soil Unit IVa is defined only at the level of Seismic Unit 4c, since the lateral extent of the thin strip of Soil Unit IVa in Seismic Unit 3d remains uncertain. A polygon is provided illustrating the area in which Soil Unit IVa might be encountered at slightly shallower intervals (see polygon in Figure 10-4). More Ground Information is required to better assess the presence and distribution of Soil Unit IVa in Seismic Unit 3d.

In the current Ground Model GMU5 (Geotechnical Soil Unit IVa) forms a series of depositional wedges along the Eastern part of the Bornholm I Site (See Section 7.6.3 above) and it also fills palaeovalleys that have been carved into the Bedrock along the same Eastern Flank (see Section 7.6.4 above). Maps illustrating its extent and thickness are provided in Figure 10-7, Chart 2.6 and Chart 3.5.

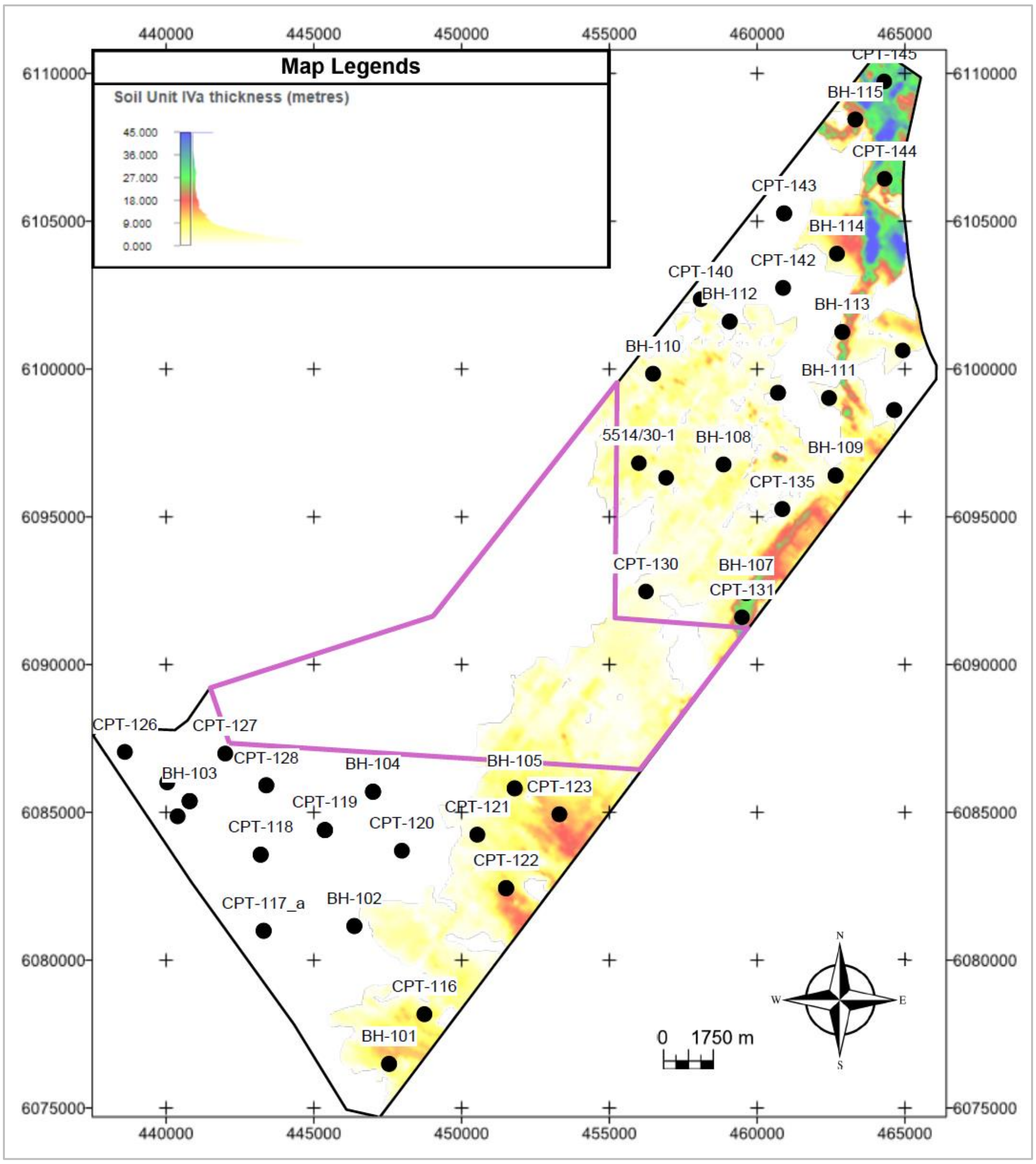


Figure 10-7. Distribution and thickness of GMU5 (Soil Unit IVa) in the Bornholm I Site.

10.7 GMU6 – Geotechnical Unit V (bedrock)

GMU6 corresponds to the bedrock. The Bornholm I Site has a rather complicated bedrock beneath the Pleistocene and Holocene sediment succession. The geology of the bedrock subcrop is discussed in Section 7.7 above. In summary, three bedrock provinces can be discerned (Figure 10-8). A southern Province (P1) that is characterised primarily by gently dipping strata and rather open folds. Here the bedrock comprises variably fractured chalk and limestone with intervals of siltstone also having been encountered. These strata are believed to be of Cretaceous age as proven by the Pernille (5514/3-1) Oil and Gas Exploration Well. North of the Pernille Well the entire Cretaceous rock succession is involved in a WNW-ESE striking monoclinal fold with a very steep southern limb where strata attain near vertical orientation. These vertical beds define the Second Bedrock Province. The monocline brings deeper stratigraphic units to shallow burial depths and the strata that subcrop beneath the Pleistocene succession to the north of this fold are of probable Jurassic-age. These Jurassic sediments comprise interbeds of sandstone, shale, and thin coals, which together define the third and northern bedrock province.

In contrast Cretaceous to the carbonates that dominate the southern province, the intercalated siliciclastic rocks of the northern province are tightly folded. Somewhat surprisingly, given the amount of structural deformation, many of the sandstone beds are very poorly cemented such that geotechnical boreholes drilled through the bedrock in the northern part of the Bornholm I Site have recovered loose sand. This phenomenon was also noted in the Pernille (5514/3-1) Well with loose sand grains having been recovered in cuttings samples from the penetrated Jurassic succession.

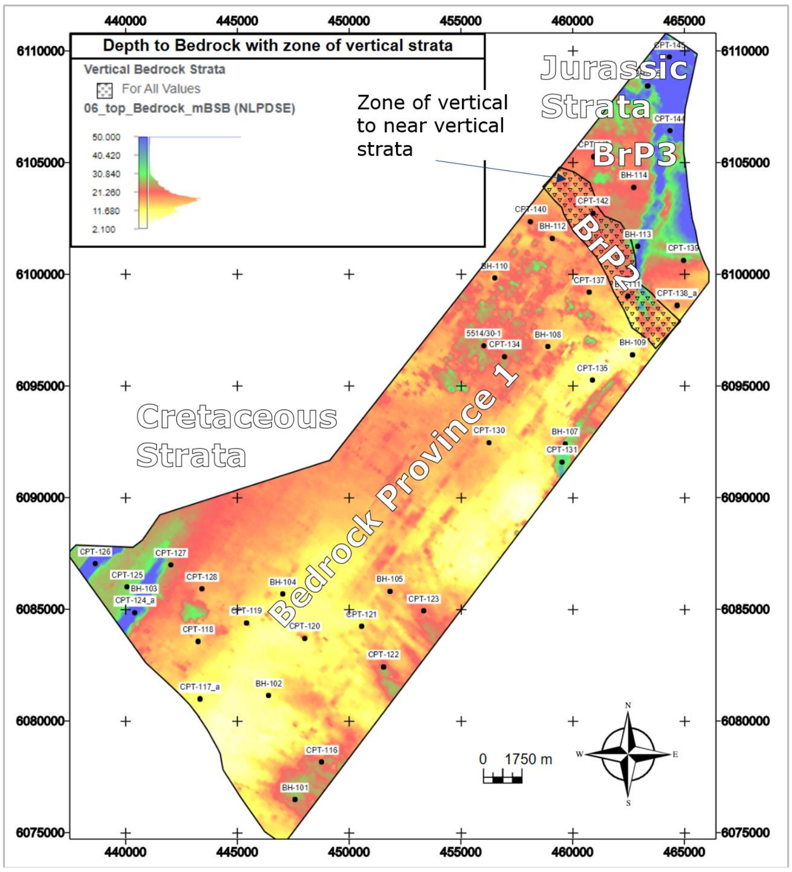


Figure 10-8. Map illustrating the depth to the top of the bedrock from the seabed. The three distinct Bedrock provinces are highlighted, with the Cretaceous strata in the South (Bedrock Province 1) being separated from Jurassic Strata (Bedrock Province 3) by the near vertical limb of a large monocline (BrP2). The polygon illustrates the one of vertical strata that separate the Cretaceous and Jurassic successions.

11. Potential issues and hazards

This chapter highlights some of the potential issues and geotechnical hazards that would need to be addressed during the development of the Bornholm I Site. These elements are flagged here since it is considered that they ought to be the focus for further study.

11.1 Seismic to Soil Unit mismatches

As stated in Section 10.1 there is a workable pairing of the Geotechnical Soil Types with the defined Seismic Units which results in the six defined Ground Model Units. However, the match between the Geotechnical Soil Units and the defined Seismic Units is not a perfect one-to-one. Table 10.1 summarises how the mapped Seismic Units in the Bornholm I Site have been matched with the Geotechnical Units that were defined in Section 8 to create mappable Ground Model Units.

Not all the Geotechnically defined Soil Units have been captured in the model and some soil units have proved difficult to capture accurately. These are discussed below.

11.1.1 Soil Unit II

Soil Unit II is rather uncommon having been defined in just two Boreholes and three CPTs. It normally represents a transition between the very soft Soil Unit Ib clays and the stiffer Soil Unit III clays. The transition is not imaged in the seismic sections, but it must be expected that such transitional layer is present at the transition between GMU2 and 3.

Table 11.1. List of those Boreholes and CPTs in which the transitional Soil Unit II has been defined.

UWI	Top Depth	Base Depth	Soil Unit	Lithology
BH-102	3.00	4.28	II	Transition clay with soft to firm strength
BH-103	0.00	2.40	II	Transition clay with soft to firm strength
CPT-102	3.40	4.00	II	Transition clay with soft to firm strength
CPT-109_a	3.22	3.50	II	Transition clay with soft to firm strength
CPT-135_a	1.30	2.00	II	Transition clay with soft to firm strength

11.1.2 The base of GMU3 (Soil Unit III)

Geotechnical Soil Unit III is largely confined to Seismic Unit 4, though it can be present at the very base of Seismic Unit 3. For practical purposes the top of GMU3 which is characterised by Soil Unit III, has been placed at the H30 Seismic Horizon which marks the top of Seismic Unit 4. This is considered a robust pick. However, the base of GMU3 (Soil Unit III) is more problematic since it often occurs within Seismic Unit 4a and has no direct seismic tie. Indeed, in parts of the Bornholm I Site Soil Unit III is missing and the soft, organic-rich clays of Soil Unit Ib pass directly into the stiff and very strong Soil Unit IVb clay tills. The mapped base to GMU (Soil Unit III) is a compromise between the picks in the CPTs and Boreholes and local adjustments to either the H30, H40 or H45 Seismic Horizons (see Section 10.4 for discussion on how the grid was created).

It is clear that Seismic Unit 4a possesses lateral changes in the Soil characteristics with both Soil Unit III and IVb being present. The principle differences between Soil Unit Type III and Soil Unit Type IVb are (i) the percentage of sand within the clay (see Table 8.2) that characterises both of the Soil Units, and (ii) the degree of consolidation; Soil Unit III is a firm cohesive sandy clay, whereas Soil Unit IVb is a very stiff to very hard sandy clay of high strength (Table 8.4).

Glacial sediments, particularly tills, are notorious for their variability in consolidation. Tills comprise sediments that have been transported by ice, but their composition and fabric will depend on whether (i) they were deformed during deposition (*i.e.*, were they deposited as sub-traction tills beneath an advancing glacier/ice sheet), or (ii) whether they were they were deposited gravitationally during a period of deglaciation (i.e. melt-out tills), and/or (iii) a combination of both mechanisms. Because of these different depositional processes tills are often spatially variable; both vertically and horizontally. Variation in sediment type and degree of consolidation is to be expected in glacial tills and should be viewed as an exception.

It is highly probable that both sub-traction and gravitational processes were active during the deposition of the glacial sediments that comprise the upper part of Seismic Unit IV; the hummocky moraines represent deposition during the melt-out phase of the LGM ice sheet and seismic evidence for internal deformation has also been noted (see for instance Figure 7-35). As a consequence, it should be of no surprise that there is variability in the degree of consolidation (stiffness, strength), nor in the sand content of the sediments that comprise the Seismic Unit IVa. An inter-fingering of both GMUs 3 and 4 (Soil Units III and IVb) should be expected to occur at this level of the stratigraphy.

11.1.3 Stratigraphically shallow Soil Unit IVa

The dense sands of Soil Unit IVa are normally associated with the mapped sand systems that define GMU5 within Seismic Subunit 4c. However, in CPTs 117 and 117_a Geotechnical Soil Type IVa sands have been defined in what has been mapped as GMU2; the sands sit within the Seismic Unit 3d (see Sections 7.5.7 & 7.5.8 for full discussions). The presence of dense sands at shallower stratigraphic levels illustrates some of the complexity observed in the site (see Section 11.2.4 below).

The dense sands in Seismic Unit 3d can be tied to a rather specific set of seismic facies and geometries that lie adjacent to a break of slope mapped on the top of Seismic Unit 4. Ramboll has created a polygon for the likely distribution of these sands (Figure 11-2). Within this polygon dense sands might be expected to occur at shallower burial depths than the current Geological Ground Model would predict.

11.2 Geological hazards highlighted by the model

A review of the distribution of the Geotechnical Soil Types raises a set of issues or hazards that are flagged below:

- Very soft sediments at shallow burial depths.
- Isolated pockets of soft, organic-rich soils in stiff glacial sediments.
- Sand overlying soft clays.
- Irregular topography developed at the top of very stiff and strong sediments.
- Potential Boulders and Block fields.
- Faults and folding introducing very variable bedrock conditions at a very short lateral distance combined with shallow bedrock depths.

11.2.1 Very soft sediments at shallow depths

One of the key hazards at the Bornholm I site are the presence of very soft clay sediments that can reach thicknesses of 30 m in the very North of the site (Figure 11-1). The map displayed in Figure 11-1 groups together all the soft sediment types, be they clay (Ib) or sand (Ia) and also incorporates the transitional Soil Unit II. It essentially displays the thickness of GMU1 and 2 as mapped on the UHR seismic (see Chapter 9). The map Soil Province map illustrated in Figure 12-2 flags those areas in which these soft soils are greater than 5 m thick and this map is used to create the Soi Zone/Province map depicted in in Figure 12-3.

