Bornholm
Energy Island Bornholm
Geotechnical Interpretative Report

Geo Job no. 206728
Report 15, 2024-02-23

Summary

In relation to Energy Island Bornholm, Energinet is planning to make the landfalls of HVDC and HVAC cables using Horizontal Directional Drilling (HDD). Between the landfalls and the Station area, where large enclosed transformer stations are planned, the cables are to be installed using trenching where the topography and other geological conditions allow, or HDD otherwise.

The overall investigation scope of works included geotechnical and geophysical investigation of selected sites for HDD with high risk due to topographic variations, complicated ground conditions or the length of the HDDs, geophysical investigations of the cable routes, and preliminary geotechnical investigations for the transformer stations. The investigation of HDD locations comprised geophysical mapping, geotechnical boreholes and geophysical borehole logging.

The present Geotechnical Interpretative Report (GIR) provides interpretation of geotechnical and hydro-geological parameters of the encountered deposits/formations based on the available ground investigation data. Principles of deriving the soil and rock parameters applicable for the design of HDD based on the currently available data are presented.

The present GIR is systemizing the available information, including the overview of the most likely risks, per geological unit. An overview of risks applicable for the whole investigation area is also presented.

This GIR is a general document. For specific design purposes of HDDs, separate design profiles with associated geotechnical parameters, must be elaborated for the design alignments of particular HDDs.

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1 Introduction

1.1 Objective and Scope of investigation and present report

In relation to Energy Island Bornholm Energinet are planning to make the landfalls of HVDC and HVAC cables using Horizontal Directional Drilling (HDD). Between the landfalls and the Station area, where large enclosed transformer stations are planned, the (buried) cables are to be installed using trenching where the topography and other geological conditions allow, or HDD otherwise.

The overall investigation scope of works included geotechnical and geophysical investigation of selected sites for HDD with high risk due to topographic variations, complicated ground conditions or the length of the HDDs, geophysical investigations of the cable routes, and preliminary geotechnical investigations for the transformer stations. The investigation of HDD locations comprised geophysical mapping, geotechnical boreholes and geophysical borehole logging.

The objective of the investigation is to provide information based on which landing locations, and the lengths and depths of the HDDs can be selected.

The purpose of this Geotechnical Interpretative Report (GIR) is to provide an interpretation of geotechnical and hydro-geological parameters of the encountered deposits/formations based on ground investigation data available, and to present derived soil and rock parameters applicable for the design of HDD. The location of the preliminary HDD alignments assumed in the investigation phase are shown in the location plan, Enclosure 15.A01.

This GIR is a general document. For specific design purposes of HDDs, separate design profiles with associated geotechnical parameters, must be elaborated for the design alignments of particular HDDs.

An assessment of chemical concentrations in material to be excavated and disposed of site is not within the scope of this GIR.

A human or end user health based risk assessment of residual chemical concentrations remaining in the ground after construction is not within the scope of this GIR.

1.2 General report overview

The current report is structured in the following sections:

1. **Introduction**: General information about the report
2. **Geology**: Geological outline of the regional and project specific geology, information about the enhancement of the prior geological model on the basis of current investigation and evaluation of the model performance based on the finds in Pilot borings
3. **Geotechnical and geophysical testing**: Summary of the testing performed for the purpose of the current project
4. **Concepts and parameter interpretation methods**: Explanation of the methods used for evaluation of geotechnical parameters presented in sections 6 – 14

5. **Risk Analysis**: Overview of the methods and risks presented in sections 6-14 and Enclosure A15.02
6. **Recent, Fill and Lateglacial deposits**
7. **Quaternary deposits**
8. **Cretaceous Arnager Greensand Formation**
9. **Jurassic Rønne Formation**
10. **Triassic Kågerød Formation**
11. **Silurian Cyrtograptus and Rastrites shale**
12. **Ordovician / Cambrian Alum shale Formation**
13. **Cambrian Læså Formation**
14. **Cambrian Hardeberga Formation**
15. **Characteristic parameters**: Overview of the parameter ranges for the formations presented in sections 6-14
16. **References**: General referenced literature used in addition to Reference reports presented in section 1.3 and Applicable codes and standards presented in section 1.4

Sections 6 to 14 are organized in 4 subsections:

- **Available information**: reference to the reports and boreholes with data for the particular deposit
- **Measured data**: listing the available information. (Note: only tests carried out for the current project are considered.)
- **Ranges of geotechnical and hydrogeological parameters**: lower bound - upper bound values for the selected parameters, based on the available Measured data, and engineering experience and judgement otherwise.
- **Risks review and commentary**: short review of the risks presented in Attachments to Reports 1-9, 12 and 13 concerning the formation of interest.

1.3 Reference Reports

[1] Geo Job no. 206293, Energy Island, Bornholm – Screening study of landfall and station area. Geological interpretation, 3D modelling and geotechnical risk assessment. Report 1, revision 1, 2022-06-15

[2] Energinet. Energiø Bornholm. Forundersøgelser for ilandføring, kabelstrækning og stationsområde. 05 – Ydelsesbeskrivelse – Dok.22/04788-5 Version 4, 2022-08-17 (in Danish)

[3] Energinet. Energiø Bornholm. Forundersøgelser for ilandføring, kabelstrækning og stationsområde. 06 – Servicebeskrivelse – Bilag 1 – Tekniske specifikationer Dok.22/04788-6 Version 2, 2022-08-17 (in Danish)

Report 1: HDD1 (landfall)

Report 2: HDD2 (landfall)

Report 3: HDD3 (landfall)

Report 4: HDD4 (landfall)

Report 5: HDD5 (landfall)

Report 6: HDD6 (landfall)

Report 7: HDD7 (landfall)

Report 8: HDD8 (cable route pass)

Report 9: HDD9 (cable route pass)

Report 10: Cable routes

Report 11: Station area

Report 12: HDD12 (landfall)

Report 13: HDD13 (landfall)

Report 14: Geological model update

1.4 Applicable Codes and Standards

[4] Dansk Standard DS 415 (1984) Dansk ingeniørforenings norm for fundering. 3. Udgave februar 1984. ISBN 87-571-0765-3.

[5] DGF-Bulletin 1 - Larsen, G., Frederiksen, J., Villumsen, A., Fredericia, J., Graversen, P., Foged, N., Boumann, J.: A guide to engineering geological soil description, 1995.

[6] DS/EN 1997-1. (2007). Eurocode 7. Geotechnical Design – Part 1: General rules.

[7] DS/EN 1997-1 DK NA:2021 National annex to Eurocode 7: Geotechnical design – Part 1: General rules

[8] DS/EN 1997-2 + AC:2011 (2011). Eurocode 7. Geotechnical Design – Part 2: Ground investigation and testing.

[9] DS/EN 1997-2 DK NA:2013 National Annex to Eurocode 7: Geotechnical design – Part 2: Ground investigation and testing

[10] DS/EN ISO 14688-1 :2018 Geotechnical investigation and testing – Identification and classification of soil – part 1: Identification and description

[11] DS/EN ISO 14688-1 :2018 Geotechnical investigation and testing – Identification and classification of soil – part 2: Principles for classification

[12] DS/EN ISO 14689-1 :2018 Geotechnical investigation and testing – Identification and classification of rock – part 1: Identification and description

[13] DS/EN ISO 22476-3:2005 - Geotechnical investigation and testing. Field testing – Part 3, Standard penetration Test

[14] EN ISO 22476 - Geotechnical investigation and testing. Field testing

[15] Ulusay R, Hudson J., (2007) The Complete ISRM Suggested Methods for Rock Characterization, Testing snd Monitoring: 1974 – 2006. ("The Blue Book".) ISRM Turkish National Group and the ISRM

[16] USACE EM 110-1-1905 Bearing capacity of soils

2 Geology

2.1 Regional Geological Background – Summary

The island of Bornholm is located in a geological fracture zone (Sorgenfrei-Tornquist Zone), separating elevated crystalline bedrock in the northeastern part of Europe and sedimentary basins to the southwest, cf. Larsen 2006, ref. [23].

The northern part of Bornholm is an up-thrusted block (horst) of crystalline bedrock and the southern part of Bornholm is largely characterised by sedimentary deposits. The southern part of Bornholm is divided into three areas by the two major fault lines orientated NW-SE, the northernmost fault separating crystalline basement from primarily Paleozoic sediments and the southern costal fault separating the Paleozoic sediments from Mesozoic sediments to the south.

The deposits in the investigation area, situated between the two major faults, of which one is situated near the coast (Coastal fault), consist primarily of Palaeozoic sediments divided into smaller structural blocks, see Figure 2.1.

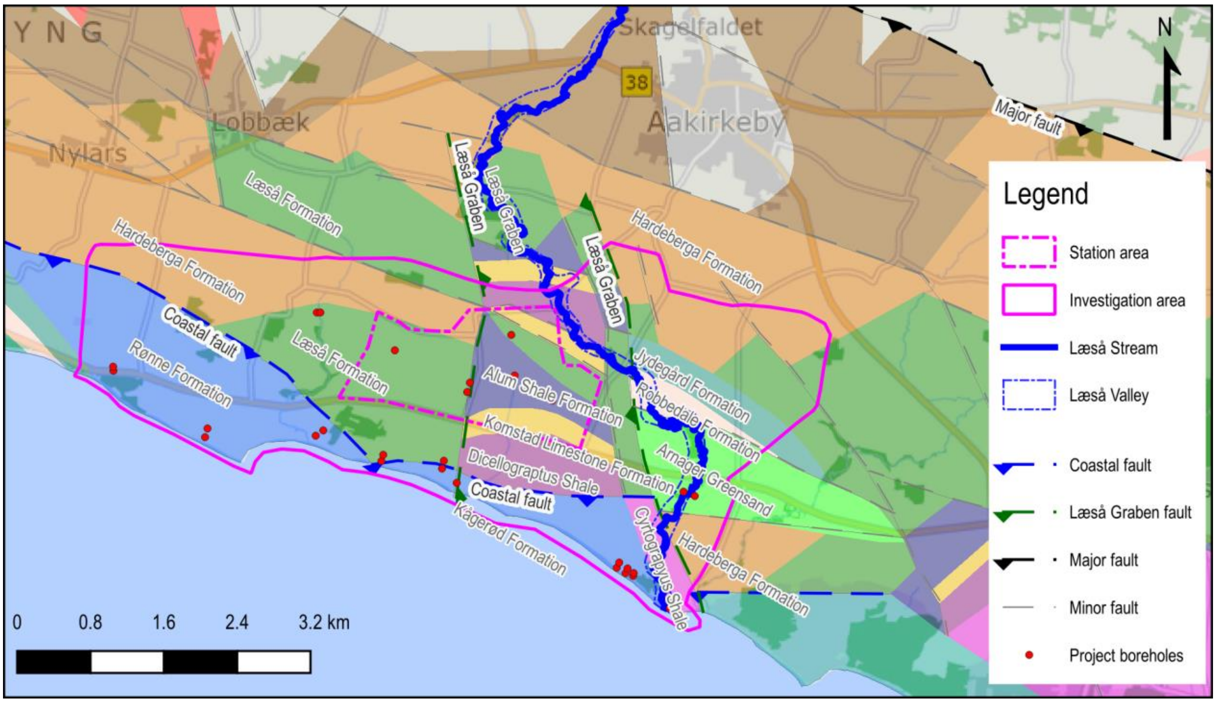


Figure 2.1 *Distribution of pre-Quaternary sediments and structural conditions in the overall investigation area (modified from VARV 1977, cf. ref [17]).*

The structural blocks are subdivided into a mosaic of smaller blocks separated by faults orientated NW-SE and N-S. The blocks are each tilted to various degrees, generally towards SE. An area with a downfaulted block (a graben system), separated by the Læså Graben faults on each side (see Figure 2.1) is found beneath the Læså stream where sediments from the youngest part of the Palaeozoic are preserved. On each side of this graben structure (Læså Graben) some Mesozoic sediments occur.