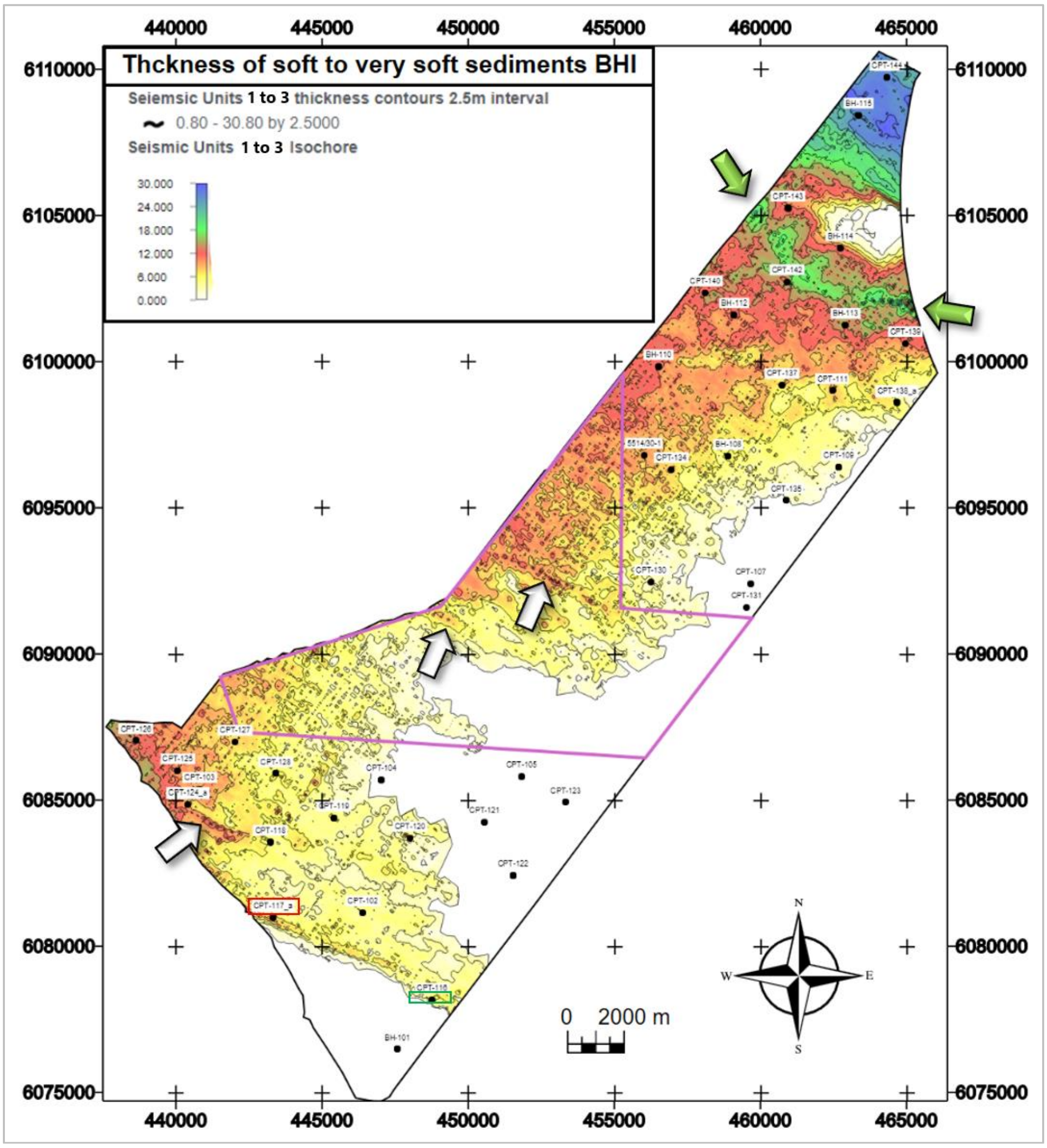


Figure 11-1. Map illustrating the thickness of soft sediments, primarily the very soft Clays of Soil Unit Ib, but also the soft sands (Soil Unit Ia). Note the local thickening along WNW to ESE aligned features (white arrows) and the local thick developed around the Unit IV ridge in the north of the site (green arrows).

Over a large part of the Bornholm I site, soft sediments dominate. These 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. Soft sediments need to be studied from a thermal conductivity point of view for cable design in a burial risk assessment.

11.2.2 Pockets of Soft Soils (Soil Unit Ib) in the eastern part of the site.

The pinch-out line of the soft, organic-rich Geotechnical Soil Unit Ib can be mapped easily enough on the UHRS but the SBP data reveals that pockets of this soil type occur after the pinch-out of the data on the UHRS dataset. When creating the Ground Model, the two data-sets that define the H30 Seismic Horizon (UHRS & SBP) have been merged into one, even though the surface is very discontinuous over the eastern part of the Bornholm I Site. Since the soft, organic-rich clays of Soil Unit Ib sit above the H30 Seismic Horizon it allows the Ground Model to at least capture some of the deeper pockets of Soil Unit Ib in the eastern part of the Site (see Figure 11-6). However, the 2D nature and spacing of the current seismic dataset cannot accurately capture the 3D geometry of these pockets and there remains a risk of encountering pockets of soft, organic-rich Soil Unit Ib within the otherwise stiff sediments of Soil Units III and IVb.

This variability in near surface sediments has also been captured in the CPTs. A prime example is the cluster of CPTs that have been obtained from the CPT-122 location, where each of the 4 CPTs has encountered a different succession of sediments (see Figure 11-7).

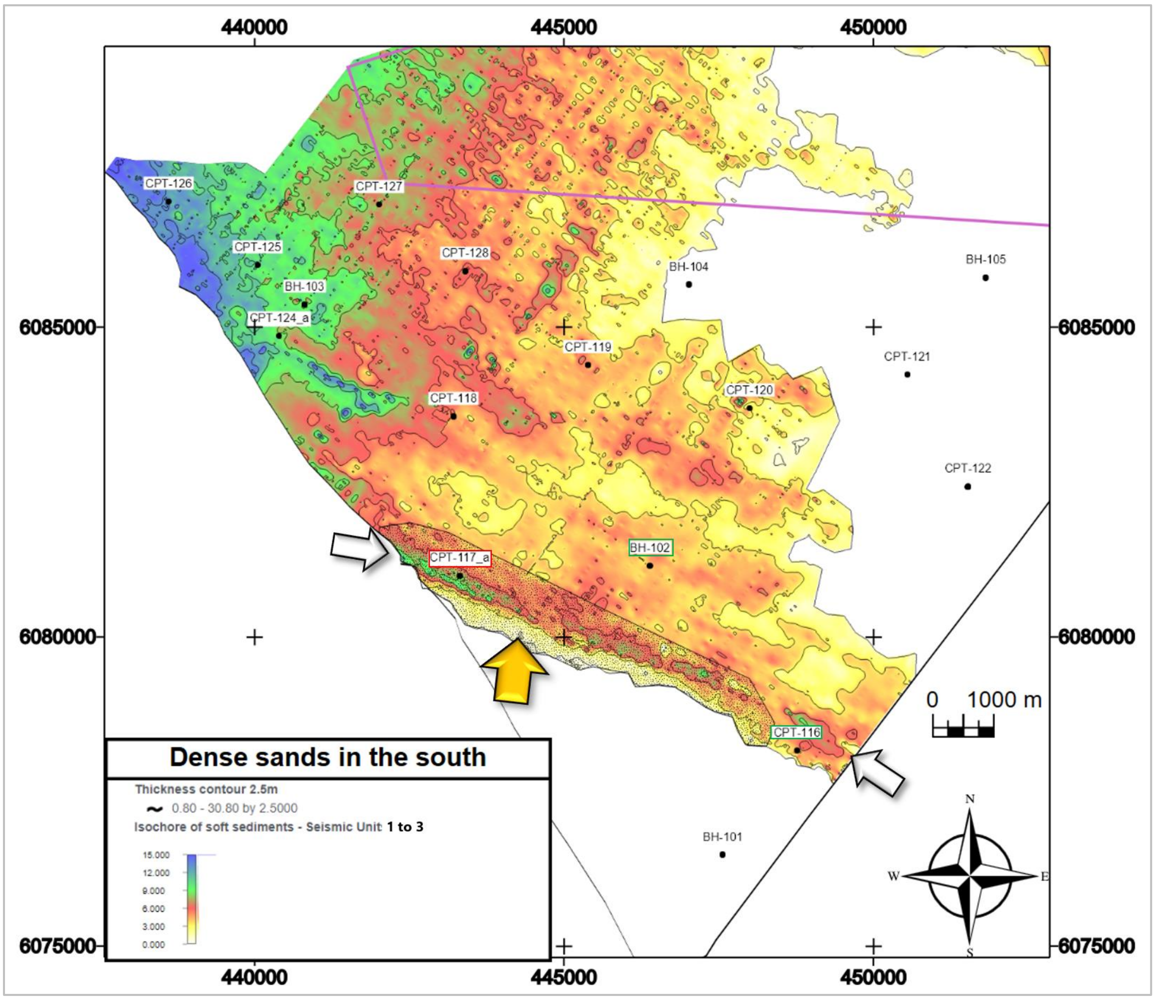


Figure 11-2. Close up image illustrating the CPT-117 site that has dense sands (Soil Unit IVa) sitting at relatively shallow levels in the site stratigraphy (within GMU2 / Seismic Unit 3). These sands have a distinctive seismic signature that is characterised by soft sediment deformation, and they pass both laterally and vertically into soft clays (Soil Units Ib and III) such that they are absent at the 102 and 116 sites. The upshot is that the thickness of the soft sediments mapped out in the map is wrong in the area defined by the stippled polygon; it is likely to be somewhat thinner adjacent to the ridge line indicated on the map.

11.2.3 Sand overlying soft sediment

At several locations shallow sands have been recorded in the CPTs and Boreholes of Bornholm I. These sands belong to Soil Unit Ia and their distribution is depicted in Figure 11-3 while the boreholes and CPTs that contain Soil Unit Ia are listed in Table 11.2. These shallow soft sands occur either directly at the seabed where they comprise Holocene sediments (Seismic Unit 1) or they are associated with the mounded sediment bodies associated with Seismic Unit 2 (see Section 7.4 above). The thickest intervals are those associated with the mounded features that have been mapped on the SBP data set (Figure 11-3). A list of those CPTs and BHs that encountered shallow soft sand is provided in Table 11.2, whilst their distribution is illustrated in Figure 11-3 and it can be seen that there is a good correspondence between the presence of sand and the distribution of Seismic Unit 2.

Where these shallow sands sit directly over soft clays (Soil Units Ib) there is a risk of punch through, however there are only a limited number of locations where this is the case, and they are depicted in Figure 11-4 and listed in Table 11.2. It can be observed in Figure 11-4 that there are several CPTs with sand over soft clay that do not correspond with current mapping of the Seismic Unit 3 soft clays; CPT-104 and CPT-122 both lie outside the mapped soft clays in Figure 11-4. This is simply a resolution issue, since the H30 Seismic Horizon has largely been mapped on the UHR seismic. The same geological surface mapped on the SBP seismic data displays a wider distribution (see Figure 11-5), as the resolution of the shallow subsurface is greatly enhanced on the SBP dataset. Here thin intervals of Seismic Unit 3 have been mapped on the SBP dataset at the CPT-104 location even though it was not possible to resolve on the Ultra High Resolution Seismic. On the other hand, Seismic Unit 3 is mapped on neither the SBP, nor the UHR Seismic, in the vicinity of the 122 location but sands have been recorded over soft clays in CPT-122_c (Figure 11-7). Indeed, Site 122 had a total of five CPT penetrations that sit in close proximity to each other and yet they appear to have encountered rather different successions (see Figure 11-7). This cluster of CPTs illustrates the potential variability that can be developed at shallow burial depths on the eastern side of the Bornholm I Site.

Table 11.2. List of CPTs and Boreholes possessing intervals of soft sand (Soil Unit Ia) from the Seabed.

UWI	Top Depth	Base Depth	Soil Unit	Lithology
BH-113	0.00	1.00	Ia	SAND
CPT-101_a	0.00	0.39	Ia	SAND
CPT-102	0.00	0.40	Ia	SAND
CPT-104	0.00	0.40	Ia	SAND
CPT-104_a	0.00	0.40	Ia	SAND
CPT-107	0.00	0.21	Ia	SAND
CPT-113	0.00	1.00	Ia	SAND
CPT-116	0.00	2.50	Ia	SAND
CPT-116_a	0.00	2.50	Ia	SAND
CPT-120	0.00	1.00	Ia	SAND
CPT-121	0.00	0.70	Ia	SAND
CPT-121_a	0.00	0.70	Ia	SAND
CPT-122	0.00	1.03	Ia	SAND
CPT-122_c	0.00	1.15	Ia	SAND
CPT-122_d	0.00	1.08	Ia	SAND
CPT-131	0.00	0.98	Ia	SAND
CPT-139	0.00	0.60	Ia	SAND

Table 11.3. Boreholes and CPTs possessing sand sitting over soft clay.

UWI	Top Depth	Base Depth	Soil Unit	Lithology
BH-113	0.00	1.00	Ia	SAND
BH-113	1.00	13.26	Ib	CLAY
CPT-102	0.00	0.40	Ia	SAND
CPT-102	0.40	3.40	Ib	CLAY
CPT-104	0.00	0.40	Ia	SAND
CPT-104	0.40	1.49	Ib	CLAY
CPT-104_a	0.00	0.40	Ia	SAND
CPT-104_a	0.40	1.49	Ib	CLAY
CPT-113	0.00	1.00	Ia	SAND
CPT-113	1.00	12.8	Ib	CLAY
CPT-120	0.00	1.00	Ia	SAND
CPT-120	1.00	3.30	Ib	CLAY
CPT-122_c	0.00	1.15	Ia	SAND
CPT-122_c	1.15	1.87	Ib	CLAY
CPT-139	0.00	0.60	Ia	SAND
CPT-139	0.60	10.80	Ib	CLAY

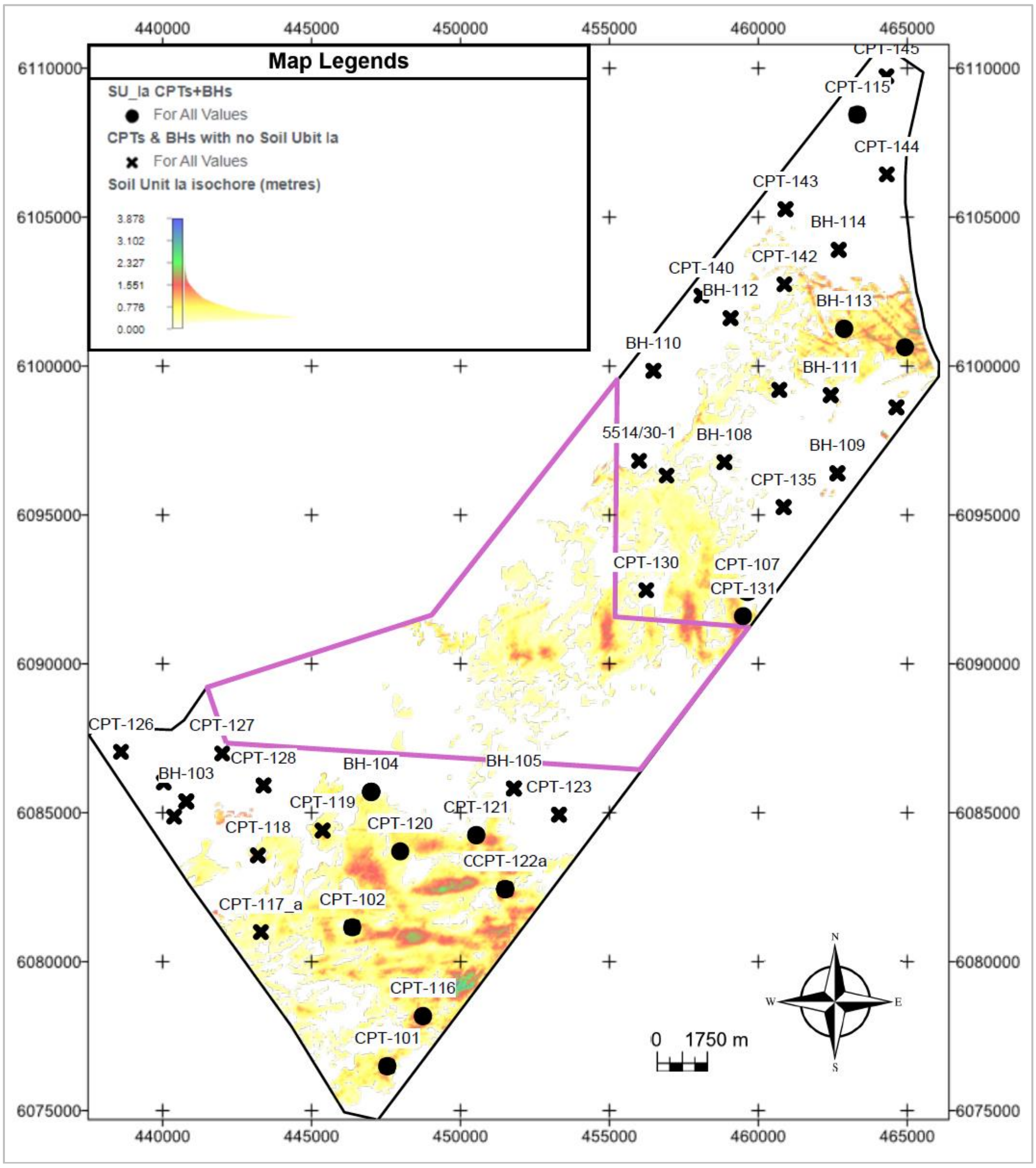


Figure 11-3. Unit 2 mounds isochore plotted together with CPTs and Boreholes (circles) that have recorded shallow sand layers below the seabed (GMU1 – Soil Unit Ia), and those that have not (crosses). The seismic mounds of Subunit 2a likely represent beach to shoreface deposits that typically have elongated depositional thicks. It appears that these mounded features corresponds well with the shallow sands encountered in the boreholes and CPTs.

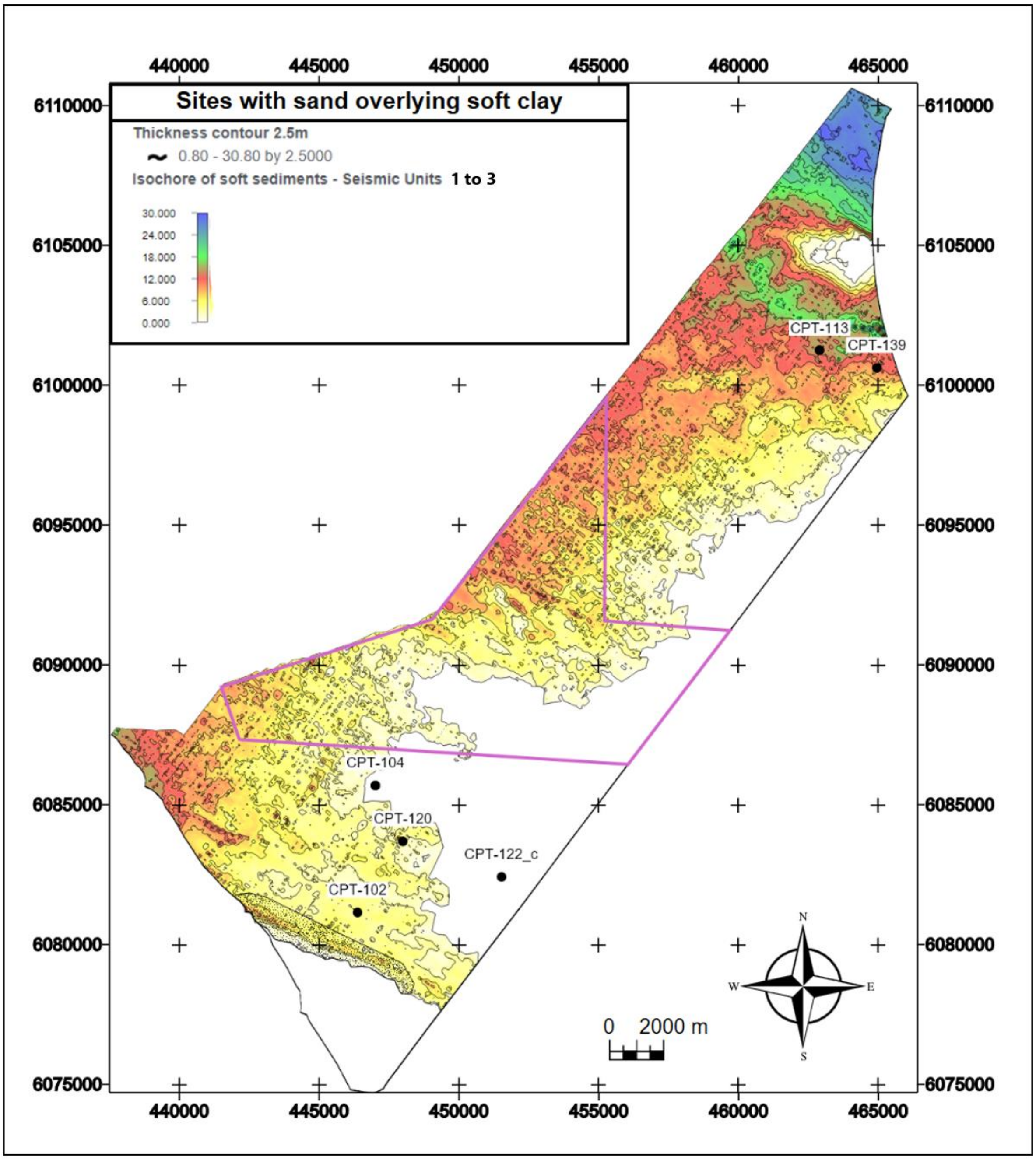


Figure 11-4. Map illustrating the CPTs in Bornholm I were shallow sand (Soil Unit Ia) has been recorded as sitting over intervals of soft clay (Soil Unit Ib). This juxtaposition poses a risk for punch through. Note that both CPT-104 and CPT-122_c sit outside the areas on which the soft clay sediments have been mapped on the UHRS seismic (see Figure 11-5 and text for discussion).

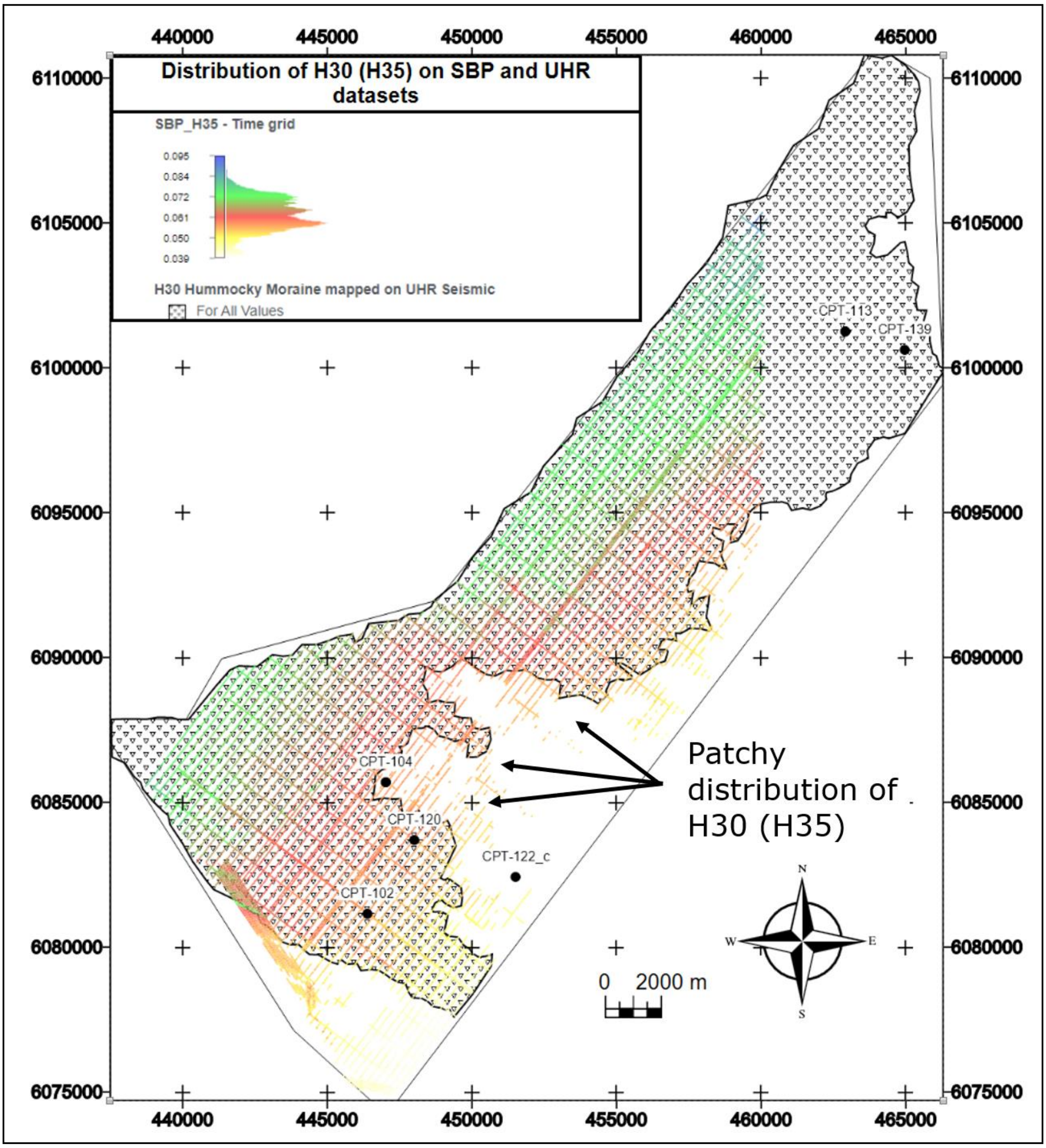


Figure 11-5. Map illustrating the extent of the H30 (H35) Seismic Horizon as mapped on the SBP dataset. Note that this surface has been mapped over a wider area than on the Ultra High Resolution seismic dataset. The polygon used to map that dataset has been added to given an idea of the wider coverage observed on the SBP data. Note the H30 (H35) Seismic Horizon has a very patchy distribution that results from it having been preserved in pockets between the hummocks of glacial Unit 4 sediments. Note that produce this map the SBP H30 (H35) Seismic Horizon has been gridded out to ca. 20 m of the actual mapped seismic, so the distribution is likely to be even more irregular than depicted here.

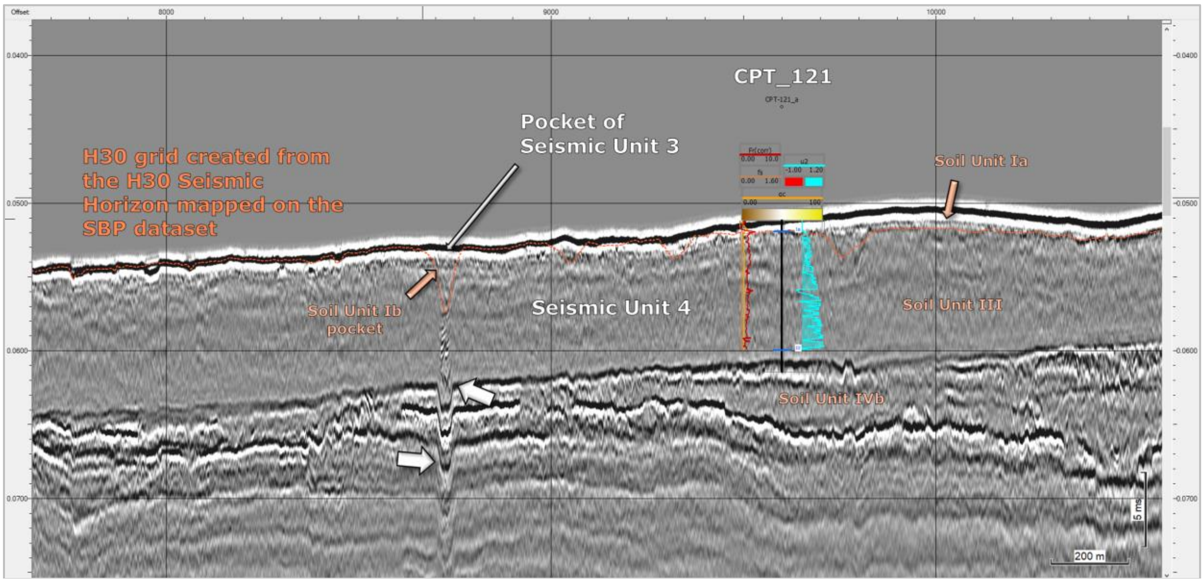


Figure 11-6. Seismic line GO5_X-011 in the vicinity of CPT-121 illustrating the presence of small, potentially isolated, pockets of Seismic Unit 3 that have been defined through mapping the SBP data. These pockets are filled by the soft, organic-rich clays of Soil Unit Ib that dominate Seismic Unit 3. These clays are likely to have low internal velocities and likely created the distinctive "pull-downs" in the underlying seismic data (white arrows).

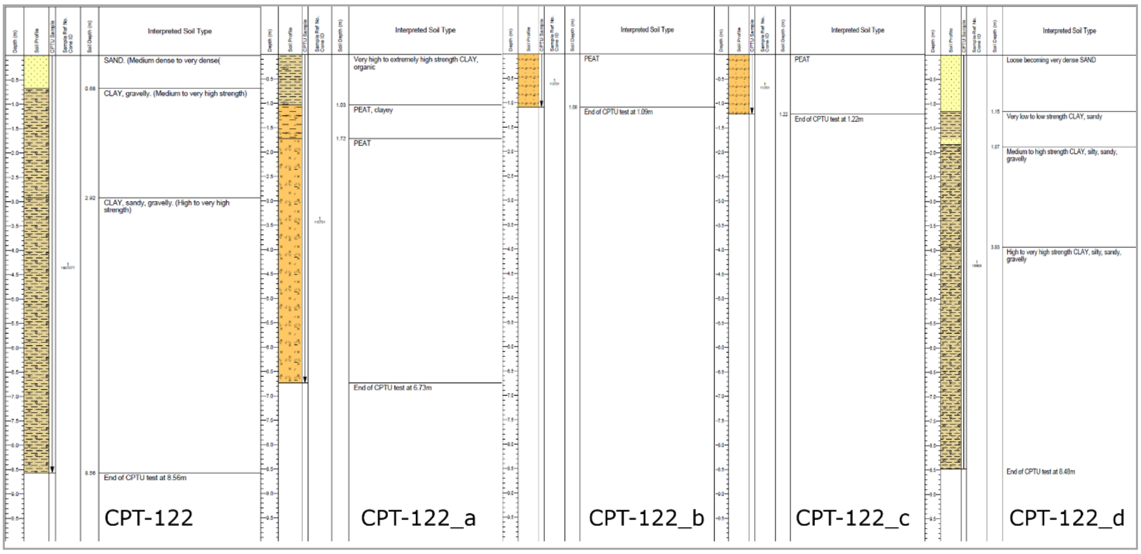


Figure 11-7. Snapshots from the Gardline report illustrating the differences recorded from the CPTs over short distances.