Table 2.1 Conceptual geology for Southern Bornholm.

Era	Period	Lithology (DGU-symbol)	Lithology description	Age / Formation	Remarks
Cenozoic	Quaternary	t, p, m, l, s	Peat, gyttja, mull, clay or sand	Postglacial / Recent	
		l, i, s, g	Clay, silt, sand, gravel		
		ds, s, dg, g	Meltwater sand, gravel	Late Glacial / Weichselian	
		ml, ms, dl, l, s	Clay till, sand till, (meltwater clay)	Glacial / Weichselian	
		ds, s, di, i	Meltwater sand, silt		
		ml, ms, dl, l, s	Clay till, sand till, (meltwater clay)		
		dl, l, ds, s, dg, g	Meltwater clay, sand, gravel		
Mesozoic	Cretaceous	as, al, ak, s, c	Glauconitic sand, clay, conglomerate	Arnager Greensand Formation	
		rs, rg, s	Sand, medium-coarse	Robbedale Formation	
		wl, l, s	Clay, minor sand-layers	Jydegård Formation	
	Jurassic	l	Clay	Rønne Formation	
		s	Sand, silty		
		l	Clay		
		s	Sand, silty		
	Triassic	l, cl	Plastic clay	Kågerød Formation	
		s	Coarse sand		
		l, cl	Plastic clay		
Paleozoic	Silurian	sr, sj, r	Shale	Cyrtograptus and Rastrites Shale	No official Formation recognized. Known as Cyrtograptus and Rastrites Shale
	Ordovician	dr, r	Shale	Dicellograptus Shale	No official Formation recognized. Known as Dicellograptus Shale
		qk, ok, k	Limestone	Komstad Limestone Formation	Known as Orthoceratite limestone
	Cambrian	ar, r	Shale, high organic content	Alum Shale Formation	
		rq, s	Sandstone	Læså Formation	Rispebjerg Sandstone Member
		kj	Fine grained sandstone, shale		Known as Green slate (Grønne skifre)
		kq	Cemented sandstone	Hardeberga Formation	Known as Balka sandstone
		eq	Cemented sandstone	Nexø Formation	
Pre-Cambrian		a, pa	Granite / Gneiss		Crystalline bedrock

The summary of the depositional history is based on the geological interpretation and conceptual geology established for the 3D geological model, ref. [1], literature (ref. [17] - [23]) and borehole descriptions for this study. A detailed account of the regional geology and the geology of the overall project area is presented in Reports 10 and 11. The table with conceptual geology for Southern Bornholm area is presented in Table 2.1.

2.2 Project Specific Geological Conditions

The general geological model of the area has been updated with findings in boreholes and geophysical investigations. The differences between the model presented in Screening study, ref. [1], and the current model presented in Report 14 are outlined in section 2.3.

A summary of boreholes made within the current investigation and used for interpretation of characteristic soil and rock parameters stated in this report, is presented in section 3.2. The soil and rock types listed in Table 2.2 appear along the HDD alignments and within the station area.

Table 2.2 Soil and rock types encountered in boreholes within the project area

Era	Period	Soil /rock type	Age / Formation
Cenozoic	Quaternary	Fill, sand mull, clay mull	Postglacial / Recent
		Clay, sand, gravel,	
		Metlwater sand	Late Glacial / Weichselian
		Glacial clay till, sand till, gravel till	Glacial / Weichselian
		Meltwater silt, sand and gravel	
		Glacial clay till, sand till, gravel till	
		Meltwater clay, sand and gravel	
Mesozoic	Cretaceous	Sand, clay, conglomerate	Arnager Greensand Formation
	Jurassic	Clay	Rønne Formation
		Sand	
	Triassic	Clay	Kågerød Formation
		Sand	
Paleozoic	Silurian	Shale	Cyrtograptus and Rastrites Shale
	Ordovician	**Shale, conglomerate**	Alum Shale Formation
	Cambrian		
		Sandstone, siltstone, shale, clay	Læså Formation
		Sandstone	Hardeberga Formation

Parameter interpretations based on in situ and laboratory testing carried out within this project for various types of soil and rock are presented in Appendices A15.1 to A15.9.

2.3 Modification of the geological model based on the current results

In the following a summary of the changes in the individual HDD areas is presented. As the investigations in HDD12 and HDD13 were done after the current revision of the model, there are no changes in these areas.

- HDD1

In the area of HDD1 the changes comprise mainly adjustments of the layers already existing in the model. The boreholes and geophysical investigations in this area did not reveal any unanticipated geological formations.

- HDD2

At HDD2, several significant changes to the model were made due to the new data from the investigation program. The position of the coastal fault was moved approx. 100 m towards the coast and the occurrence of clay in the Kågerød Formation was added to the model.

- HDD3

In the area around HDD3, the coastal fault was moved approx. 50 m towards the coast; south of the fault the Quaternary layers were thicker than expected in the previous model, and this was changed in the model.

- HDD4

In the HDD4 area, the coastal fault was moved approx. 200 m closer to the coast, and the internal occurrence of sand and clay in the Kågerød Formation was adjusted, primarily based on the geophysical investigation.

- HDD5

Around HDD5 the position of two faults was adjusted to match the observed data and an area with complex faulted geology was identified and delineated based on the geophysical investigation.

- HDD6

At HDD6, a likely secondary fault, parallel to the coastal fault, has been identified.

- HDD7

In the area of HDD7 the presence of the Alum Shale Formation was observed, and this is included in the model. As the HDD7 area is outside the Læså Graben this was not expected and the occurrence of the Alum Shale Formation was revised.

- HDD8

Around HDD8 the occurrence of Hardeberga Formation and Læså Formation was changed according to the borehole data.

- HDD9

At HDD9 there has been no significant changes to the model.

2.4 Pilot borings

Following the site investigation presented in Reports 1-13, three pilot borings have been made. The placement of pilot borings is outlined in Figure 2.2, where they are respectively labelled as Pilot HDD1 – Pilot HDD3 in agreement with the as-built data received from Energinet:

HDD1_As_Built_UTM_Data_2300257_Villy Poulsen_Sondre Landevej_Bornholm_Denmark
HDD2_As_Built_UTM_Data_2300319_Villy Poulsen_Sose_Bornholm_Denmark
HDD3_As_Built_UTM_Data_2300346_Villy Poulsen_Vest_Bornholm_Denmark

Figure 2.2 Positions of the pilot borings

In the following, the pilot borings are referred to as Pilot boring 1 – 3, for Pilot HDD1 to HDD3, in order to avoid confusion with the HDD investigation locations HDD1 – HDD3.

The geological sample descriptions made on the muck samples retrieved during drilling of the pilot borings are presented in Annexes Pilot Boring 1 to Pilot Boring 3, Geological sample descriptions pages. The data obtained from pilot borings is taken into account considering the following:

- The position of the drilling line is determined with smaller accuracy in comparison to the alignment of a geotechnical boring.
- The exact placement of the drilled out sample along the drilling line is determined with smaller accuracy in comparison to the samples collected in geotechnical borings.
- The collected samples contain a mixture of the drilling mud and the drilled out soil/rock material, which challenges the geological description.

The soil/rock types interpreted along Pilot Borings are depicted in the Annexes Pilot Boring 1 to Pilot Boring 3, Geological profiles. The geological profiles generally show a good agreement between the descriptions of the retrieved samples from the pilot borings and the overall geological model.

3 Geotechnical and Geophysical Testing

3.1 General

The investigations within the HDD areas, along the cable routes and within the station area have included:

- Geotechnical drilling
- Geotechnical in situ testing comprising field vane tests and SPT measurements in soils
- Geophysical investigations comprising geophysical borehole logging and geophysical mapping by tTEM, DualEM and ERT
- Geotechnical laboratory testing on soil and rock comprising sample description, classification tests, thermal conductivity tests, UU tests, UCS test, Indirect (Brazilian) tensile strength test, Equotip hardness testing

3.2 Drilling

The geotechnical borings carried out in relation to this specific project are listed in Table 3.1 and shown in Enclosure 15.A01. No boreholes have been carried out for cable routes (Report 10) and HDD13 (Report 13).

Table 3.1 Geotechnical borings carried out in relation to Energy Island Bornholm

Borehole	Drilling method	X-coordinate UTM33, Euref89	Y-coordinate UTM33, Euref89	Ground level, [m DVR90]	Depth of borehole, [mbgl]
1-1-2	8" Cased Shell & Auger	487965.11	6100483.69	+17.9	35.00
1-1-3	8" Cased Shell & Auger and coring	487965.91	6100528.36	+22.7	35.00
1-2-2	8" Cased Shell & Auger and coring	490100.07	6099588.60	+14.5	35.25
1-2-3	8" Cased Shell & Auger and coring	490186.91	6099638.75	+18.1	35.50
1-3-2	8" Cased Shell & Auger and coring	491586.00	6098944.06	+19.9	35.00
1-4-1	8" Cased Shell & Auger and coring	493242.62	6097871.28	+5.7	35.20
1-4-2	8" Cased Shell & Auger and coring	493275.04	6097926.55	+14.7	35.00
1-4-3	8" Cased Shell & Auger and coring	493333.22	6097803.99	+6.4	35.25
1-4-4	8" Cased Shell & Auger and coring	493359.65	6097854.49	+13.6	35.50
1-4-5	8" Cased Shell & Auger and coring	493413.54	6097767.93	+8.5	35.50
1-4-6	8" Cased Shell & Auger and coring	493422.35	6097798.31	+10.9	35.50
1-5-1	4" Cased Shell & Auger	493780.00	6097381.81	+1.4	3.50
1-5-2	8" Cased Shell & Auger and coring	493801.75	6097433.34	+13.6	35.40
1-6-1	8" Cased Shell & Auger and coring	490789.69	6099251.52	+23.2	35.20
1-6-2	8" Cased Shell & Auger and coring	490815.05	6099317.70	+29.7	40.15
1-7-1	8" Cased Shell & Auger and coring	491440.02	6099113.02	+26.2	40.20
1-7-2	8" Cased Shell & Auger and coring	491466.92	6099196.67	+31.5	35.20
1-12-1	8" Cased Shell & Auger and coring	488897.96	6099675.59	+18.5	50.00
1-12-2	8" Cased Shell & Auger and coring	488932.55	6099768.34	+16.4	35.00
2-1-1	8" Cased Shell & Auger and coring	490227.80	6100926.05	+43.0	35.20
2-1-2	8" Cased Shell & Auger and coring	490265.97	6100923.27	+43.4	35.50
2-5-1	8" Cased Shell & Auger and coring	494157.20	6098578.36	+21.5	36.20
2-5-2	8" Cased Shell & Auger and coring	494038.97	6098636.04	+19.7	36.20
3-1	4" Cased Shell & Auger	491039.29	6100438.84	+42.1	5.40
3-2	4" Cased Shell & Auger	492316.42	6100500.15	+41.2	3.30
3-3	4" Cased Shell & Auger	492698.87	6099749.07	+39.6	3.00
3-4	4" Cased Shell & Auger	491786.43	6099921.24	+36.5	6.30
3-5	4" Cased Shell & Auger	491823.14	6100020.43	+36.2	5.00
3-6	4" Cased Shell & Auger	492315.67	6100056.26	+36.5	5.00

3.3 Geotechnical In Situ Testing

A series of field tests has been carried out along the intervals of boreholes which were drilled by shell and auger. The field tests include:

- Field vane test
- SPT

The results of the field vane tests and SPT measurements are presented on borehole profiles in accordance with Danish practice.

3.4 Geotechnical Laboratory Testing

Classification tests are carried out on bag samples from the intervals drilled by shell and auger, as well as on core samples of soil from the cored intervals.

The classification tests on soil samples comprised

- Visual soil description
- Determination of water content
- Atterberg limits on cohesive soils
- Grain size distribution
- Particle density (specific gravity)
- Organic content (loss on ignition)
- Determination of density
- Thermal conductivity

Triaxial UU tests have been carried out on a few samples.