11.2.4 Irregular topography above very stiff sediments

The Top of Seismic Unit 4, as defined by the H30 Seismic Horizon, is a very uneven surface that can locally have significant topography. Given that this surface coincides, for the most part, with the change between soft clays (Soil Unit Ib) to stiff clays and sands (Soil Units III/IVb) it is perhaps the most important geotechnical boundary across the site.

Figure 11-8 shows the depth to which this unit is likely to be encountered below the seabed; it is found at very shallow burial depths across the eastern part of the Bornholm I Site, as well as over the bathymetric high in the north and a second high at the very south of the site, where there is a pronounced step in the thickness of Seismic Unit 4. The impact of having the glacial drift sediments of Seismic Unit 4 sitting very close to the seabed is demonstrated nicely by comparing the Figure 11-8 with the seabed surface substrate classification presented in the Geophysical Survey report (GEOxyz, 2022). The map is reproduced here in Figure 11-9 and shows how those areas in which Seismic Unit 4 (Soil Units III & IVb+a) sits at, or lie very close to, the seabed the substrate is dominated by gravelly and stoney sands (Figure 11-9). The coarse debris that is sat on the seabed is believed to have been reworked directly from the glacial drift sediments.

Given that uneven, hummocky surface at the top of Seismic Unit 4 normally marks the change between the soft organic-rich clays of Geotechnical Soil Unita Ib into very dense sandy clays and clay-tills (Soil Units III and IVb) there is an obvious danger for tilt development, especially in the case of multiple-legged foundations.

11.2.5 Potential Boulders and Block fields

As is described in previous chapters (see Section 7.6), the H30 (H35) Seismic Horizon marks a change in the depositional environment across the Bornholm I Site. The hummocky moraines were created during the retreat of the Last Glacial Maxima Ice Sheet from the Bornholm region. Deposition switched from a setting that was influenced by the direct action of ice and/or ice melt, to a setting in which sediments appear to have been deposited in a standing water body, with lacustrine through to marine conditions having been previously reported from these "Baltic Lake" sediments (see Section 7.5). It is very likely that blocks and boulders were deposited as the ice sheet retreated. As Borehole BH-114 demonstrates rafts of semi-coherent rock, in this case, highly altered chalk (see Figure 7-32 & Figure 7-33), have been locally deposited by the ice-sheets.

The top of Seismic Unit 4, marked primarily by the top of GMU3, is therefore likely to be not only be a hazard due to its inherent topography (see above), but also due to the possible presence of blocks and boulders that have likely been deposited during the retreat of the LGM Ice-Sheet. It is interesting to note that many of the CPTs have reached their terminal depths at the top of this unit, with CPT operations having to be stopped short of their planned depths owing to the equipment reaching its maximum load or that the cone-tip had deflected to such a degree that the that the test had to be terminated. Both of these stop criteria could have been caused by the CPTs having encountered blocks or even boulders. During the geotechnical ground investigation it was not noted in BH103 coarse gravel to cobble after 54m, also noted in the drilling remarks. Moreover cobbles were noted in BH109 and BH113.

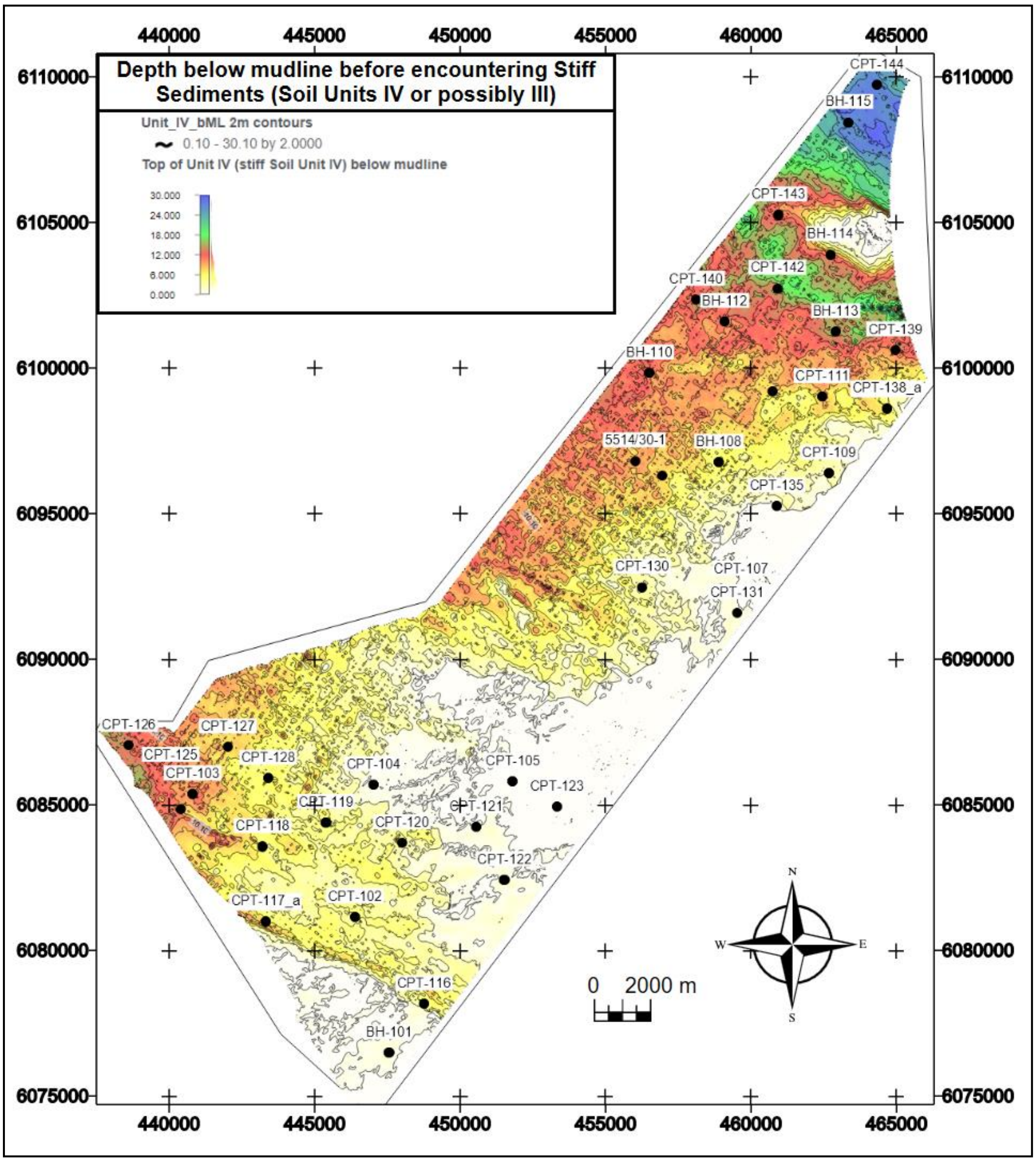


Figure 11-8. Map illustrating the depth at which the stiffer soil types that define GMUs3 and 4 are likely to be encountered. This corresponds to depth below seabed at which either Geotechnical Soil Unit III or IVb, might be expected to occur. This map displays the most probable top to Seismic Unit 4 (hence the stiff, strong clay tills of Soil Units III & IVb), having been adjusted by the shallow units that have been picked on the SBP seismic. Stiff soil units (predominantly Soil Units III & IVb) lie very close to the seabed over the bathymetric high in the North, along the eastern part of the Site and across a linear step in the very south of the site (see Figure 7-16 & Figure 7-17 for seismic lines across this step). These areas with glacial drift sediments (tills and moraines) close to the seabed coincided with gravelly and stony substrate sediments (see Figure 11-9).

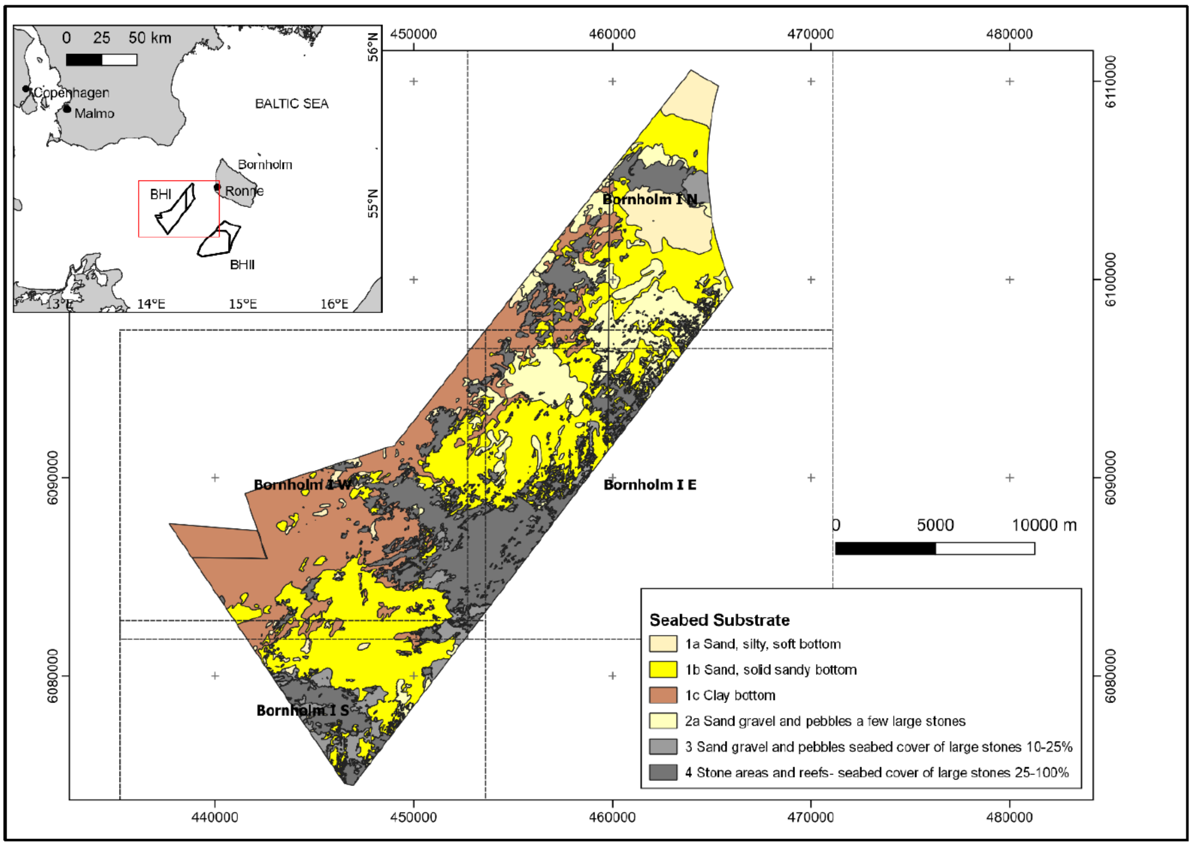


Figure 11-9. Seabed substrate classification map reproduced from the Geophysical Survey Report (Ref (GEOxyz, 2022)) Note how those areas dominated by gravelly and stony sand (Units 3 and 4) coincide to the areas in which the Glacial Drift sediments of Seismic Unit IV sit at or close to the seabed. The stiff, dense Soil Unit IV (locally Soil Unit III) sit at very shallow depths in these areas.

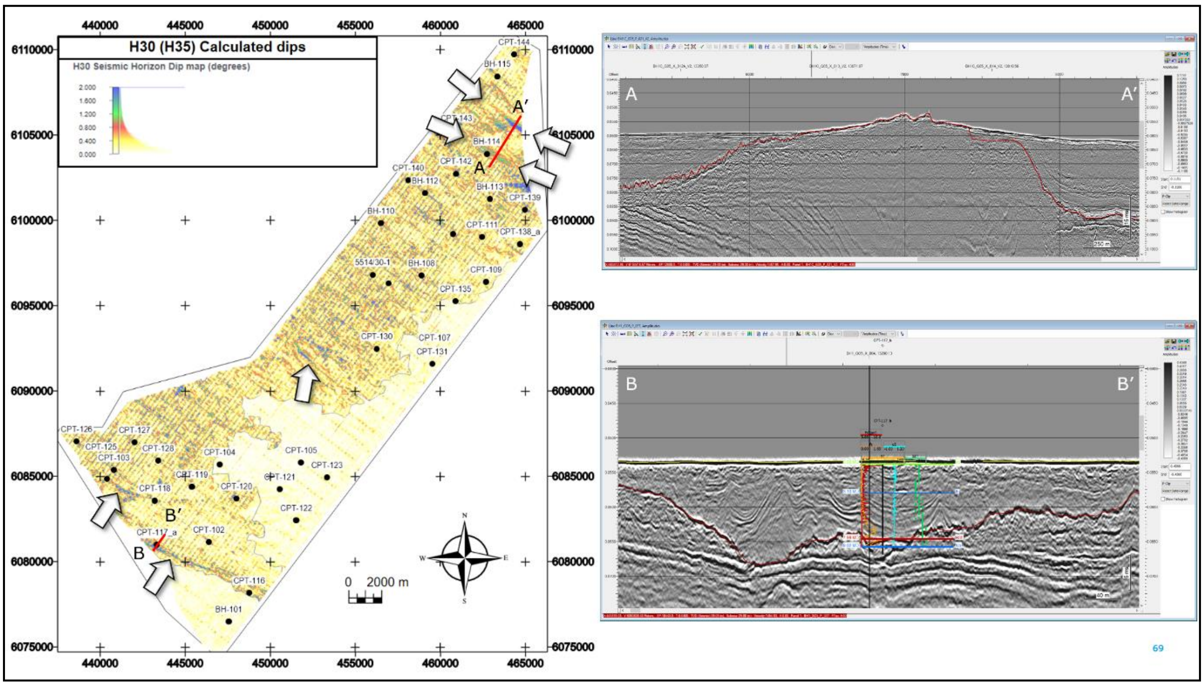


Figure 11-10. Dip map created from the H30 time map and its average velocity. Slopes in excess of 2 degrees on the top of Seismic Unit IV and its dense sandy clay till (Soil Unit IVb) are locally developed (white arrows), particularly across the Seismic Unit IV ridge in the north of the site. Most of the steep slopes are aligned NW-SE and likely follow the orientation of the hummocky moraines developed at the top of the unit.

11.2.6 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. The Bedrock Provinces described in section 10.7 and Figure 10-8 can help identifying such a risk.

12. Soil Zonation and Soil Provinces

12.1 Introduction

The Ground Model provides an understanding of the subsoil conditions for future offshore wind farms. This chapter reviews the key geological units that have properties which are key to foundation design. The water depth range in Bornholm I 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 chapter are orientated for early phase development. This analysis considers the current site investigation and should be updated after additional Ground Information is recovered from the Bornholm I Site.

A Soil Zonation has been developed based on the Ground Model Units and the inherent geotechnical properties of the defined Soil Units. The Zonation is presented in Table 12.1 and it serves as the basis for grouping the primary geological properties that are deemed 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 provinces (Figure 12-3).

The most prevalent geological features from a design basis are the depth to the bedrock, designated in the soil zone code by an alphabetic code A, B, C (see Table 12.1) and the thickness of the shallow soft, organic-rich Baltic Lake/Sea clays (defined by GMU2, Soil Unit Ib; designated by numbers, 1, 2 and 3; see Table 12.1). Other Soil Types are present across the site, such as tills and dense 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 (Soil Unit Ib) are represented in the Ground Model by Unit 2 (GMU2). These soils pose several challenges for OWFs. Firstly, they offer insufficient support for wind turbine foundations. Secondly, they are challenging for cable routing across the site since the insulating effect of organic-rich clays can lead to overheating of cables. Finally, as discussed in Chapter 9, the soft clays present difficulties for jack-up installation vessels, where leg penetration issues may be expected in the soft clay intervals. This can lead to large footprints after leg extraction. The soft clays of GMU2 also create difficulties during geotechnical investigation campaigns with heavy CPT rigs vulnerable to significant settlements.

In addition to water depth, depth to the top of the bedrock is another important driver for the design of wind turbine foundations. Indeed, together with the bedrock character, the depth of the top bedrock below seabed is normally one of the main drivers for selecting a foundation type. As described in the Chapter 8, a variety of bedrock lithologies have been encountered by the Bornholm I boreholes with Cretaceous Limestones, Mudstones and Chalk characterising Bedrock Province 1 in the South and middle part of the Site and Jurassic Sandstones, claystones and even coals being recorded from the northern part of Bornholm I (Bedrock Province 3; see Figure 10-8).

12.2 Soil zonation

Two zonations have been created to better understand the spatial distribution of the rock depths and thickness of the soft soils of Soil Unit Ib.

The type of foundation employed for the turbines is primarily defined by the depth of the top bedrock. For this reason, Bornholm I has been divided into three areas based on the predicted depth at which the bedrock is likely to be encountered below the seabed. The subdivisions are:

- Top Bedrock less than 15 m below the seabed (A in Table 12.1).
- Top Bedrock between 15 and 40 m below the seabed (B in Table 12.1).
- Top Bedrock greater than 40 m below the seabed (C in Table 12.1).

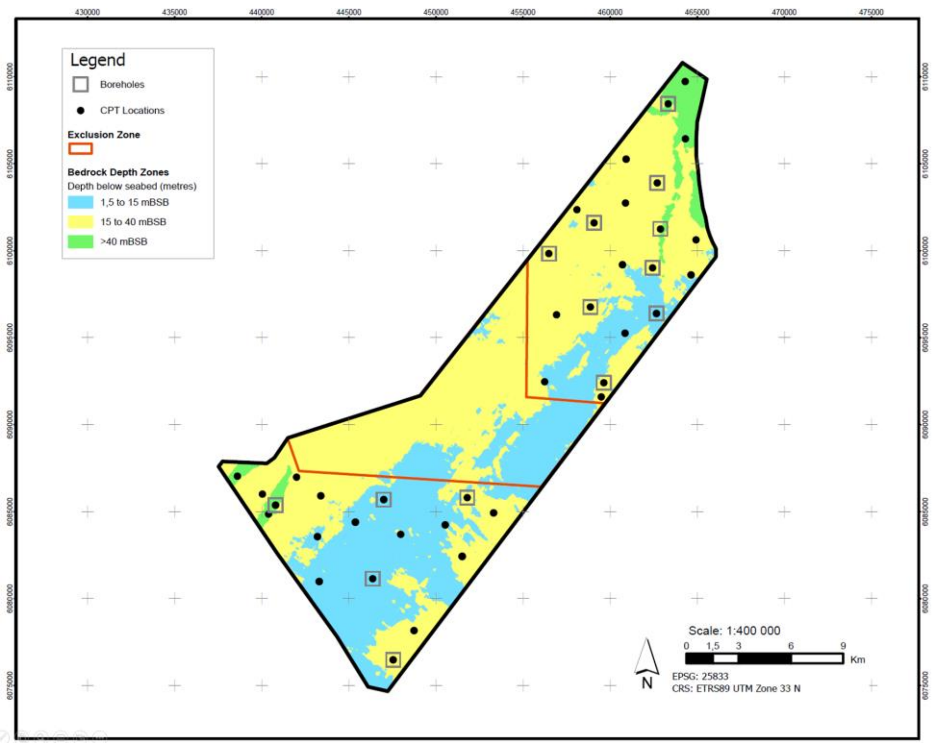


Figure 12-1. Distribution of the three key bedrock depth zones across the Bornholm I Site.

The first class of bedrock is where it sits shallower than 15 m below the seabed (Table 12.1) and is represented with blue colour in Figure 12-1 and Chart 4.3. The most common foundation types 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 or rock layers. Since soft clay soils with low strength (Soil Unit Ib) are present across much of the Bornholm I Site (see Figure 12-2), the Soil Province classification needs to incorporate both of these geotechnically important features. It is anticipated that soft clay soils will challenge the potential foundation type and a drilled solution needs to be considered when the bedrock sits close to the seabed.

The second zone (Zone B in Table 12.1) is represented with yellow colours in Figure 12-1. Here the bedrock sits at intermediate depths (15 to 40 m) below the seabed. In this case, suction caisson foundations will not reach bedrock depth and these types of foundations become feasible. In some instances, monopile foundations could also be installed without the need of drilling depending on the pile penetration but they would require strong sediments to support the monopile. 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 also on the permeability of the soils sitting over the bedrock. Permeability will have to be investigated in detail.

The third zone is the deep bedrock (Zone C in Table 12.1), where the bedrock sits more than 40 m below the seabed (Figure 12-1). Those areas in the Bornholm I Site with deep bedrock are represented with green colours in Figure 12-1 but are very limited. In this zone multi-piled (jacket) or single pile (monopile) foundations can be installed without the need of drilling. Yet here again thick intervals of soft soil could likewise prove problematic.

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 must be noted that the drilling is complex, time consuming and hence a more expensive option than driving.

The second geotechnical criterion revolves around the thickness of the soft, organic clays of GMU2 (Soil Unit Ib). The subsurface soft clay soils of Soil Unit Ib, which characterise the Baltic Lake successions of Seismic Units 1, 2b and 3 are low strength layers. Their distribution is illustrated in Figure 12-2 where a cut off of 5 m has been implemented to provide the second element of the Soil Zonation;

- Soil Unit Ib (soft, organic-rich clays) are either absent, or at least only present in isolated pockets and/or are very thin (Subzone 1 in Table 12.1).
- Where the Soil Unit Ib is laterally persistent but less than 5 m thick (Subzone 2 in Table 12.1)
- Where the Soil Unit Ib is both laterally persistent and of greater thickness than 5 m (Subzone 1 in Table 12.1)

Green colour represents the areas where the soft soils have a thickness below 5 m, and red colour represents the areas where the soft soils have a thickness more than 5 m.

The presence of thick intervals of shallow, soft clay (Soil Unit Ib) could significantly affect the foundation design. Furthermore, a solid knowledge of the properties of these soft, organic-rich shallow sediments is required, particularly along potential cable routes.

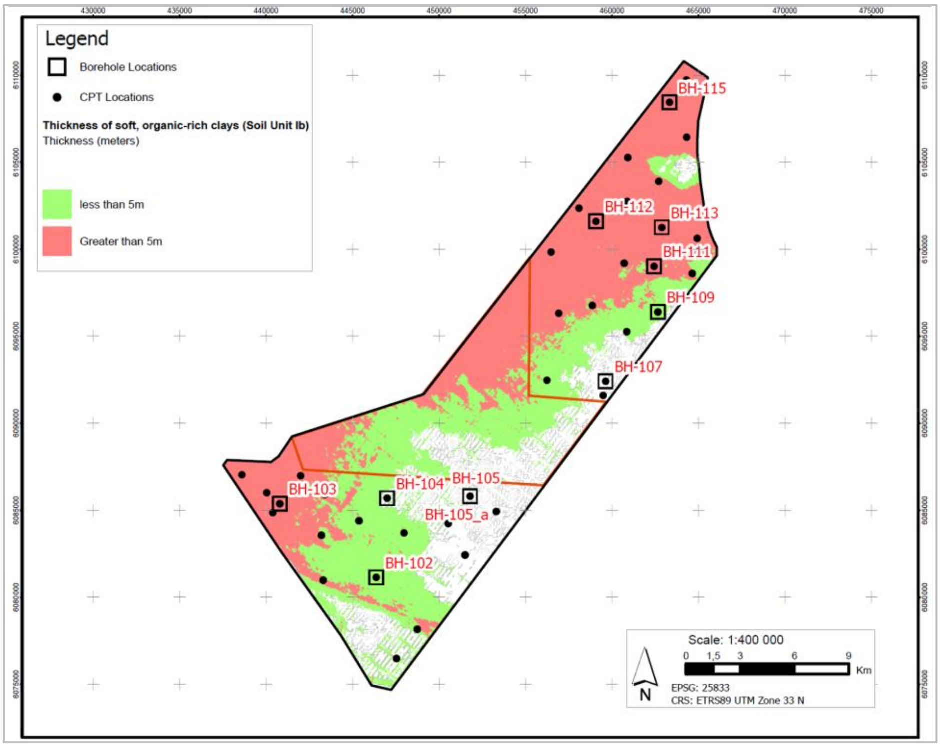


Figure 12-2. Distribution of the Soft Soil Unit Ib clays subdivided into those areas where they are less than 5m thick and those parts of the Bornholm I Site where they exceed 5m.

12.3 Soil provinces

A soil province map has been created using the aforementioned criteria, with the site having been subdivided first based on the depth to the bedrock, then on the thickness of the soft, organic-rich shales (Table 12.1). Therefore, to provide a thorough geological overview with respect to foundation conditions, the two maps of soft clay 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 (GMU2; Soil Unit Ib) and the depth of the top bedrock (top of GMU6; Soil Unit V) below the seabed. The same general colour scheme used for the previous map of Figure 12-1 was employed for Figure 12-3.

The nine soil provinces that have been defined based on the soil zonation are summarised 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, reducing the upper 8.6m of soft soils in less than 5m, CPT-103/BH-103 would be considered a representative profile for the C2 soil province. Similarly, omitting the upper 8.6m of soft soils CPT-103/BH-103 would be considered a representative profile for the C3 soil province.

Table 12.1 Soil Zones / Provinces.

Bedrock Zone	Code related to soft organic clay (Soil Unit Ib) thickness	Description	Corresponding examples from geotechnical data
A	1	Soft clay > 5m Top bedrock < 15m	CPT-108/BH-108 & CPT-110/BH-110
	2	Soft clay < 5m Top bedrock < 15m	CPT-102/BH-102 & CPT-109/BH-109
	3	No Soft clay Top bedrock < 15m	CPT-104/BH-104
B	1	Soft clay > 5m Top bedrock =15-40m	CPT-111/BH-111 & CPT-112/BH-112 & CPT-114/BH-114 & CPT-115/BH-115
	2	Soft clay < 5m Top bedrock =15-40m	CPT-105/BH-105 & CPT-107/BH-107
	3	No Soft clay Top bedrock =15-40m	CPT-101/BH-101
C	1	Soft clay > 5m Top bedrock > 40m	CPT-103/BH-103 & CPT-113/BH-113
	2	Soft clay < 5m Top bedrock > 40m	*No available examples however reducing the upper 8.6m of soft soils in less than 5m, CPT-103/BH-103 would be considered a representative profile
	3	No Soft clay Top bedrock > 40m	* No available examples however omitting the upper 8.6m of soft soils CPT-103/BH-103 would be considered a representative profile

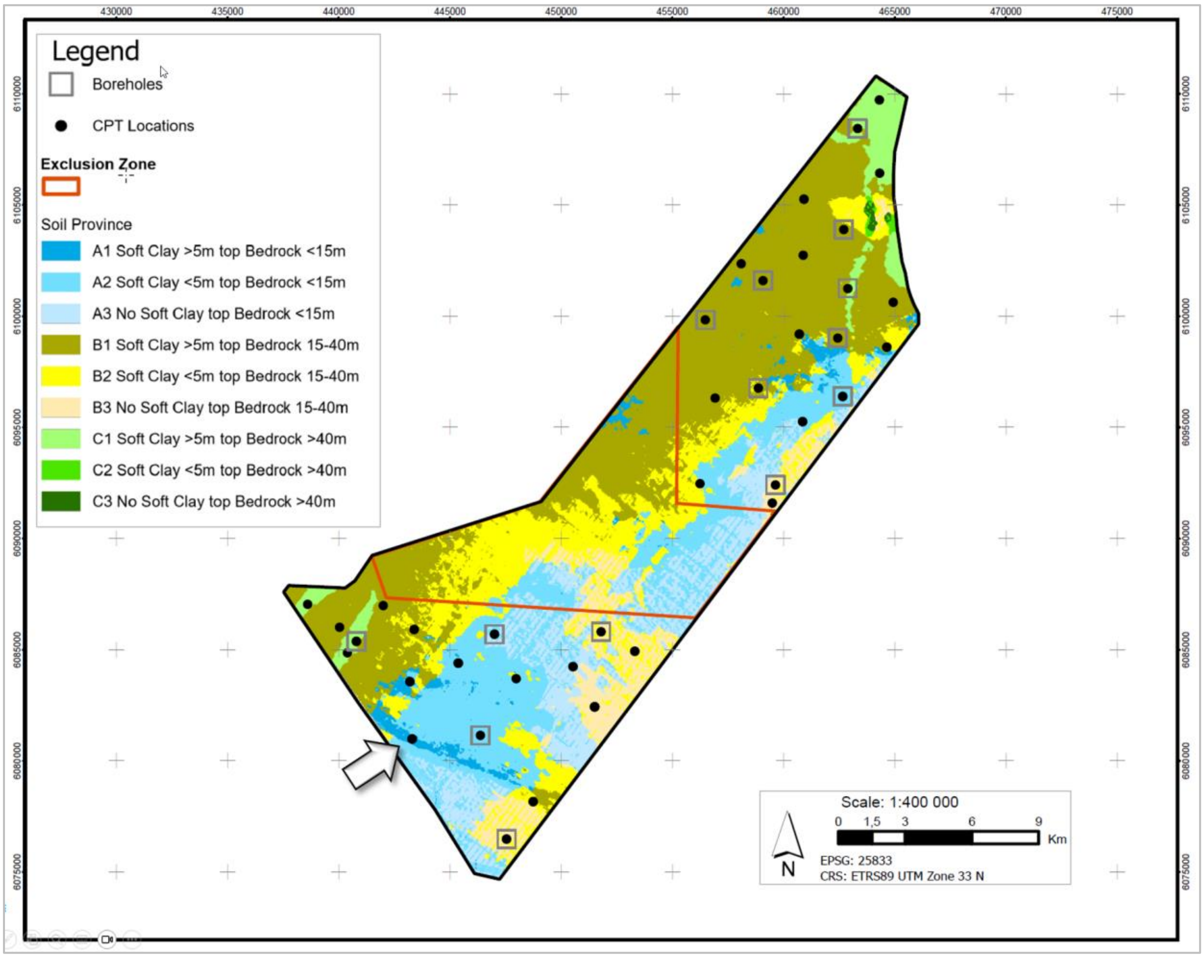


Figure 12-3. Soil Zone map. Note the trough of potential thick (>5m thick) Soft Clays (Soil Unit Ib) in the south of the Bornholm I Site that coincides with relatively shallow bedrock. CPT-117 (arrowed) indicates that dense sand (Soil Unit IVa) can occur in this area at shallower stratigraphic levels and this area needs further investigation.