The geological description and classification of the core samples of rock comprised

- Registration of induration
- Registration of fractures
- Registration of TCR (Total Core Recovery) and RQD (Rock Quality Designation)
- Core photos
- Visual soil/rock description
- Determination of water content
- Determination of unit weight
- Determination of void ratio
- Organic content
- Particle density (specific gravity)
- Eqoutip hardness (by Bambino tester)

One UCS test and one Indirect (Brazilian) tensile strength test have been carried out.

3.5 Geophysical Borehole Logging

Geophysical borehole logging have comprised:

- Natural gamma logging
- Calliper logging (borehole dimension)
- Resistivity logging
- Conductivity logging
- OTV (Optical Televiewer logging)
- HiRAT (High-Resolution Acoustic Televiewer)

The test programme is shown in Table 3.2. Geophysical borehole logging has not been carried out for HDD3 (Report 3), cable routes (Report 10), station area (Report 11) and HDD13 (Report 13).

Table 3.2 Geophysical borehole logging programme

	Boreholes	**Geophysical logging**					
Location	Borehole No	Natural gamma	Calliper	Formation Resistivity	Formation Conductivity	HiRAT	OTV
HDD1	1-1-2	-	-	-	-	-	-
	1-1-3	-	-	-	-	-	-
HDD2	1-2-2	X	-	-	-	X	-[1]
	1-2-3	X	-	-	-	X	-[1]
HDD3	1-3-2	-	-	-	-	-	-
HDD4	1-4-1	X	X	X	X	X	-[1]
	1-4-2	X	X	X	-	X	-[1]
	1-4-3	X	X	X	X	X	-[1]
	1-4-4	X	-	-	-	X	-[1]
	1-4-5	X	-	-	-	X	-[1]
	1-4-6	X	X	X	-	X	-[1]
HDD5	1-5-1	-	-	-	-	-	-
	1-5-2	X	X	-	X	X	X
HDD6	1-6-1	X	X	-	-	X	X
	1-6-2	X	X	-	-	X	X
HDD7	1-7-1	X	X	-	-	X	X
	1-7-2	X	X	-	-	X	X
HDD8	2-1-1	X	X	X	-	X	X
	2-1-2	X	X	-	-	X	X
HDD9	2-5-1	X	X	X	-	X	X
	2-5-2	X	X	X	-	X	X
HDD12	12-1-1	X	X	X	-	X	-[1]
	12-1-2	X	X	X	-	X	-[1]

[1] Not attempted/carried out due to low visibility

3.6 Geophysical Mapping

Geophysical mapping comprised:

- DualEM
- tTEM
- ERT

The test programme is shown in Table 3.3. All DualEM results from HDD areas (i.e. not including the station area) are presented in the Report 10 Cable routes.

Table 3.3 Geophysical mapping programme

	ERT	DualEM	tTEM
HDD1	-	X	X
HDD2	-	X	X
HDD3	-	X	-
HDD4	-	X	X
HDD5	-	X	X
HDD6	-	-	X
HDD7	-	-	X
HDD8	X	-	-
HDD9	X	-	-
Cable routes	-	X (from HDD areas)	-
Station area	-	X	-
HDD12	-	-	X
HDD13	-	-	X

4 Concepts and parameter interpretation methods

4.1 General

The overall purpose of the current GIR is to present derived strength and deformation parameters and the hydrogeological parameters relevant for the design of HDD per geological formation encountered.

The interpretations are carried out according to DS/EN 1997-1, section 2.4.5.2, ref. [6], in combination with interpretation methods used in Danish practice as described in the present GIR. The derived parameters are presented in sections 6 – 15 as ranges between Lower bound (LB) and Upper bound (UB) values.

Due to the limited amount of data, some of parameters are based on engineering experience and judgement. The following theoretical background shows concepts that have been used in the interpretation.

4.2 Classification of soils

4.2.1 Classification of soils based on particle size distribution

The soil classifications based on particle size distributions used in Denmark are given in DGF Bulletin No.1, ref. [5].

Particle size analyses are carried out for all soil types, whereas soils dominated by particles finer than 0.063 mm are classified as fine grained soils (silt and clay) and particle size distributions are obtained based on the combined results from sieving and hydrometer tests.

4.2.2 Classification of fine grained soils based on Atterberg limits and clay content

In sample descriptions in Denmark, the guide provided in DGF Bulletin 1, ref. [5], is used for the determination of plasticity.

According to Danish practice, the liquid limit, w_L, and the plasticity index, I_p, are used to classify clays and silts as shown in Table 4.1.

Table 4.1 Classification of fine-grained soils with respect to plasticity according to DGF Bulletin 1, ref. [5]

Soil description	**Liquid limit** wL [%]	**Plasticity index** Ip [%]	**Clay** [%]	**USCS**
CLAY, very high plasticity	>80	>50		CV
CLAY, high plasticity	50-80	25-50		CH
CLAY, medium plasticity	30-50	10-25		CM
CLAY, silty / sandy	<30	7-10	15-20	CL
CLAY, very silty /sandy	<30	4-7	10-15	CL
SILT, very clayey		4-7	<10	ML
SILT, clayey / sandy		<4	<10	ML

Soil stickiness after Geodata 1995 classification, cf. Marinos et al. 2008, ref. [27], is evaluated based on the water content, w, plastic limit, w_p, and plasticity index, I_p. The term stickiness refers to the soil sticking on the surfaces of the drilling equipment.

Soil clogging potential after Thewes and Burger 2004 classification, cf. Marinos et al. 2008, ref. [27], is evaluated based on the plasticity index I_p, and consistency index, $I_c = (w_L - w)/I_p$. The term clogging refers to the soil clogging/blocking the drilling equipment.

Further classification of the fine grained soils based on Atterberg limits includes evaluation of activity per Williams 1958, cf. Fredlund 1975, ref. [30] (see also Netterberg 2019, ref. [32]). Activity is used to indicate the potential for slaking which would lead to instabilities during the excavation and in general, whenever an unsupported boring is subject to a significant water flow. Slaking of the soil denotes breaking down of the material upon wetting and expansion, a term describing volume increase due to wetting, while the fabric of the material remains unbroken High and very high expansion potential are interpreted as a potential for slaking.

4.2.3 Sensitivity of clays based on field vane tests

Sensitivity of clays represents the loss of clay strength due to remoulding at a constant water content. It is evaluated after Skempton and Northey 1952, ref. [33], as a ratio of shear strengths measured by field vane test in undisturbed and remoulded soil, strength ratio c_{fv}/c_{rv}, along the depth of a borehole, see Table 4.2.

Table 4.2 Classification of clays in terms of sensitivity after Skempton and Northey 1952, ref. [33]

Classification	Strength Ratio
Insensitive	< 1
Low sensitivity	1 - 2
Medium sensitivity	2 - 4
Sensitive	4 - 8
Extra sensitive	8 - 16
Quick	> 16

4.2.4 Classification of coarse grained soils based on SPT

The SPT N value is often used to determine the relative density of soils. The N values are however dependent on the coarseness and gradation of sand, overburden pressure, and length of the rod inducing the blows. Corrections to the N value defined by DS/EN 1997-2, ref. [8], and DS EN ISO 22476, ref. [14], are accounted for as follows.

- Energy ratio, E_r, cf. ref. [14], is taken as 60, such that the normalized blowcount, $E_r/60 \cdot N$, remains equal to the measured N.
- For fine sands, the N values are reduced in the ratio C_{Coars} of 55/60 and for coarse sands increased in the ratio C_{Coars} of 65/60, cf. ref. [8].
- Aging effect cf. ref. [8] is not taken into account.
- Energy losses due to the length of the rods are accounted for as per Table 4.3, cf. ref. [14].

Table 4.3 SPT N correction factor in sands due to rod length

Rod length below the anvil [m]	Correction factor, C_{Rod}
10	1.0
6 – 10	0.95
4 – 6	0.85
3 – 4	0.75

- Overburden correction for normally consolidated sand using Equation 4-1, cf. ref. [14].

$$C_N = \sqrt{\frac{98}{\sigma_v'}}$$

Equation 4-1

- The resulting normalized blowcount is thus obtained as

$$N_{1,60} = E_r/60 * C_{Coars} * C_{Rod} * C_N * N$$

Equation 4-2

Table 4.4 Correlation of adjusted SPT N value, $N_{1,60}$ and relative density index, I_d, cf. ref. [14]

	Very loose	Loose	Medium Dense	Dense	Very dense
$N_{1,60}$	0 - 3	3 - 8	8 - 25	25 - 42	42 - 58
I_D (%)	0 - 15	15 - 35	35 - 65	65 - 85	85 - 100

Hereafter, in fine sand and silt, it is possible to correct $N_{1,60}$ for the dilatancy in saturated conditions (water table correction) according to Equation 4-3, cf. ref. [8].

$$N_{1,60}{}^{corr} = 15 + \frac{1}{2}(N_{1,60} - 15)$$

Equation 4-3

4.3 Soil strength parameters

4.3.1 Undrained shear strength

Undrained shear strength of the cohesive soils found across the project is measured primarily by field vane in intact and remoulded soils, and with a limited number of UU tests on core samples.

Based on experience, the undrained shear strength, c_u, for Danish Glacial clay till and meltwater clay is assessed from vane shear strength measurements, as

$$c_u = \mu \cdot c_{fv}$$

Equation 4-4

where $\mu \approx 1$. The relation is typically valid for c_{fv} < 400 -500 kPa; for harder tills, cementation, fracturing etc. may govern the undrained shear strength determined in laboratory tests.

A few index triaxial UU tests have been carried out on pre-Quaternary cohesive soils encountered on this project, with results of limited applicability. Relations between undrained shear strength and vane shear strength for the pre-Quaternary cohesive soils have not yet been established. Generally, only measured vane shear strengths are available/applicable in these deposits for the evaluation of undrained shear strength. For the current purpose, it is assumed that the equation Equation 4-4 is applicable with the $\mu \approx 1$.

4.3.2 Drained (effective) shear strength, angle of friction

The shear strength in drained conditions is defined by cohesion intercept in terms of effective stress (hereafter: effective cohesion), c', and angle of shear resistance in terms of effective stress (hereafter: friction angle), ϕ'.

In frictional deposits where SPTs have been carried out, the estimated friction angles are based on these measurements using the correlations suggested by DS/EN 1997-2 + AC:2011, ref. [8], presented in Table 4.5.

Table 4.5 Correlation between the density index and the effective angle of shearing resistance (friction angle), cf. ref. [8]

Table F.3 — Correlation between the density index (Id) and the effective angle of shearing resistance of silica sands, (φ'), in degrees

Density index I_D	Fine		Medium		Coarse	
%	Uniform	Well-graded	Uniform	Well-graded	Uniform	Well-graded
40	34	36	36	38	38	41
60	36	38	38	41	41	43
80	39	41	41	43	43	44
100	42	43	43	44	44	46

NOTE This example was published by the US Army Corps of Engineers (1993). For additional information and examples, see X.3.3. 3.

The correlation presented in Table 4.5 is derived for an effective cohesion of 0, cf. ref. [16].

4.4 Soil stiffness parameters

The oedometer moduli for Quaternary depostis are based on Danish experience.

In the absence of direct measurements, the former Danish standard, DS 415, ref.[4], proposes the evaluation of oedometric modulus for intact inorganic clay layers as:

$$E_{oed} = 4000 / w \times c_{fv}$$

Equation 4-5

The Equation 4-5 estimates too high values in hard clays. General range is thereby considered applicable for a typical water content of Danish clay till in a range of 15-20 %, i.e. ratio c_{fv} [kPa] / w [%] < 10.

As a first estimate of the oedometric stiffness of the highly overconsolidated pre-Quaternary clays, it may be assumed that it correlates to the field vane strength, c_{fv}, with a factor of about 100.

In the overconsolidated pre-Quaternary sands, elastic modulus is assumed to be of the order of 1 x $N_{1,60}$ in [MPa].