12.4 Examples of representative soil profiles 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 Appendix 4. The analysis of various borehole/CPT locations in different sections reveals distinct patterns in soil provinces and bedrock depths. Each section used as an example illustrates a clear differentiation between deep, shallow, and intermediate depths to top bedrock scenarios.

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 encountered in depth above the 15 m. From the available geotechnical locations, two of them belong to this zone, namely CPT-108/BH-108 and CPT-110/BH-110 and both of them represent clay dominated positions. 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 Table 12.2. This profile is CPT-110/BH-110, where the CPT profile is presented in Figure *12-4* .

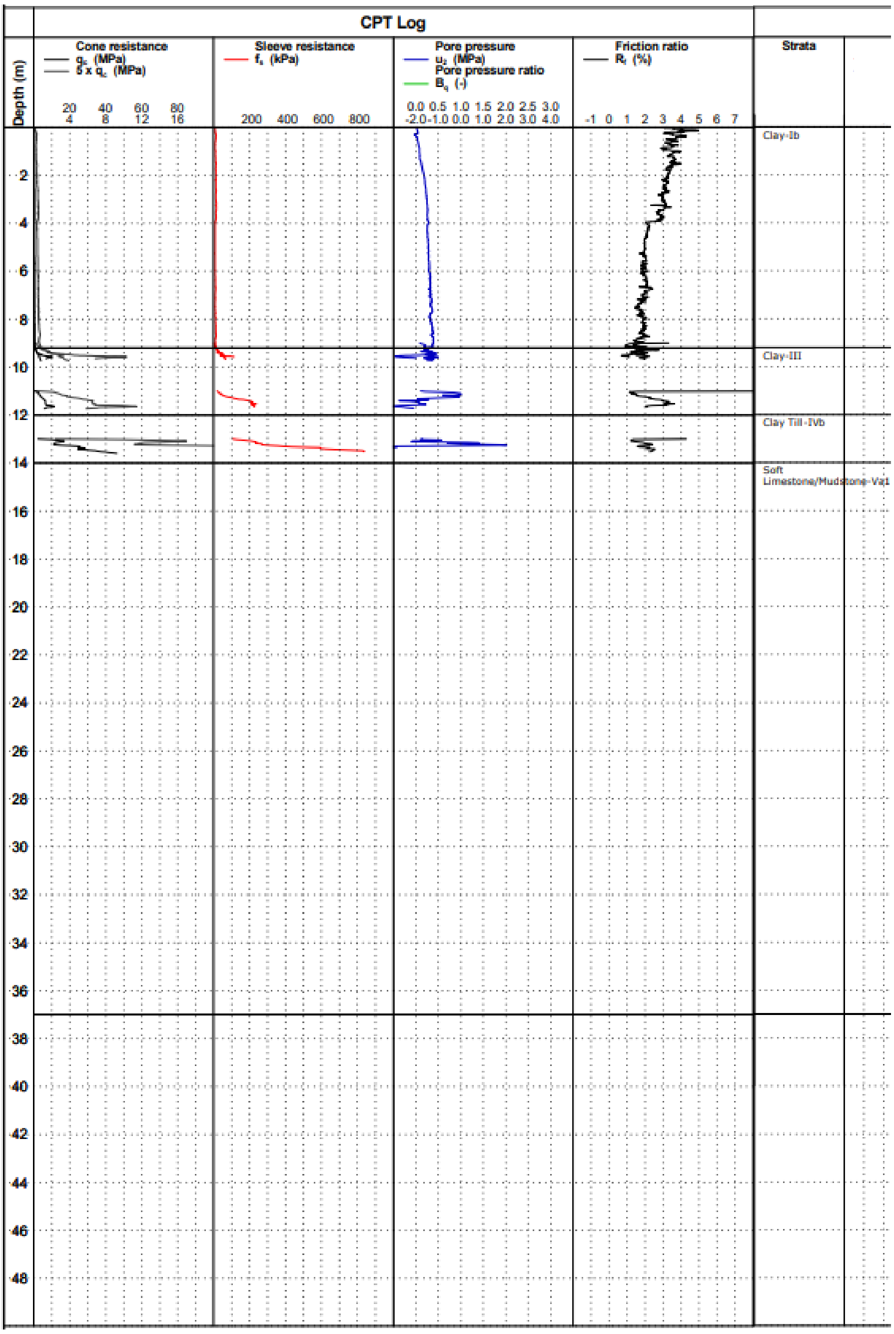


Figure 12-4 CPT measurements for CPT-110/BH-110 found as representative for zone A1.

Table 12.2 Soil stratigraphy for CPT-110/BH-110 found as representative for zone A1.

Top [mbsb]	Bottom [mbsb]	Integrated ground model unit	Soil Unit	Soil/Rock Type
0.0	9.2	GMU2	Ib	Clay
9.2	12.0	GMU3	III	Clay
12.0	14.0	GMU4	IVb	Clay till
14.0	37.0	GMU6	Va1	Mudstone

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 found in depth above the 15 m. From the available geotechnical locations, two of them belong to this zone, namely CPT-102/BH-102 and CPT-109/BH-109 and both of them represent mostly clay dominated positions with sand layers of less than 1 m thickness. One representative profile is selected for this zone due to its deepest measurements of CPT. This profile is CPT-102/BH-102, where the CPT profile is presented in Figure 12-5. The stratigraphy in table format is presented in Table 12.3.

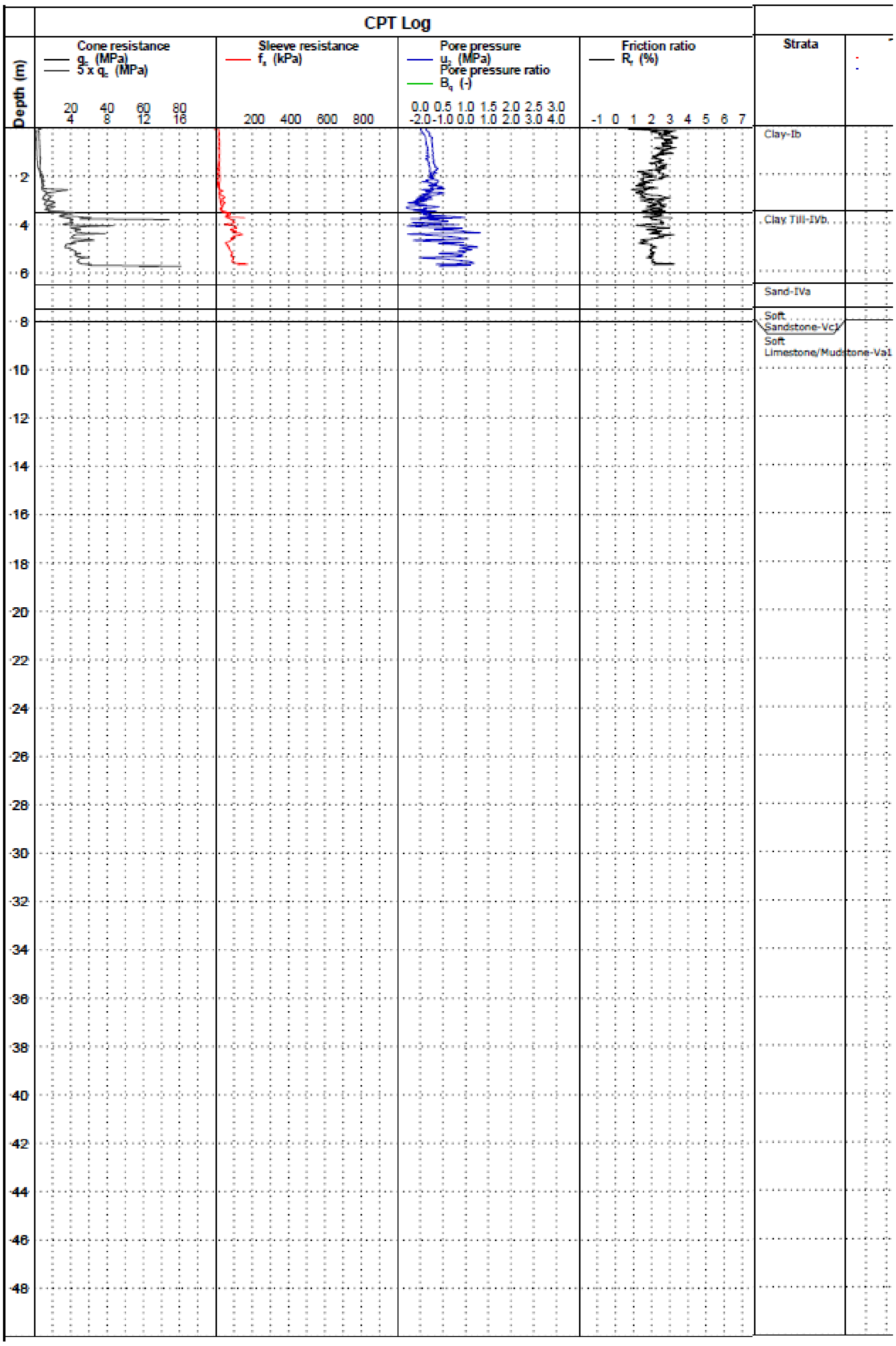


Figure 12-5 CPT measurements for CPT-109/BH-109 found as representative for zone A2.

Table 12.3 Soil stratigraphy for CPT-109/BH-109 found as representative for zone A2.

Top [mbsb]	Bottom [mbsb]	Integrated ground model unit	Soil Unit	Soil/Rock Type
0.0	3.5	GMU2	Ib	Clay
3.5	6.5	GMU4	IVb	Clay till
6.5	7.5	GMU5	IVa	Sand
7.5	8.0	GMU6	Vc1	Sandstone
8.0	69.7	GMU6	Va1	Siltstone

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-104/BH-104, where the CPT profile is presented in Figure 12-6. The stratigraphy in table format is presented in Table 12.4.