In general, Poisson's ratio in drained conditions is assumed to be of the order of ~0.25 – 0.33 in frictional deposits, ~0.3 – 0.4 in cohesive deposits and 0.15 – 0.25 in rocks.

4.5 Classification of rock

4.5.1 Core descriptions

The core descriptions of the rocks include registration of degree of fracturing and induration together with core loss/total core recovery (TCR) and RQD. Here, TCR is defined as the total length of the core pieces in the core. TCR and RQD are presented in borehole profiles in Reports 1 - 13.

RQD describes the fracture density of the core, and is calculated as a ratio (in percent) between total length of core pieces which are longer than 100 mm, and length of core run.

In addition to the geological core descriptions, OTV and HiRAT logs are used in particular for the observations of fracturing.

4.5.2 Induration

The degree of induration of the rock is recorded on a scale of H1 to H5, in accordance with DGF-Bulletin 1, ref. [5].

The degrees of induration can be correlated to ISRM Rock Grade, see ref. [15], and DS-EN-ISO 14689-1, ref. [12], as shown in Table 4.6.

Table 4.6 Correlation between degree of induration, ISRM rock grade and general rock strength and deformation properties. Notes: σ_{ci} - unconfined compressive strength of intact rock.

Degree of induration	ISRM rock grade	DS-EN-ISO 14689-1	σ_{ci}
[-]	[-]	[-]	[MPa]
H1	R0	not defined	0.25-1
H2	R1	Very weak	1-5
H3	R2	Weak	5-25
H4	R3+R4	Medium strong to strong	25-100
H5	R5+R6	Very strong to extremely strong	100-500

4.5.3 Degree of fracturing

The degree of fracturing of the rock is recorded on a scale from S1 to S5 based on the observed distance between the fractures. This parameter, however, depends on the observed surface; e.g., many of the fractures observed on cores are typically caused by the coring process, due to damage induced by the drilling technique. The degrees of fracturing of intact rock in Danish practice are presented against the bedding thickness defined by ISO 14689-1, ref. [12].

Table 4.7 Degree of fracturing of intact rock according to Danish practice, cf. DGF-Bulletin 1 [5]

Symbol	Term	Distance between fractures	Bedding thickness cf. DS-EN-ISO 14689-1
S1	Unfractured	No fractures observed	Thick to very thick
S2	Slightly fractured	Greater than 10 cm. No vertical fractures	Thin to medium
S3	Fractured	Between 6 and 10 cm	Thin
S4	Very fractured	Between 2 and 6 cm	Very thin
S5	Crushed, blocky	Less than 2 cm	Thinly to thickly laminated

4.5.4 Occurrence of induration and fracturing

The occurrence of induration and fracturing is shown in so called “carpet” plots. These plots are depicting the percentage of a each induration or fracturing that occurs at a same depth or level across all the available boreholes.

The occurrence diagrams per formation are presented where applicable in Appendices to this report, and they refer to the levels in m DVR90.

4.6 Rock strength

4.6.1 Unconfined compressive strength

Unconfined compressive strength, σ_c, is obtained by means UCS testing and via correlation with Leeb rebound hardness measured in Equotip hardness tests using Bambino tester. In the plots in sections 6-14, the correlated values of unconfined compressive strength are denoted UCS*.

The unconfined compressive strength is correlated to the results of the Leeb rebound hardness using the relation of Aoki & Matsukura 2008, ref. [24],

$$\sigma_c \text{ [MPa]} = 0.000008 * \text{HLD}^{2.5}$$

Equation 4-6

The results are considered to represent the response of intact rock.

4.6.2 Friction angle and cohesion

The first order estimate for the friction angle according to Madland method, ref. [26] is estimated from the ratio σ_c / σ_t of unconfined compressive strength σ_c, and tensile strength σ_t, given by Equation 4-9

$$\phi = \sin\left(\frac{\sigma_c/\sigma_t - 4}{\sigma_c/\sigma_t - 2}\right)^{-1}$$

Equation 4-7

The same model assumes cohesion given by Equation 4-8:

$$c = \sqrt{3}\sigma_t$$

Equation 4-8

However, considering the fracturing state of the rock, c in the shales of the current project should generally be considered to vanish.

In harder rocks (i.e. Hardeberga Formation), no tests are available for the above shown consideration of c via tensile strength. The angle of friction and cohesion are based on general experience.

4.7 Rock modulus

For the current assessment of intact rock modulus, E_{int}, an approximate modulus ratio, MR, is used based on guidelines from Hoek and Diedrichs 2006, ref. [25]; see Table 4.8.

Table 4.8 Guidelines for the selection of MR values for sedimentary rocks cf. Hoek and Diedrichs 2006, ref. [25]

Rock type	Class	Group	Texture			
			Coarse	Medium	Fine	Very fine
Sedimentary	Clastic		Conglomerates 300–400 Breccias 230–350	Sandstones 200–350	Siltstones 350–400 Greywackes 350	Claystones 200–300 Shales 150–250[a] Marls 150–200
	Non-clastic	Carbonates	Crystalline limestones 400–600	Sparitic limestones 600–800	Micritic Limestones 800–1000	Dolomites 350–500
		Evaporites		Gypsum (350)[b]	Anhydrite (350)[b]	
		Organic				Chalk 1000 +

Hereafter, the intact rock modulus is obtained per Equation 4-9

$$E_{int} = MR\ \sigma_{ci}$$

Equation 4-9

4.8 Permeability

Permeability of frictional deposits is estimated considering the Hazen’s relation (Equation 4-10):

$$k = 0.01\ D_{10}^2$$

Equation 4-10

where k is in m/s, for D_{10} in mm. This equation is derived for clean silica sands, and the results are used cautiously where deemed applicable. Due to the general lack of measurements, most of the permeability estimates are based on Danish experience and engineering judgement.

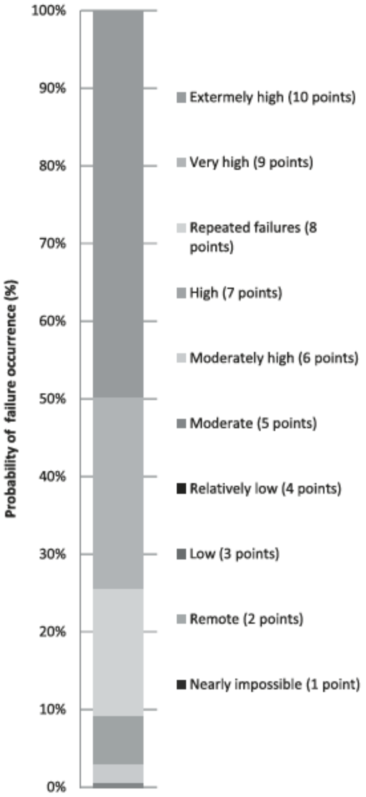
Permeability of cohesive deposits is based on Danish experience and engineering judgement due to the general lack of measurements.

Permeability of rock mass in situ is dominated by the fracture pattern within a wide area, especially in the fault zones, and cannot be evaluated based on the current data. The rock matrix permeability estimates are based on general experience and engineering judgement due to the general lack of measurements.

5 Risk Analysis

5.1 General concept of Risk Analysis

The risks presented in the Risk Analysis attachments of Reports 1-9, 12 and 13 are evaluated and presented in respect to the Failure mode and Effect Analysis (FMEA) for HDD projects, cf. Krechowicz et al. 2022, ref. [31]. The method is based on the probability of occurrence, severity of the risk, and the detection scales, see Figure 5-1.



FMEA scale for severity and detection in HDD projects

Severity scale	Severity rank	Detection scale	Detection rank
Hazardous	10	Absolute uncertainty	10
Serious	9	Very remote	9
Extreme	8	Remote	8
Major	7	Very low	7
Significant	6	Low	6
Moderate	5	Moderate	5
Low	4	Moderately high	4
Minor	3	High	3
Very mintor	2	Very high	2
None	1	Almost certain	1

Figure 5-1 FMEA scales for HDD projects, cf. Krechowicz et al. 2022, ref. [31].

Herein, detection rank 1 means that the risk is detected with the current investigation, and detection rank 10 means that the risk is not possible to detect with the current investigation programme.

Based on the risk analyses presented in Reports 1-9, 12 and 13, and the risk reviews presented in sections 6.4 – 14.4, the risks applicable across the whole project are presented in the Enclosure 15.A02 in the form of Risk Matrix. Herein, the risks are rated with five levels of consequence and likelihood. See further explanation of the Risk Matrix in pages 3 and 4 of the Enclosure 15.A02.

5.2 Overview of geotechnical risks

The following issues during construction were evaluated in the Risk Analysis attachments to the HDD Reports 1-9, 12 and 13.

- Conditions on the entrance pit, based on the observations during the in situ investigations, geophysical borehole logging, collected geotechnical data and geological model

- Vertical positioning of the alignment, based on the geological model, available geotechnical data and experience
- Mapped landslides, cf. Svennevig et al. 2020, ref. [35]
- Presence and position of potentially instable layers, based on geophysical borehole logging, collected geotechnical data and geological model
- Mixed face conditions – potentially risky interfaces and blow-out risks, based on geophysical borehole logging, collected geotechnical data and geological model
- Slaking and soil expansion potential, based on Atterberg limits, cf. Netterberg 2019, ref. [32][31]
- Risk of soils sticky behaviour, based on Atterberg limits, cf. Marinos et al. 2008, ref. [27]
- Risk of soil clogging behavior, based on Atterberg limits, cf. Marinos et al. 2008, ref. [27]
- Presence of boulders and other hard inclusions, based on geophysical borehole logging, collected geotechnical data and geological model, and experience with Danish tills cf. ref. [29]
- Hydrogeology and loss of drilling fluid, based on geophysical borehole logging, collected geotechnical data and geological model, and Blue spot area maps from Styrelsen for Datastyning og Infrastruktur, ref. [34].

In the Risk Analysis attachments to the Reports 1-9, 12 and 13, these risks are analysed per location. Sections 6.4 – 14.4 present the risks sorted per formation.

6 Recent, Fill and Lateglacial Quaternary deposits

6.1 Available information

Recent, Fill and Lateglacial deposits are encountered in presently carried out geotechnical boreholes summarized in Table 6.1 and Figure 6.1.

Table 6.1 Overview of encountered Recent, Fill and Lateglacial deposits encountered in geotechnical boreholes carried out in relation to Energy Island Bornholm

Appendix no.	Deposits / Formation	Description	Report no.	Boreholes
A15.1	**Recent, fill and Lateglacial deposits**			
	o, s, g, m	Fill; sand, gravel, sand mull	5	1-5-1, 1-5-2
	o, l, m	Fill; clay, clay mull	6, 7	1-6-2, 1-7-1
	l	Clay	4, 11	1-4-2, 3-1 to 3-5
	s	Sand	4, 5	1-4-3, 1-4-5, 1-5-2
	g	Gravel	6	1-6-2
	m	Clay mull	3, 7, 8, 9, 11, 12	1-3-2, 1-7-2, 2-1-2, 2-5-1, 3-6, 1-12-2
	m	Sand mull	1, 2, 4, 6, 8, 9, 12	1-1-2, 1-1-3, 1-2-2, 1-4-1 to 1-4-4, 1-4-6, 1-6-1, 2-1-1, 2-5-2, 1-12-1
	l	Lateglacial clay	1	1-1-3
	s	Lateglacial sand	1, 2	1-1-2, 1-1-3, 1-2-2,

Figure 6.1 Location of boreholes with Recent, Fill and Lateglacial deposits; the boreholes are marked with blue dots

Layers of fill, mull, clay, sand and gravel are present in all boreholes in various combinations and thicknesses, whereas Lateglacial deposits of meltwater sand and clay are only present in the boreholes at HDD1 and to some extent at HDD2, i.e. in the western part of the area. Generally, the layers of mull and recent deposits are 0.3 to 0.4 m thick, but locally the thickness is up to 1 m. In areas with fill, the fill layers are 1 to 2.3 m thick.

At HDD1, in boreholes 1-1-2 and 1-1-3 there is Lateglacial meltwater sand with thin layers of Lateglacial meltwater clay in borehole 1-1-3. The Lategalcial deposits are 2.0 m to 2.5 m thick. At HDD2 there is a 0.3 m thick layer of Lateglacial sand in borehole 1-2-1 whereas the deposit is not present in borehole 1-2-3.

6.2 Measured data

The measured data is summarized in Table 6.2, and presented in Appendix A15.1. The extent of the encountered deposits vary from very local to widespread. Typically, more than one type of deposits of this age is encountered within one HDD entry area. Therefore, herein the widest ranges of parameters are presented for all of the deposit types of this age as for one geotechnical unit.

Table 6.2 Overview of measured data for Recent, Fill and Late-glacial deposits encountered in geotechnical boreholes carried out in relation to Energy Island Bornholm

Measured	**Appendix A15.1 section**	**Comment**	**Min**	**Max**
Water content [%]	1.1	All deposits	2.9	30
Grain size distribution; D10 [mm]	1.2	All deposits	-	0.135
Atterberg limits /Plasticity index [%]	1.3	Lateglacial clay	12.1	
Field vane shear strength [kPa]	2.1	Fill / Recent clay	60	170
		Lateglacial clay	120	170

6.3 Ranges of geotechnical and hydrogeological parameters

These deposits are generally not investigated for strength and stiffness as they are considered to be non-bearing strata. The supposed ranges of applicable parameters are presented in Table 6.3

Table 6.3 Ranges of geotechnical parameters in Recent, Fill and Lateglacial Quaternary deposits.

Soil description	γ		γ'		ϕ'		c'		c_u		k		Eoed	
	kN/m³		kN/m³		°		kPa		kPa		m/s		MPa	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Recent, Fill & Lateglacial deposits	16	20	6	10	15	36	0	0	10	200	1e-3	1e-9	n/a	n/a

6.4 Risks review and commentary

Regarding the shallow top deposits, in the Risk Analysis Attachments to Reports 1-9, 12 and 13, the risks evaluated in reference to Krechowicz et al. 2022 include:

F25 Unexpected natural obstacles

The probability of the occurrence of unexpected natural obstacles is relatively high across the area. The risks concern primarily site approach, hence conditions on the drilling pit (entrance pit), including eventual water clogging in the rain events. These shallow deposits across the site include variable man-made (fill) and natural frictional and cohesive deposits. The extent of the encountered types varies across the site; the deposits encountered in particular boreholes may be of a local occurrence or extent across wider areas. It is therefore of importance to do geotechnical site recognition for the chosen site. See Establishing drilling pits in Enclosure 15.A02.

7 Quaternary Glacial deposits

7.1 Available information

Glacial deposits are encountered in presently carried out geotechnical boreholes summarized in Table 7.1 and depicted in Figure 7.1.

Table 7.1 Overview of Glacial deposits encountered in geotechnical boreholes carried out in relation to Energy Island Bornholm

Appendix no.	Deposits / Formation	Description	Report no.	Boreholes
A15.2	**Quaternary Glacial deposits**			
	ml	Clay till	2, 3, 4, 5, 6, 7, 8, 9, 11, 12	1-2-2, 1-2-3, 1-3-2, 1-4-1 to, 1-4-6, 1-5-2, 1-6-1, 1-7-1, 1-7-2, 2-1-2, 2-5-1, 2-5-2, 3-1 to 3-6, 1-12-1, 1-12-2,
	ms	Sand till	4, 5, 11, 12	1-4-1, 1-4-2, 1-4-4, 1-4-5, 1-5-2, 3-4, 3-5, 1-12-1, 1-12-2
	mg	Gravel till	3, 6, 8, 9, 12	1-3-2, 1-6-1, 2-1-2, 2-5-1, 1-12-2
	dl	Glacial meltwater clay	3, 4, 9, 11, 12	1-3-2, 1-4-2, 2-5-1, 3-4, 3-5, 1-12-1
	di	Glacial meltwater silt	9, 11, 12	2-5-1, 3-5, 1-12-1
	ds	Glacial meltwater sand	4, 5, 9, 11, 12	1-4-1, 1-4-2, 1-4-4, 1-4-5, 1-4-6, 1-5-2, 2-5-2, 3-4, 3-6, 1-12-1, 1-12-2
	g	Glacial gravel	4, 6, 8	1-4-6, 1-6-1, 2-1-1, 2-1-2
		Cobbles / boulders	3, 4, 6	1-3-2, 1-4-5, 1-4-6, 1-6-1

Figure 7.1 Location of boreholes with Quaternary Glacial deposits; the boreholes are marked with blue dots

The Quaternary deposits were deposited and reworked by at least two large glacial advances leaving an upper and lower clay till with interbedded meltwater deposits, sandy till and gravelly till. After deposition of the lower clay till followed a phase of a stagnant/melting ice cover and deposition of meltwater sediments in meltwater

channels and lakes. When the upper clay till was deposited, the previously deposited meltwater sediments were to some extent deformed or reworked into sandy or gravelly till by the overriding glacier.
The first glacial advances across the area have – in some places more than other – also reworked the pre-Quaternary deposits, mixing them into the tills.

Clay till is present in almost all of the boreholes. The presence of other tills and meltwater deposits varies irregularly throughout the area and in some boreholes, it is difficult to distinguish between the different types of deposits. The thickness of the Quaternary deposits varies from approx. 1 m to more than 13 m.

Glacial deposits contain cobbles and boulders. Sandstone was encountered in boreholes 1-3-2 and 1-6-1, a granite boulder of ~50 cm is encountered in borehole 1-4-5, while quartzite/quartzitic stones (some possibly of Hardeberga Formation origin) were found in boreholes 1-4-5, 1-4-6 and 1-6-1. The granite and sandstone from borehole 1-3-2 were cored, while the other cobbles/boulders were milled through.

7.2 Measured data

The measured data is summarized in Table 7.2 and presented in Appendix A15.2.

Table 7.2 Overview of measured data for Glacial deposits encountered in geotechnical boreholes carried out in relation to Energy Island Bornholm

Measured	Appendix A15.2 section	Comment	Min	Max
Water content [%]	1.1	Clay till	4.6	27.0
		Gravel till	10.0	17.5
		Meltwater clay	16.0	19.5
		Meltwater silt	13.5	27.0
		Meltwater sand	4.6	22.0
Grain size distribution; D10 [mm]	1.2	Clay till	-	0.002
		Gravel till	0.007	0.063
		Meltwater clay	-	-
		Meltwater sand	-	0.109
Atterberg limits /Plasticity index [%]	1.3	Clay till	11.7	28.0
		Meltwater clay	10.7	11.6
Organic matter [%]	1.4	Meltwater clay	1.8	
Thermal conductivity [W/(mK)]	1.5	Clay till	1.85	2.18
Field vane shear strength [kPa]	2.1	Clay till	36*	>700
SPT, N1,60 [-]	2.2	In frictional deposits	11	65
Equotip hardness / σ_c [MPa]	2.3	Granite boulder in clay till	170	

* Low values may occur due to laminae of silt and sand

7.3 Ranges of geotechnical and hydrogeological parameters

The ranges of applicable parameters are presented in Table 7.3.

Table 7.3 Ranges of geotechnical parameters in Glacial deposits.

Soil description	γ		γ'		ϕ'		c'		c_u		k		Eoed	
	kN/m^3		kN/m^3		°		kPa		kPa		m/s		MPa	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Clay till	20	23	10	13	n/a	n/a	n/a	n/a	50	>700	1e-11	1e-8	10	>100
Sand/Gravel till	20	23	10	13	38	>40	0	0	n/a	n/a	1e-7	1e-4	25	>100
Meltwater silt and clay	20	22	10	12	n/a	n/a	n/a	n/a	50	>350	1e-11	1e-7	10	>50
Meltwater sand	19	22	9	13	35	>40	0	0	n/a	n/a	1e-7	1e-3	25	>100

7.4 Risks review and commentary

Regarding the Glacial deposits, in the Risk Analysis Attachments to Reports 1-9, 12 and 13, the risks evaluated in reference to Krechowicz et al. 2022 include:

F25 *Unexpected natural obstacles*
F27 *Borehole collapse and/or blowout*
F29 *Drilling fluid runoff (insufficient fluid pressure)*

Glacial deposits across the site include till and meltwater deposits of variable gradation and plasticity. The extent of the encountered types varies across the site; the deposits encountered in particular boreholes may be of a local occurrence or extent across wider areas. It is therefore of importance to do geotechnical site recognition for the chosen site. See Establishing drilling pits in Enclosure 15.A02.

Presence of boulders and other inclusions is confirmed during the investigation. The strength of the cored granitic boulder is tested (see Table 7.2), while the sandstones encountered at other locations were milled through.

Aside from encountering a large stone, borehole collapse and/or blowout may be affected by

- Sticky and clogging behaviour, (risk not high, see Appendix A15.2, section 1.3)
- Slaking and soil expansion, (risk not high, see Appendix A15.2, section 1.3)

Finally mixed face conditions between the various Glacial layers, as well as towards the other units, and local hydrogeological conditions may lead to both collapse and fluid runoff, and require specific site based assessment. See Risk Analysis Attachments to Reports 1-9, 12 and 13.

8 Cretaceous deposits of Arnager Greensand Formation

8.1 Available information

Cretaceous deposits of Arnager Greensand Formation are encountered in presently carried out geotechnical boreholes depicted in Figure 8.1 and summarized in Table 8.1.

Table 8.1 Overview of Arnager Greensand Formation deposits encountered in geotechnical boreholes carried out in relation to Energy Island Bornholm

Appendix no.	Deposits / Formation	Description	Report no.	Boreholes
A15.3	**Cretaceous deposits of Arnager Greensand Formation**			
	al, as, s	Glauconitic clay and sand	9	2-5-1 and 2-5-2

Figure 8.1 Location of boreholes with Cretaceous Arnager Greensand Formation; the boreholes are marked with blue dots

Arnager Greensand Formation represents the youngest Mesozoic sediments in the investigation area. The base of the Arnager Greensand deposits is represented by an erosional boundary to the Robbedale and Jydegaard Formations. A conglomerate consisting of cemented glauconitic sand represents the lower part of the formation and is superseded by grey-green, glauconitic, bioturbated sand deposits.

Cretaceous clay and sand of Arnager Greensand Formation are found from 7.2 mbgl in borehole 2-5-1, and 5.8 mbgl in borehole 2-5-2 and to the bottom of both boreholes,. The clay is dark greenish grey, medium plasticity to very sandy and glauconitic. The sand is dark greyish olive, fine, well graded and slightly clayey to very clayey and glauconitic.

8.2 Measured data

The measured data is summarized in Table 8.2 and presented in Appendix A15.3.

Table 8.2 Overview of measured data for Cretaceous deposits encountered in geotechnical boreholes carried out in relation to Energy Island Bornholm

Measured	**Appendix A15.3 section**	**Comment**	**Min**	**Max**
Water content [%]	1.1	Sand	24.8	28.6
		Clay	21.0	32.0
Grain size distribution; D10 [mm]	1.4	Sand, 1 test	0.004	
Atterberg limits /Plasticity index [%]	1.5	Clay	16.5	27.7
Thermal conductivity [W/(mK)]	1.6	Sand, 1 test	1.82	
		Clay, 1 test	1.65	
Bulk density [g/cm^3]	1.3	Sand	1.92	1.95
Dry density [g/cm^3]	1.3	Sand	1.55	1.62
Particle density [g/cm^3]	1.2	Sand, 1 test	2.66	
		Clay, 1 test	2.68	
Field vane shear strength [kPa]	2.1		450	>700

8.3 Ranges of geotechnical and hydrogeological parameters

Table 8.3 Ranges of geotechnical parameters in Cretaceous deposits of Arnager Greensand Formation.