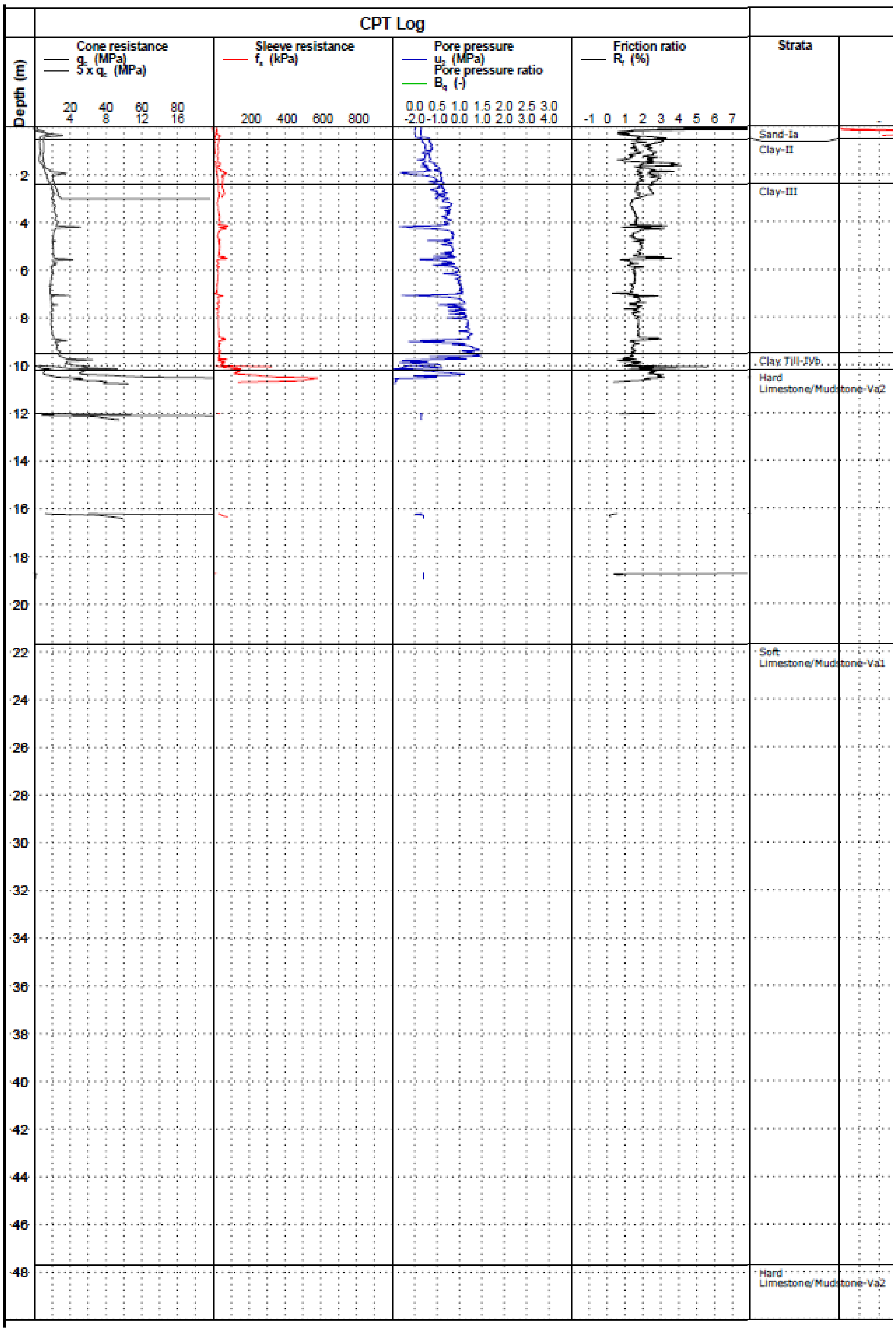


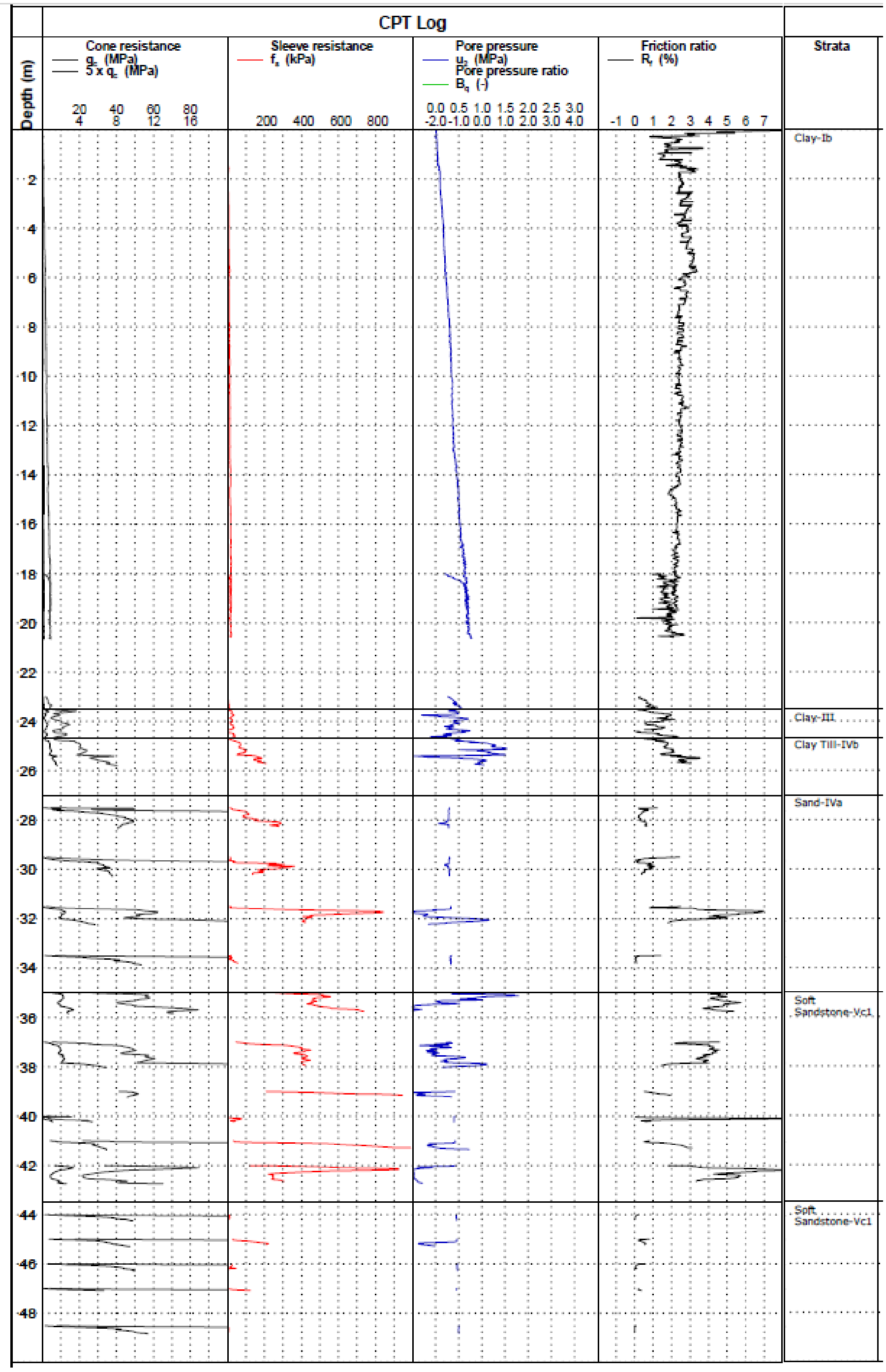
Figure 12-6 CPT measurements for CPT-104/BH-104 found as representative for zone A3.

Table 12.4 Soil stratigraphy for CPT-104/BH-104 found as representative for zone A3.

Top [mbsb]	Bottom [mbsb]	Integrated ground model unit	Soil Unit	Soil/Rock Type
0.0	0.5	GMU1	Ia	Sand
0.5	2.4	GMU3	II	Clay
2.4	9.5	GMU3	III	Clay
9.5	10.2	GMU4	IVb	Clay till
10.2	21.7	GMU6	Va2	Limestone
21.7	47.7	GMU6	Va1	Siltstone
47.7	51.0	GMU6	Va2	Limestone
51.0	54.0	GMU6	Va1	Mudstone
54.0	55.0	GMU6	Va2	Limestone
55.0	70.0	GMU6	Va1	Mudstone

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, four of them belong to this zone, namely CPT-111/BH-111, CPT-112/BH-112, CPT-114/BH-114 and CPT-115/BH-115 and all of them represent mainly clay dominated positions with sand layers in two of them of less than 3m thickness. One representative profile is selected for this zone due to its deepest presence of soft Soil Unit Ib. This profile is CPT-115/BH-115, where the CPT profile is presented in Figure 12-7. The stratigraphy in table format is presented in Table 12.5.


CPT Log
Depth (m)
Cone resistance
qc (MPa)
5 x qc (MPa)
20 40 60 80
4 8 12 16
Sleeve resistance
fs (kPa)
200 400 600 800
Pore pressure
u2 (MPa)
Pore pressure ratio
Bq (-)
0.0 0.5 1.0 1.5 2.0 2.5 3.0
-2.0 -1.0 0.0 1.0 2.0 3.0 4.0
Friction ratio
Rf (%)
-1 0 1 2 3 4 5 6 7
Strata
Clay-Ib
Clay-III
Clay Till-IVb
Sand-IVa
Soft Sandstone-Vc1
Soft Sandstone-Vc1
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48

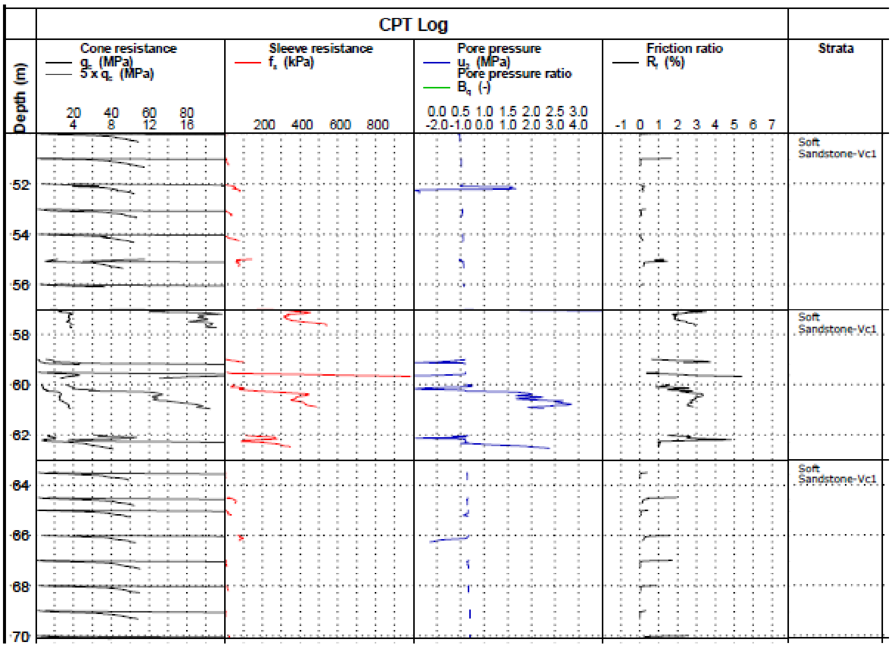


Figure 12-7 CPT measurements for CPT-115/BH-115 found as representative for zone B1.

Table 12.5 Soil stratigraphy for CPT-115/BH-115 found as representative for zone B1.

Top [mbsb]	Bottom [mbsb]	Integrated ground model unit	Soil Unit	Soil/Rock Type
0.0	23.5	GMU2	Ib	Clay
23.5	24.7	GMU3	III	Clay
24.7	27.0	GMU4	IVb	Clay till
27.0	35.0	GMU5	IVa	Sand/Gravel
35.0	43.5	GMU6	Vc1	Sandstone
43.5	57.0	GMU6	Vc1	Sandstone
57.0	63.0	GMU6	Vc1	Sandstone
63.0	70.1	GMU6	Vc1	Sandstone

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, two of them belong to this zone, namely CPT-105/BH-105 and CPT-107/BH-107. One representative profile is selected for this zone due to its highest strength. This profile is CPT-105/BH-105, where the CPT profile is presented in Figure 12-8. The stratigraphy in table format is presented in Table 12.6.

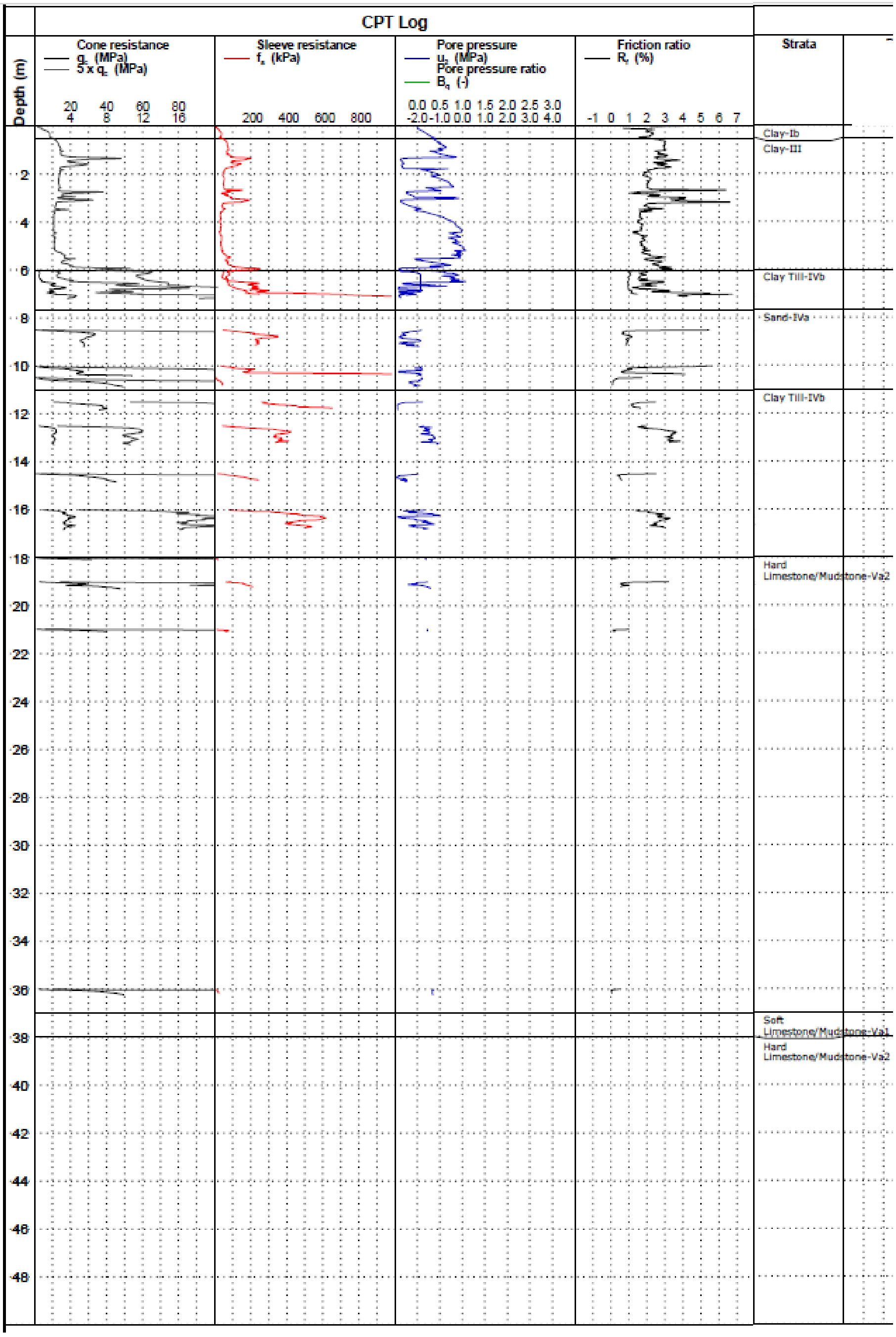


Figure 12-8 CPT measurements for CPT-105/BH-105 found as representative for zone B2.

Table 12.6 Soil stratigraphy for CPT-105/BH-105 found as representative for zone B2.

Top [mbsb]	Bottom [mbsb]	Integrated ground model unit	Soil Unit	Soil/Rock Type
0.0	0.5	GMU2	Ib	Clay
0.5	6.0	GMU3	III	Clay
6.0	7.7	GMU4	IVb	Clay till
7.7	11.0	GMU5	IVa	Sand
11.0	18.0	GMU4	IVb	Clay till
18.0	37.0	GMU6	Va2	Limestone
37.0	38.0	GMU6	Va1	Siltstone
38.0	69.0	GMU6	Va2	Limestone

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, one of them belong to this zone, namely CPT-101/BH-101, where the CPT profile is presented in Figure 12-9. The stratigraphy in table format is presented in Table 12.7.

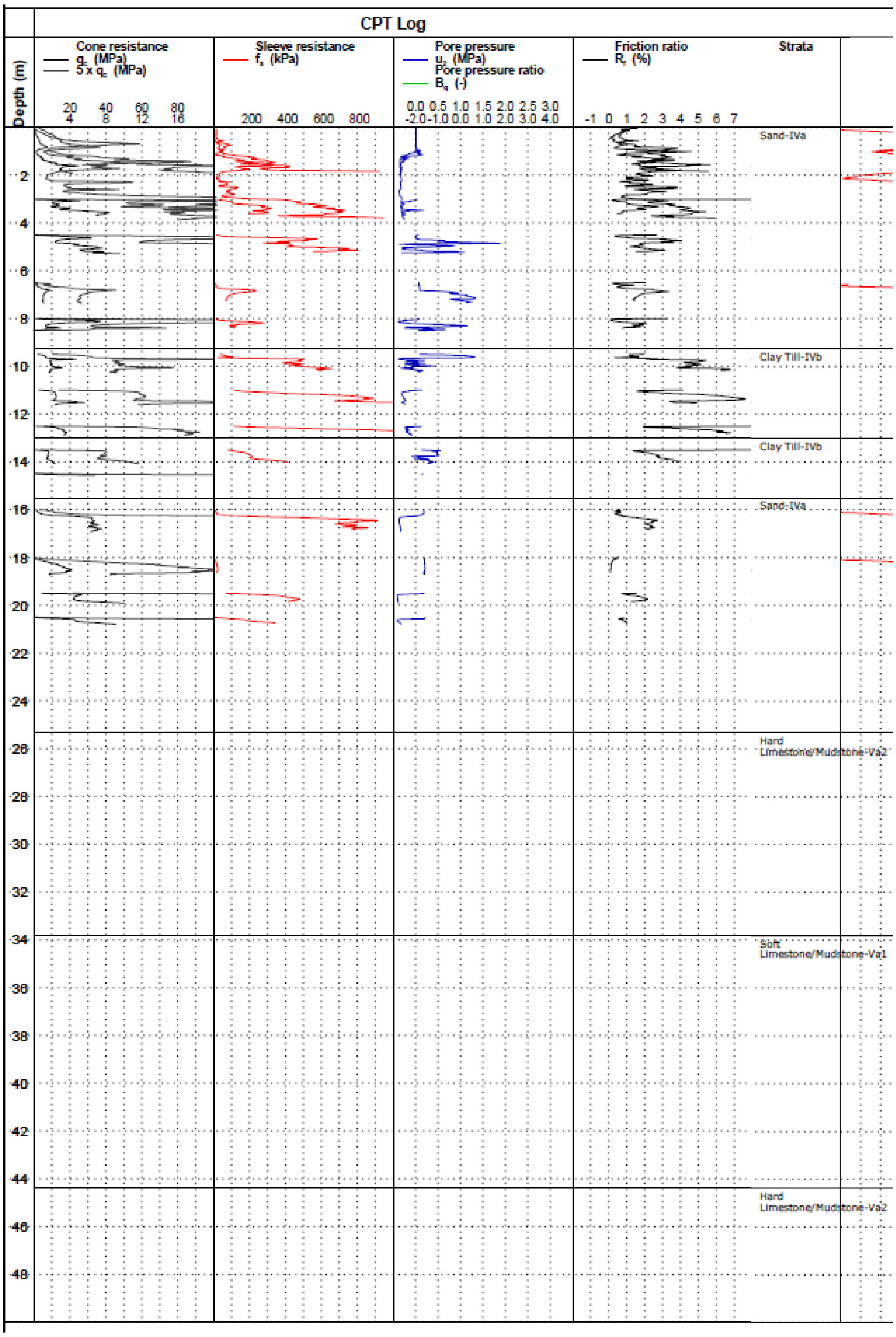


Figure 12-9 CPT measurements for CPT-101/BH-101 found as representative for zone B3.