Soil description	γ		γ'		ϕ'		c'		c_u		k		Eoed	
	kN/m^3		kN/m^3		°		kPa		kPa		m/s		MPa	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Clay	19	20	9	10	n/a	n/a	n/a	n/a	450	>700	1e-11	1e-9	30	70
Sand	19	20	9	10	38	>40	0	0	n/a	n/a	1e-9	1e-5	50	>100

8.4 Risks review and commentary

Regarding the Cretaceous deposits, in the Risk Analysis Attachments to Reports 1-9, 12 and 13, the risks evaluated in reference to Krechowicz et al. 2022 include:

F27 *Borehole collapse and/or blowout*
F28 *Blocking of the drilling pipe because of the swelling of the clay*
F29 *Drilling fluid runoff (insufficient fluid pressure)*

Cretaceous deposits are encountered only on HDD9 location, under the deposits on the stream bed of Læså stream.

Borehole collapse and/or blowout may be affected by

- Sticky and clogging behaviour, (up to high, see Appendix A15.3, section 1.5)
- Slaking and soil expansion, (medium, see Appendix A15.3, section 1.5)

Finally, mixed face conditions, depending on vertical placement of HDD, and local hydrogeological conditions may lead to both collapse and fluid runoff, and require specific site based assessment. See Risk Analysis Attachment to Report 9, and Enclosure 15.A02.

9 Jurassic deposits of Rønne Formation

9.1 Available information

Jurassic deposits of Rønne Formation are encountered in presently carried out geotechnical boreholes depicted in Figure 9.1 and summarized in Table 9.1

Table 9.1 Overview of Rønne Formation deposits encountered in geotechnical boreholes carried out in relation to Energy Island Bornholm

Appendix no.	Deposits / Formation	Description	Report no.	Boreholes
A15.4	**Jurassic Rønne Formation**			
	l, s	Clay, sand	1	1-1-2 and 1-1-3
	l, s	Clay, sand	2	1-2-2
	l, s	Clay, sand	12	1-12-1 and 1-12-2

Figure 9.1 Location of boreholes with Jurassic deposits of Rønne Formation; the boreholes are marked with blue dots

The Rønne Formation deposits consist of sand and clay, with few, thin layers of silt. Generally, the clay is of medium to high plasticity but in the lower part of the deposit in borehole 1-2-2, from approx. 23 mbgl, it is described as clay of very high plasticity. The sand is generally described as *fine to medium, sorted to well sorted*, in the upper part of the boreholes, and *medium, sorted*, or *fine to medium, well sorted*, in the lower parts – with room for variations.

In one borehole, 1-12-2, between 8 and 10 mbgl, sandstone which could be drilled through by shell and auger has been found. In the same borehole, sandstone with a thickness of 30 - 35 cm has been encountered at two levels (17 and 20 mbgl, respectively). The sandstone is described to contain iron cement, possibly siderite. It has not been encountered in other boreholes, hence the extent of the layer is unknown.

9.2 Measured data

The measured data is summarized in Table 9.2 and presented in Appendix A15.4.

Table 9.2 Overview of measured data for Jurassic deposits of Rønne Formation encountered in geotechnical boreholes carried out in relation to Energy Island Bornholm

Measured	**Appendix A15.4 section**	**Comment**	**Min**	**Max**
Water content [%]	1.1	Clay	11.5	38
		Sand	2.2	30.0
		Sandstone	2.2	3.5
Particle density [g/cm^3]	1.2	Clay	2.63	2.65
		Sand	2.65	2.66
		Sandstone	3.09	3.51
Unit weight [kN/m^3]	1.3	Sandstone	28.2	32.3
Grain size distribution; D10 [mm]	1.4	Sand	0.003	0.093
Atterberg limits /Plasticity index [%]	1.5	Clay	8.2	38.2
Organic matter [%] *	1.6	Sand	0.91	19.14
		Clay	6.81	8.51
Thermal conductivity [W/(mK)]	1.7	Sand	1.11	2.52
		Silt	1.70	
		Clay	1.59	2.42
Field vane shear strength [kPa]	2.1	Clay	223-589 (increasing trend)	>701
SPT, N1,60 [-]	2.2	Sand	17	67
UU/UUrem** [kPa/kPa]	2.1	Clay	33/38	84/125
Equotip hardness / σ_c [MPa]	2.3	Sandstone	30	79

*Measured only on the samples where presence of organic matter was indicated

**Not used for strength evaluation. See Appendix 15.4

9.3 Ranges of geotechnical and hydrogeological parameters

Table 9.3 Ranges of geotechnical parameters in Jurassic deposits of Rønne Formation.

Soil description	γ		γ'		ϕ'		c'		c_u		k		Eoed	
	kN/m^3		kN/m^3		°		kPa		kPa		m/s		MPa	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Clay	19	21	9	11	n/a	n/a	n/a	n/a	200-600	>700	1e-11	1e-9	20	>70
Sand	18	20	8	10	38	>40	0	0	n/a	n/a	1e-7	1e-4	50	>100

9.4 Risks review and commentary

Regarding the Jurassic deposits of Rønne Formation, in the Risk Analysis Attachments to Reports 1, 2 and 12, the risks evaluated in reference to Krechowicz et al. 2022 include:

F25 *Unexpected natural obstacles*
F27 *Borehole collapse and/or blowout*
F28 *Blocking of the drilling pipe because of the swelling of the clay*
F29 *Drilling fluid runoff (insufficient fluid pressure)*

Jurassic deposits of Rønne Formation are encountered in the western part of the investigation area, directly under the shallow, recent deposits, or under the Glacial deposits. The very heavy sandstone with iron cement (possibly siderite) encountered on the location HDD12 was not expected. It is not encountered in other locations, and the horizontal propagation of it is unknown, though presumed limited. The expected parameters of the encountered sandstone, based on the available measurements, are presented in Table 9.4, for general information.

Table 9.4 Ranges of geotechnical parameters in Jurassic sandstone of Rønne Formation.

Rock description	γ		γ'		ϕ'		c'		σ_c		k		Eint	
	kN/m^3		kN/m^3		°		kPa		MPa		m/s		GPa	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Sandstone	28	30			>40				30	79	1e-11	1e-9	8	>30

Borehole collapse and/or blowout may be affected by

- Sticky and clogging behaviour, (up to high, see Appendix A15.4, section 1.3)
- Slaking and soil expansion, (medium level, see Appendix A15.4, section 1.3)

Finally, mixed face conditions between sand and clay layers, and in particular when encountering sandstone, including the local hydrogeological conditions may lead to both collapse and fluid runoff, and require specific site based assessment. See Risk Analysis Attachments to Reports 1, 2 and 12, and Enclosure 15.A02.

10 Triassic Deposits of Kågerød Formation

10.1 Available information

Triassic deposits of Kågerød Formation are encountered in presently carried out geotechnical boreholes depicted in Figure 10.1 and summarized in Table 10.1.

Table 10.1 Overview of Kågerød Formation deposits encountered in geotechnical boreholes carried out in relation to Energy Island Bornholm

Appendix no.	Deposits / Formation	Description	Report no.	Boreholes
A15.5	**Triassic Kågerød Formation**			
	l	Plastic clay	2	1-2-2 and 1-2-3
	l, s	Plastic clay, sand	3	1-3-2
	l, (s)	Plastic clay, (sand)	4	1-4-1 to 1-4-6

Figure 10.1 Location of boreholes with Triassic deposits of Kågerød Formation; the boreholes are marked with blue dots

The Triassic deposits of Kågerød Formation primarily consist of clay of variable plasticity, from very sandy to medium plasticity to very high plasticity clay. The upper part of the clay is generally of very high to high plasticity. The plasticity decreases with depth as the deposits become more sandy towards the bottom of the boreholes.

At HDD2 location, west of the Læså graben, the clay is generally of high to very high plasticity and the sand content is very limited. East of the Læså graben, at HHD3, the clay plasticity is medium to high and a 5 m thick layer of sand is interbedded in the clay. At HDD4, there are layers of alternating sand and clay, with a tendency of the deposit becoming more sandy towards the bottom to the boreholes.

10.2 Measured data

The measured data is summarized in Table 10.2 and presented in Appendix A15.5.

Table 10.2 Overview of measured data for Triassic deposits of Kågerød Formation encountered in geotechnical boreholes carried out in relation to Energy Island Bornholm

Measured	**Appendix A15.5 section**	**Comment**	**Min**	**Max**
Water content [%]	1.1	Clay	13.5	48.1
		Sand	16.0	30.0
Particle density [g/cm^3]	1.2	Clay	2.68	2.70
Unit weight [kN/m^3]	1.3	Clay	2.9	3.30
Grain size distribution; D10 [mm]	1.4	Sand	0.131	
Atterberg limits /Plasticity index [%]	1.5	Clay	17.7	66.6
Thermal conductivity [W/(mK)]	1.7	Sand	2.43	
		Clay	1.18	2.65
Field vane shear strength [kPa]	2.1	Clay	140 - 701 (increasing trend)	>701
SPT, N1,60 [-]	2.2	Sand	17	67
UU [kPa]**	2.1	Clay	57	283

**Cautiously considered for LB determination in Table 10.3

10.3 Ranges of geotechnical and hydrogeological parameters

Table 10.3 Ranges of geotechnical parameters in Triassic deposits of Kågerød Formation.

Soil description	γ		γ'		ϕ'		c'		c_u		k		Eoed	
	kN/m^3		kN/m^3		°		kPa		kPa		m/s		MPa	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Clay	18	22	8	12	n/a	n/a	n/a	n/a	200	>700	1e-11	1e-9	15	>70
Sand	19	22	9	12	38	>40	0	0	n/a	n/a	1e-9	1e-4	30	>50

10.4 Risks review and commentary

Regarding the Triasic deposits of Kågerød Formation, in the Risk Analysis Attachments to Reports 2, 3 and 4, the risks evaluated in reference to Krechowicz et al. 2022 include:

F27 *Borehole collapse and/or blowout*
F28 *Blocking of the drilling pipe because of the swelling of the clay*
F29 *Drilling fluid runoff (insufficient fluid pressure)*

Triassic deposits are encountered both east and west of the Læså graben, and the vane results indicate a certain difference in plasticity and strength between the tested soil profiles. Therefore, the severity of risks may vary between locations. In general, borehole collapse and/or blowout may be affected by

- Sticky and clogging behaviour, (generally high, see Appendix A15.5, section 1.5)
- Slaking and soil expansion, (generally high, see Appendix A15.5, section 1.5)

Local hydrogeological conditions may lead to both collapse and insufficient pressures, in relation also to the proximity of the fault zone. At some of the tested locations where Kågerød Formation is found artesian pressures are recorded, hence evaluation requires specific site based assessment. See Risk Analysis Attachments to Reports 2, 3 and 4, and Enclosure 15.A02.

11 Silurian Cyrtograptus and Rastrites Shale

11.1 Available information

Silurian Cyrtograptus and Rastrites Shale is encountered in presently carried out geotechnical borehole depicted in Figure 11.1 and summarized in Table 11.1.

Table 11.1 Overview of Silurian Cyrtograptus and Rastrites shale encountered in geotechnical boreholes carried out in relation to Energy Island Bornholm

Appendix no.	Deposits / Formation	Description	Report no.	Boreholes
A15.6	**Silurian Cyrtograptus and Rastrites shale**			**Boreholes**
	sr, sj	Shale	5	1-5-2

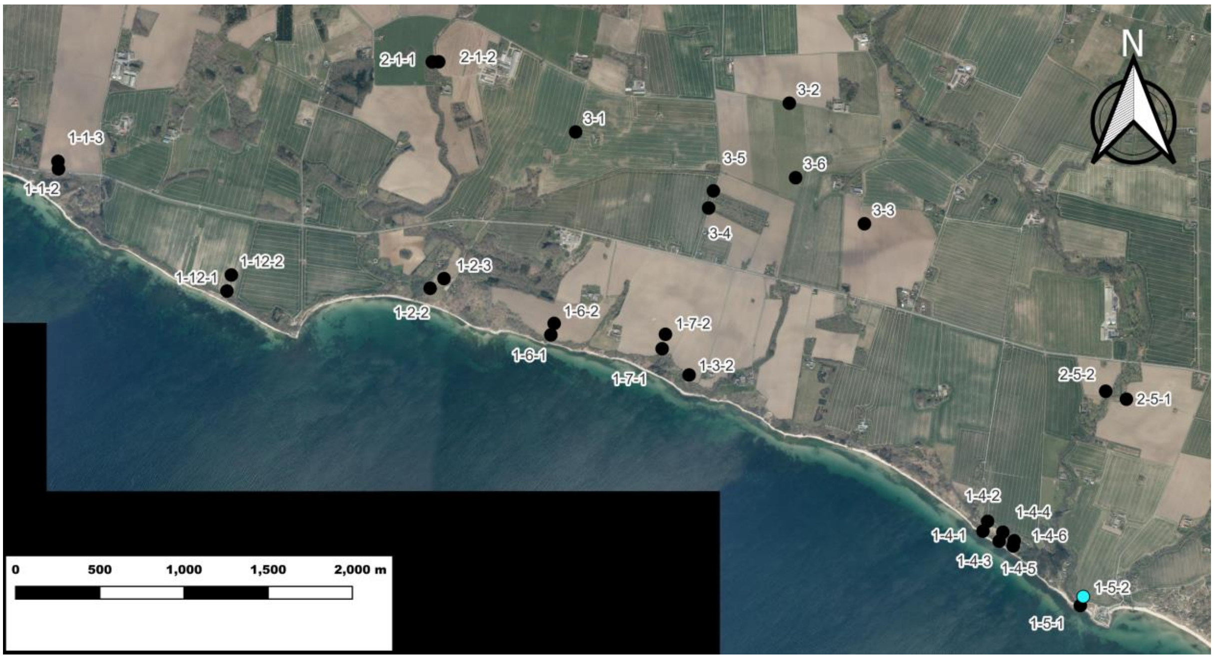


Figure 11.1 Location of boreholes with Silurian Cyrtograptus and Rastrites shale; the boreholes are marked with blue dots

The Silurian Cyrtograptus and Rastrites Shale consist of dark, thinly laminated shale found from 4.76 mbgl in borehole 1-5-2 to the bottom of the borehole at 35.4 mbgl. The upper 0.5 m of the shale is slightly hardened and highly fractured. With depth, several vertical fractures, some calcite filled, are recorded in the cores. The shale alternates between calcareous and non-calcareous, and contains thin inclined silt and calcite laminae along the entire cored length.

11.2 Measured data

The measured data is summarized in Table 11.2.

Table 11.2 Overview of measured data for Silurian Cyrtograptus and Rastrites Shale encountered in geotechnical boreholes carried out in relation to Energy Island Bornholm

Measured	**Appendix A15.6 section**	**Comment**	**Min**	**Max**
Water content [%]	1.1	Whole deposit	3.1	8.7
		Below 10 mbgl	3.1	4.1
Particle density [g/cm^3]	1.2		2.77	2.78
Unit weight [kN/m^3]	1.3		24.5	26.4
SPT, N/penetration [-/cm]	2.1	Above 5 mbgl	50/14.5cm	
RQD	1.4		0	10
Equotip hardness / σ_c [MPa]	2.1	Parallel to coring, Z	20.5	38.9
		Orthogonal to coring, X	9.5	35.9
		Orthogonal to coring, Y	4.5	29.1

11.3 Ranges of geotechnical and hydrogeological parameters

Table 11.3 Ranges of geotechnical parameters in Sulurian Cyrtograptus and Rastrites Shale.

Rock description	γ		γ'		ϕ'		c'		σ_c		k		Eint	
	kN/m^3		kN/m^3		°		kPa		MPa		m/s		GPa	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Shale	24	27	14	17	16	25	0	0	4.5	39	1e-11	1e-5	5	>10

11.4 Risks review and commentary

Regarding the Cyrtograptus and Rastrites shale, in the Risk Analysis Attachment to Report 5, the risks evaluated in reference to Krechowicz et al. 2022 include:

F25 *Unexpected natural obstacles*
F28 *Blocking of the drilling pipe because of the swelling of the clay*
F29 *Drilling fluid runoff (insufficient fluid pressure)*

The core retrieved from the borehole 1-5-2 is crushed, generally limiting the possibility for mechanical testing of the properties of the rock mass and matrix. The shale rock is generally considered frail and with a certain swelling potential.
The observed natural obstacles include hard inclusions in the form of anthraconite balls. Due to the fault zone, there is a potential for infilled and/or large fractures / cavities, and otherwise risky interfaces.

The dominant risk, however, lies in the loss of the drilling fluid through the fractures and cavities, as the deposit is within the fault zone. See further in the Attachment RA to Report 5, where cavities of several decimetres are depicted. See also Enclosure 15.A02.

12 Ordovician / Cambrian shale of Alum Shale Formation

12.1 Available information

Ordovician / Cambrian shales of Alum Shale Formation are encountered in presently carried out geotechnical boreholes depicted in Figure 12.1 and summarized in Table 12.1.

Table 12.1 Overview of Alum Shale Formation encountered in geotechnical boreholes carried out in relation to Energy Island Bornholm

Appendix no.	Deposits / Formation	Description	Report no.	Boreholes
A15.7	**Ordovician / Cambrian shale of Alum shale Formation**			
	ar, r	Shale	7	1-7-1 and 1-7-2.

Figure 12.1 Location of boreholes with Alum shale; the boreholes are marked with blue dots

Alum shale, black, hardened to very hardened, fissile, very organic and non-calcareous, constitutes the pre-Quaternary surface in boreholes 1-7-1 and 1-7-2, where it is found in thickness of 15 m and 7 m, respectively. Core samples of the Alum Shale generally have extremely closely to very closely spaced discontinuities, but the borehole walls appear to be stable.

In borehole 1-7-1, a 0.4 m thick layer of black clayey and sandy gravel, reported as Cambrian is found below the glacial deposits at the transition to the hardened shale. The gravel is believed to consist of Alum shale reworked by glacier activity.

According to the geological model of the investigation area presented in Report 11, Alum shale is possible to find at a shallow depth in the Station area, where it occurs under Glacial clay till and on top of Rispebjerg Sandstone Member and/or Læså Formation. It is suspected, with reservation, that the samples 5 and 6 from Station area borehole 3-3 described as clay with gravel of black shale may originate from Alum shale Formation.

12.2 Measured data

The measured data is summarized in Table 12.2.

Table 12.2 Overview of measured data for Alum Shale Formation encountered in geotechnical boreholes carried out in relation to Energy Island Bornholm

Measured	Appendix A15.6 section	Comment	Min	Max
Water content [%]	1.1	Whole deposit	2.6	23
		Rock matrix (undisturbed rock)	2.6	3.8
Particle density [g/cm^3]	1.2		2.69	
Grain size distribution, D10 [mm]	1.3	Crushed shale	-	
Organic content [%]	1.4		6.06	11.9
Unit weight [kN/m^3]	1.5		22.3	26.2
RQD	1.6		0	47
Field vane shear strength [kPa]	2.1	Crushed shale above 5.5 mbgl		>359
Brazilian indirect tensile strength σ_t [MPa]	2.2	Orthogonal to coring, Y	3.4	
UCS, σ_c [MPa]	2.3	Parallel to coring, Z	37.1	
Equotip hardness / σ_c [MPa]	2.3	Parallel to coring, Z	20.5	38.9
		Orthogonal to coring, X	9.5	35.9
		Orthogonal to coring, Y	4.5	29.1

12.3 Ranges of geotechnical and hydrogeological parameters

Table 12.3 Ranges of geotechnical parameters in Alum Shale Formation.

Rock description	γ		γ'		ϕ'		c'		σ_c		k		Eint	
	kN/m^3		kN/m^3		°		kPa		MPa		m/s		GPa	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Shale	22	27	12	17	20	25	0	0	25	58	1e-11	1e-5	>5	>10

12.4 Risks review and commentary

Regarding the Alum shale, in the Risk Analysis Attachment to Report 7, the risks evaluated in reference to Krechowicz et al. 2022 include:

F25 *Unexpected natural obstacles*
F28 *Blocking of the drilling pipe because of the swelling of the clay*
F29 *Drilling fluid runoff (insufficient fluid pressure)*

The cores retrieved from the boreholes are very fractured, generally limiting the possibility for mechanical testing of the properties of the rock mass and matrix. The shale rock is generally considered frail. Moderate to high organic content (see Table 12.2) generally increases soaking capacity of the shale, which is associated with a lower strength. Swelling potential of the shale can be related e.g. to the observed content of glauconite and unhardened materials depicted in Attachment RA to Report 7.

The dominant risk, however, lies in the loss of the drilling fluid through the fractures and cavities, as the deposit is within the fault zone, and/or insufficient fluid pressures to overcome eventual intensive local water pressures may occur in the fault zone. See Risk Analysis Attachments to Report 7, and Enclosure 15.A02.

13 Cambrian deposits of Læså Formation

13.1 Available information

Cambrian deposits of Læså Formation are encountered in presently carried out geotechnical boreholes depicted in Table 13.1 and Figure 13.1.

Table 13.1 Overview of Cambrian deposits of Læså Formation encountered in geotechnical boreholes carried out in relation to Energy Island Bornholm

Appendix no.	Deposits / Formation	Description	Report no.	Boreholes
A15.8	**Cambrian deposits of Læså Formation**			
	g, l	Gravel, Clay (weathered sandstone / claystone)	6	1-6-1 and 1-6-2
	kj	Siltstone	6	1-6-1 and 1-6-2
		Claystone	6	1-6-1 and 1-6-2
		Fine grained sandstone	6	1-6-1 and 1-6-2
		Fine grained sandstone	7	1-7-1 and 1-7-2

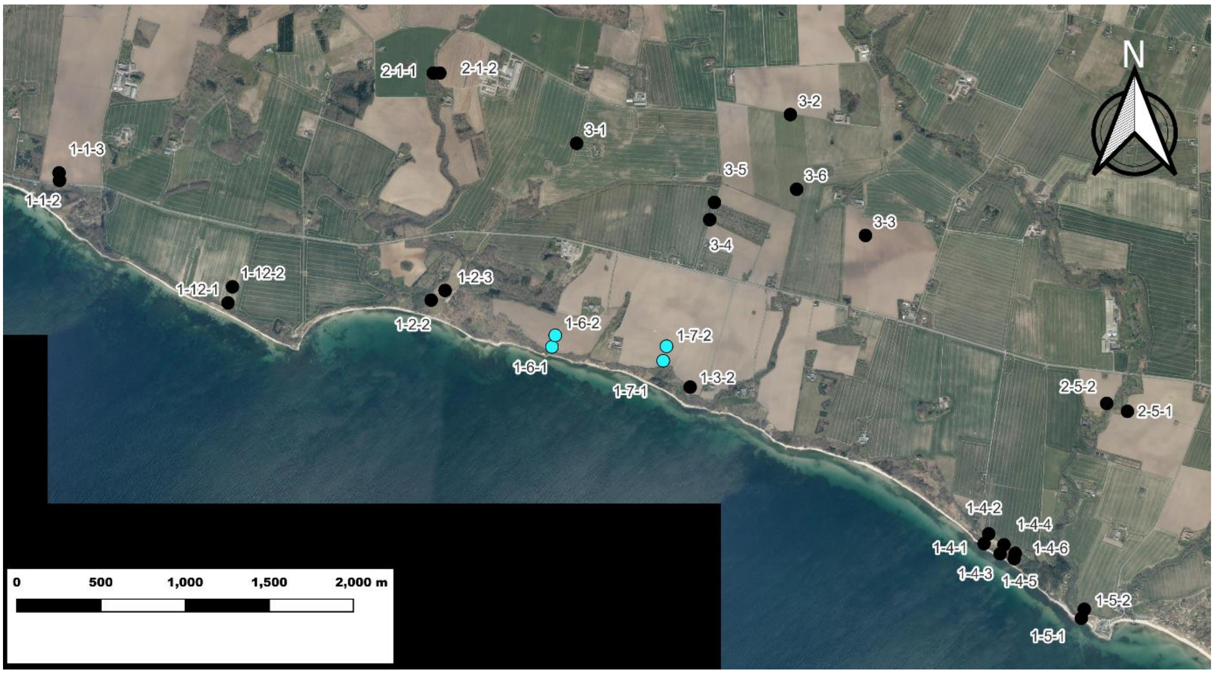


Figure 13.1 Location of boreholes with Cambrian deposits of LæsåFormation; the boreholes are marked with blue dots

Siltstone and sandstone of Cambrian age (Læså Formation) appear rather different in the boreholes 1-6-1 and 1-6-2; the rock is generally more coarser-grained in borehole 1-6-2. In borehole 1-6-1, sandy and very hardened siltstone is found. In borehole 1-6-2, fine-grained, very hardened and cemented sandstone and siltstone are found. A medium thick layer (0.6 m) described as Cambrian gravel and clay is found close to the pre-Quaternary surface in borehole 1-6-1, from 4.65-5.25 mbgl. Though the gravel is interpreted as downfall during drilling work, the clay is believed to represent an interval of highly weathered siltstone, possibly caused by dissolution from percolating meteoric water along fractures in the siltstone or leaching of clay from overlying glacial till. The sandstone and siltstone found on location HDD7 vary in colour from very light to very dark grey, with thin laminae to medium beds of claystone/siltstone of prominent colours (e.g. green, yellow and brown).