Table 12.7 Soil stratigraphy for CPT-101/BH-101 found as representative for zone B3.

Top [mbsb]	Bottom [mbsb]	Integrated ground model unit	Soil Unit	Soil/Rock Type
0.0	9.3	GMU5	IVa	Sand (mix)
9.3	13.0	GMU4	IVb	Clay till
13.0	15.5	GMU4	IVb	Clay till
15.5	25.3	GMU5	IVa	Sand
25.3	33.8	GMU6	Va2	Limestone
33.8	44.4	GMU6	Va1	Limestone
44.4	64.0	GMU6	Va2	Limestone
64.0	70.0	GMU6	Va1	Limestone

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, two of them belong to this zone, namely CPT-103/BH-103 and CPT-113/BH-113. One representative profile is selected for this zone due to its deepest presence of soft Soil Unit Ib. This profile is CPT-113/BH-113, where the CPT profile is presented in Figure 12-10. The stratigraphy in table format is presented in Table 12.8.

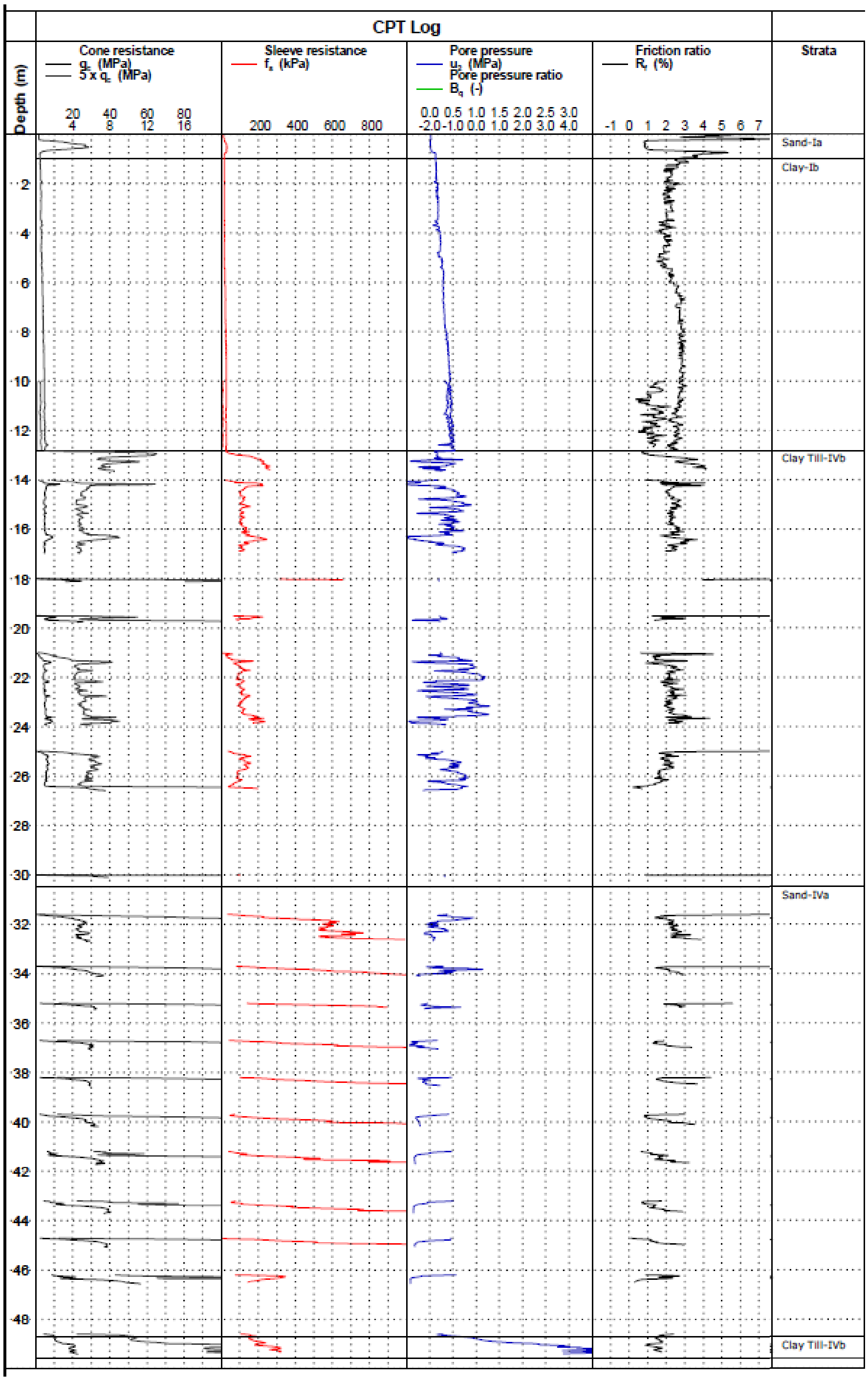


Figure 12-10 CPT measurements for CPT-113/BH-113 found as representative for zone C1.

Table 12.8 Soil stratigraphy for CPT-113/BH-113 found as representative for zone C1.

Top [mbsb]	Bottom [mbsb]	Integrated ground model unit	Soil Unit	Soil/Rock Type
0.0	1.0	GMU1	Ia	Sand
1.0	12.8	GMU2	Ib	Clay
12.8	30.5	GMU4	IVb	Clay till
30.5	48.7	GMU5	IVa	Sand
48.7	49.6	GMU4	IVb	Clay till
49.6	70.0	GMU5	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 8.6 m of soft soils in less than 5 m, CPT-103/BH-103 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	4.9	GMU2	Ib	Clay
4.9	22.5	GMU3	III	Clay
22.5	27.0	GMU4	IVb	Clay till
27.0	28.5	GMU5	IVa	Sand
28.5	52.0	GMU4	IVb	Clay till
52.0	53.2	GMU6	Va2	Limestone
53.2	54.0	GMU6	Va1	Limestone
54.0	70.1	GMU6	Vb1	Chalk

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, there is not available example however omitting the upper 8.6m of soft soils CPT-103/BH-103 would be considered a representative profile. The stratigraphy in table format for an artificial profile representing soil zone C3 is presented in Table 12.10.

Table 12.10 Soil stratigraphy as representative for zone C3.

Top [mbsb]	Bottom [mbsb]	Integrated ground model unit	Soil Unit	Soil/Rock Type
0.0	22.5	GMU3	III	Clay
22.5	27.0	GMU4	IVb	Clay till
27.0	28.5	GMU5	IVa	Sand
28.5	52.0	GMU4	IVb	Clay till
52.0	53.2	GMU6	Va2	Limestone
53.2	54.0	GMU6	Va1	Limestone
54.0	70.1	GMU6	Vb1	Chalk

13. Summary

Water depth varies moderately across the Bornholm I site from ca. 27 m in the far south to over 45 m in the North. There is a gradual increase in water depth from the southern part of the site towards both the West and North. A bathymetric high located in the north-eastern part of the site is believed to reflect relict topography developed over a large relict moraine ridge.

Comparison with the bathymetry map illustrates that there is a broad correlation between seabed grain size and increasing water depth. This is most evident in the southern and central parts of the Bornholm I site where there is a clear transition from sand (locally gravel and pebble-rich) to clay substrates with increasing water depth. Where the glacial sediments subcrop at, or very close to the seafloor the seabed is typically littered with stones and pebbles likely directly reworked from glacial tills and/or moraines.

Four seismic units have been mapped out on the Sub-bottom profiler data and on the multichannel Ultra-High Resolution Seismic data. The seismic surfaces that define the Seismic Units have been integrated with Geotechnical Soil Units to create a Ground Model across the site. Six Ground Model Units are defined and designated by GMU1 to GMU6 with increasing stratigraphic depth. The Ground Model Units are dominated by one of the Soil Units that have been characterised from the Ground Information recovered from the Borehole and CPT Geotechnical Campaigns. However, there is some variability and thin intervals of other Soil Units are locally present in the GMUs.

The shallow Ground Model Unit 1 (GMU1) is dominated by loose soft sands (Soil Unit Ia). It corresponds to Seismic Unit 2a which defines a series of mounded features, particularly in the southern and eastern part of the Bornholm I Site. GMU2 is primarily comprised of soft, organic-rich clays (Soil Unit Ib) and it corresponds to Seismic Units 1, 2b and 3. This unit encompasses the bulk of the Holocene and latest Pleistocene Baltic Lake/Sea succession that was deposited following the retreat of the LGM Ice-Sheet. Locally sands have been fed into this lake/marginal sea system so intervals of Soil Unit IVa (dense stiff sand) can be locally present (see polygon in Figure 11-2, Figure 7-16 & Figure 7-17).

The soft clays of GMU2 bury a very irregular landscape that was created by the retreat of the Last Glacial Maxima Ice Sheet from the vicinity of the Bornholm I area. The H30 (H35) Seismic Horizon maps out this surface. Below the hummocky terrain created by the retreat of the ice sheet, Seismic Unit 4 is characterised by the stiffer clays of Soil Units III and IVb. These two Soil types respectively define GMU3 and 4 and they comprise a large proportion of sediments in Seismic Unit 4. GMU3 and 4 have been mapped across the site but there remains uncertainty on the exact position of the contact between these two GMUs. The contact between Soil Units III and IVb, whilst clear in the Boreholes and CPTs, but does not always coincide with a seismic event. Soil Type IVb comprises stiff, strong silty clays that have been deposited either as tills or as distal fine grained fans. GMU5 represents the sandy part of the fan-systems, as well as palaeovalley plugs along the eastern and northern part of the Bornholm I Site. GMU5 is dominated by the dense stiff sands of Soil Unit IVa, though interbeds of stiff clay (Soil Unit IVb) can be encountered. The dense sands GMU5 (Soil Unit IVa) were deposited as distinct fan-systems or have plugged palaeovalleys (potentially tunnel valleys), carved into the bedrock.

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, organic-rich clays that define GMU2 (Soil Unit Ib). 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 drived 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 investigation.

14. References

Andrén, E. A. (2000). The Holocene history of the southwestern Baltic Sea as reflected in a sediment core from the Bornholm Basin. *Boreas, 29*, 233-250.

Andrén, T. B.-S.-B. (2014). IODP Site M0065. *Proceedings of the Integrated Ocean Drilling Program, 347*.

Baldi, G., Bellotti, R., Ghionna, V., Jamiolkowksi, M., Presti, L., & D.C.F. (1989). Modulus of Sands from CPT's and DMT's. *Proceedings of the Twelfth International Conference on Soil Mechanics and Foundation Engineering.* Rio de Janeiro.

Björck, S. (1995). A review of the history of the Baltic SEa 13.0-8.0 ka BP. *Quaternary International , 27*, 19-40.

BS EN ISO 14689:2018. Geotechnical investigation and testing-Identification, description and classification of rock. (n.d.). London, England: British Standrards Institute.

Clayton L., A. J. (2008). Ice-walled-lake plains: Implications for the origin of hummocky glacial topography in middle North America. *Geomorphology, 97*, 237-248.

Deeks, N. R. (2012). Basin inversion in a strike-slip regime: the Tornquist Zone, Southern Baltic Sea. *Geological Society, London, Special Publication, 88*(319-338.).

DNVGL-RP-C207. (2019). *Statistical representation of soil data.* DNVGL.

Erlström, M. T. (1997). Structure and tectonic evolution of the Tornquist Zone and adjacent sedimentary basins in Scania and the Southern Baltic Sea area. *Tectonophysics, 271*, 191-215.

Gardline. (2023). *11783 - Preliminary Geotechnical Investigation for Energy Island - Bornholm I and Bornholm II Offshore Wind Farms, Baltic Sea.* Gardline Limited, 8583pp.

Gardline. (2023). *Preliminary Geotechnical Investigation for Energy Island - Bornholm I and Bornholm II Offshore Wind Farms, Baltic Sea: Volume II: Measured and Derived Geotechnical Parameters and Final Results Report Ref: 11783.*

GEOxyz. (2022). *SN2021_015 - Geophysical Survey For Offshore Wind Farms And Energy Island BORNHOLM I.*

Graversen, O. (2010). Structural analysis of superposed fault systems of the Bornholm horst block, Tornquist Zone, Denmark. *Bulletin of the Geological Society of Denmark*, 25-49.

Hambrey, M. H. (1997). Genesis of "humocky moraines" by thrusting in glacier ice: evidence from Scotland and Svalbard. *Journal of the Geological Society of London, 154*, 623-632.

International Standards Organisation, ISO 19905-1:2016(E) Petroleum and natural gas industries-Site-specific assessment of mobile offshore units-Part 1:Jack ups. (n.d.).

Jamiolkowksi, M., Presti, L., DCF., & Manaseero, M. (2001). Evaluation of Relative Density and Shear Strength of Sands from CPT and DMT. *ASCE Geotechnical Special Publication No. 119*, 201-238.

Jensen, J. P. (2021). *Geology desk study offshore Bornholm, Baltic Sea Windfarm investigations.* Copenhagen: Geological survey of Denmark and Greenland (GEUS).

Liboriussen, J. A. (1987). The tectonic evolution of the Fennoscandian Border. *Tectonophysics, 137*, 21-29.

Lunne, T., Robertson, P., & Powell, J. (1997). *Cone Penetration Testing in Geotechnical Practice.* Spon Press-Taylor & Francis Group.

Mayne, P. (2017). Stress history of soils from cone penetration tests. *Soils and Rocks, 40*, 203-218.

Mogensen, T. a. (2003). Triassic and Jurassic transtension along part of the Sorgenfrei–Tornquist Zone in the Danish Kattegat. *Geological Survey of Denmark and Greenland Bullietin, 1*, 439-458.

Network Stratigrpahic Consulting Limited. (2023). *Biostratigraphic analysis of three core samples from offshore Bornholm, Baltic Sea.*

Norsk Hydro. (1989). *Pernille-1 Final Well Report.*
Rix, G., & Stokoe, K. (1991). Correlation of initial tangent modulus and cone penetration resistance. *1st International Symposium on Calibration Chamber Testing/ISOCCT1.* Postdam, NY.
Robertson, P., & Cabal, C. (2022). Guide to Cone Penetration Testing for Geotechnical Engineering. *Gregg Drilling & Testing, Inc. 7th Edition*.
Schmertmann, J. (1978). Guidelines for cone penetration test performance and design. *Dept. of Transportation, FHWA, R.78-209.* Washington D.C.
The Society of Naval Architects and Marine Engineers (SNAME). (August 2008). Technical & Research Bulletin 5-5A: Guidelines for Site Specific Assessment of Mobile Jack-Up Units, Rev. 3.