13.2 Measured data

The measured data is summarized in Table 13.2.

Table 13.2 Overview of measured data for Læså Formation encountered in geotechnical boreholes carried out in relation to Energy Island Bornholm

Measured	**Appendix A15.6 section**	**Comment**	**Min**	**Max**
Water content [%]	1.1	Sandstone	0.9	9.2
		Siltstone	0.7	10.6
		Claystone	0.6	
Particle density [g/cm³]	1.2	Sandstone	2.67	
		Siltstone	2.75	
		Claystone	2.85	
Grain size distribution, D10 [mm]	1.3	Siltstone	0.74	
Unit weight [kN/m³]	1.5	Sandstone	25.3	26.3
		Siltstone	23.8	26.4
		Claystone	26.1	
RQD	1.6	Whole formation	0	100
Equotip hardness / σ_C [MPa]	2.1	All samples	29	148

13.3 Ranges of geotechnical and hydrogeological parameters

Table 13.3 Ranges of geotechnical parameters in rocks of Læså Formation.

Rock description	γ		γ'		ϕ'		c'		σ_c		k		Eint	
	kN/m³		kN/m³		°		kPa		MPa		m/s		GPa	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Sandstone/ Siltstone/ Claystone	22	27	12	17	~35		0	0	30	150	1e-11	1e-5	>5	>10

13.4 Risk review and commentary

Regarding the Cambrian deposits of Læså Formation, in the Risk Analysis Attachments to Reports 6 and 7, the risks evaluated in reference to Krechowicz et al. 2022 include:

F27 *Borehole collapse and/or blowout*
F29 *Drilling fluid runoff (insufficient fluid pressure)*

Blowout/collapse risks within the formation are related to the alternation between the sedimentary rocks of variable grain size, including glauconite, both open and infilled fractures, where the infill varies in colour from yellow and red to greenish and dark greenish grey. The colour mentioned herein is indicating variable plasticity of the infill. Hereto, the sparse measured data for soil that is possibly of Læså Formation is presented in Table 13.4.

Table 13.4 Overview of measured data for soil possibly of Læså Formation encountered in geotechnical boreholes carried out in relation to Energy Island Bornholm

Measured	**Appendix A15.6 section**	**Comment**	**Min**	**Max**
Water content [%]	1.1	Cambrian clay	14.6	17.7
		Cambrian gravel	4.8	
Organic content [%]	1.4	Cambrian clay	2.5	

The dominant risk, however, lies in the loss of drilling fluid through the fractures and cavities, as the deposit is within the fault zone, and/or insufficient fluid pressures to overcome eventual artesian pressure that have been registered on the locations with Læså Formation. See Risk Analysis Attachments to Reports 6 and 7, and Enclosure 15.A02.

14 Cambrian sandstone of Hardeberga Formation

14.1 Available information

Cambrian deposits of Hardeberga Formation are encountered in presently carried out geotechnical boreholes depicted in Table 14.1 and Figure 14.1.

Table 14.1 Overview of Cambrian deposits encountered in geotechnical boreholes carried out in relation to Energy Island Bornholm

Appendix no.	Deposits / Formation	Description	Report no.	Boreholes
A15.9	**Cambrian sandstone of Hardeberga Formation**			
	kq/q	Sandstone	8	2-1-1 and 2-1-2

Figure 14.1 Location of boreholes with Cambrian deposits of Hardeberga Formation; the boreholes are marked with blue dots

The colour of the Hardeberga sandstone varies from black to grey, greenish grey and reddish brown, with thin laminae to large parties of dark reddish brown mudstone in the upper part. Thin to medium beds of conglomerate of slightly hardened mudstone with sand nodules and clay laminae are registered between 23 and 25 mbgl. The lower resistivities in Cambrian sandstone formation coincide with the depths of the mudstone laminae within the sandstone. Otherwise, the sandstone exhibits the expected resistivities of up to 1000 ohm·m.

The sandstone contains medium to thick (40 to 85 cm) layers of conglomerate, consisting of slightly hardened mudstone with non-hardened clay parts from around 22.4-22.8 mbgl in 2-1-1 and 23.5-24.4 mbgl in borehole 2-1-2.

14.2 Measured data

The measured data is summarized in Table 14.2.

Table 14.2 Overview of measured data for Cambrian rocks of Hardeberga Formation encountered in geotechnical boreholes carried out in relation to Energy Island Bornholm

Measured	**Appendix A15.6 section**	**Comment**	**Min**	**Max**
Water content [%]	1.1	Sandstone	0.4	8.6
		Conglomerate	3.8	
Particle density [g/cm³]	1.2	Sandstone	2.73	2.76
Grain size distribution / D10 [mm]	1.3	Conglomerate	0.005	
Atterberg limits/ Plasticity index [%]	1.4	Conglomerate	11.2	
Unit weight [kN/m³]	1.5	Sandstone	22.5	26.3
		Conglomerate	25.6	
Field vane strength [kPa]	2.1	Uppermost sandstone	>701.5	
RQD	1.6	Whole formation	0	87
Equotip hardness / σ_C [MPa]	2.2	Uppermost sandstone with mudstone laminae	11	
		Sandstone	83	197
		Conglomerate	13.4	

14.3 Ranges of geotechnical and hydrogeological parameters

Table 14.3 Ranges of geotechnical parameters in rocks of Hardeberga Formation.

Rock description	γ		γ'		ϕ'		c'		σ_c		k		Eint	
	kN/m³		kN/m³		°		kPa		MPa		m/s		GPa	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Sandstone	22	27	12	17	>35	-	0	0	25	>100	1e-11	1e-5	>5	>10

14.4 Risks review and commentary

Regarding the Hardeberga sandstone, in the Risk Analysis Attachment to Report 8, the risks evaluated in reference to Krechowicz et al. 2022 include:

F25 *Unexpected natural obstacles*
F28 *Blocking of the drilling pipe because of the swelling of the clay/drilled out rock*
F29 *Drilling fluid runoff (insufficient fluid pressure)*

In the generally hard rocks of Hardeberga Formation blocking risks are not expected. However, in the encountered layer of Cambrian conglomerate, found in both available boreholes, these risks may be higher. Found in both boreholes, the layer of conglomerate is described as less indurated and more fractured than the rest of the rock mass. From here stems the risk of the drilling fluid runoff. See Risk Analysis Attachment to Report 8, and Enclosure 15.A02.

15 Characteristic parameters and observed hydrogeological conditions

15.1 Characteristic parameters

The determination of characteristic parameters has been carried out according to the Eurocode DS EN 1997-1, in combination with interpretation methods used in Danish practice as described in the present GIR.

The geotechnical parameters are derived specifically for each soil/rock unit from geotechnical information acquired within this project. Where no relevant data are available, estimates are based on Danish experience and engineering judgement. The characteristic geotechnical parameters in this GIR are presented as lower and upper bound values where applicable, LB and UB, respectively, see Table 15.1 and Table 15.2

The GIR is a general document. For specific design purposes of HDDs, separate design profiles with associated geotechnical parameters within the range defined by upper and lower bound values specified in this GIR must be elaborated for the design alignments of particular HDDs.

Table 15.1 Parameter ranges in soils

Soil description	γ		γ'		ϕ'		c'		c_u		k		Eoed	
	kN/m^3		kN/m^3		°		kPa		kPa		m/s		MPa	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Recent, Fill and Lateglacial deposits														
All top deposits	16	20	6	10	15	36	0	0	10	200	1e-3	1e-9	n/a	n/a
Glacial deposits														
Clay till	20	23	10	13	n/a	n/a	n/a	n/a	50	>700	1e-11	1e-8	10	>100
Sand/Gravel till	20	23	10	13	38	>40	0	0	n/a	n/a	1e-7	1x-4	25	>100
Meltwater silt and clay	20	22	10	12	n/a	n/a	n/a	n/a	50	>350	1e-11	1e-7	10	>50
Meltwater sand	19	22	9	13	35	>40	0	0	n/a	n/a	1e-7	1e-3	25	>100
Cretaceous deposits of Arnager Greensand Formation														
Clay	19	21	9	11	n/a	n/a	n/a	n/a	450	>700	1e-11	1e-9	30	70
Sand	19	20	9	10	38	>40	0	0	n/a	n/a	1e-9	1e-5	50	>100
Jurassic deposits of Rønne Formation														
Clay	19	21	9	11	n/a	n/a	n/a	n/a	200	>700	1e-11	1e-9	20	>70
Sand	18	20	8	10	38	>40	0	0	n/a	n/a	1e-9	1e-4	50	>100
Triassic deposits of Kågerød formation														
Clay	18	22	8	12	n/a	n/a	n/a	n/a	200	>700	1e-11	1e-9	15	>70
Sand	19	22	9	12	38	>40	0	0	n/a	n/a	1e-9	1e-4	30	>50

Table 15.2 Parameter ranges in rocks

Rock description	γ		γ'		ϕ'		c'		σ_c		k		Eint	
	kN/m³		kN/m³		°		kPa		MPa		m/s		GPa	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Silurian Cyrtograptus and Rastrites Shale														
Shale	24	27	14	17	16	25	0	0	4.5	39	1e-11	1e-5	5	>10
Ordovician / Silurian shale of Alum shale Formation														
Shale	22	27	12	17	20	25	0	0	25	58	1e-11	1e-5	>5	>10
Cambrian deposits of Læså Formation														
Sandstone/ Siltstone/ Claystone	22	27	12	17	~35	-	0	0	30	150	1e-11	1e-5	>5	>10
Cambrian sandstone of Hardeberga Formation														
Sandstone	22	27	12	17	>35	-	0	0	25	>100	1e-11	1e-5	>5	>10

15.2 Hydrogeological conditions

Regarding observed water tables and risk of cracks and faults at a specific HDD location, refer to the corresponding HDD report, as the measured water tables and location of cracks and faults cannot be assigned to a specific deposit.

In the HDD boreholes, the standpipe has been installed for readings of the primary water table, i.e. the pressure in the assumed primary aquifer (magazine/reservoir). Besides, local, secondary water tables may occur. These water tables will vary with precipitation and the time of the year.

Further, attention shall be paid to water bearing cracks and faults as the high permeability of these can increase the inflow of groundwater. See also Enclosure 15.A02.

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