COBRA Cable Site Investigation in the Wadden Sea, Denmark

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ABSTRACT
Energinet.dk and TenneT plan to develop a 320-350 km long high voltage DC cable between Endrup, Denmark, and Eemshaven, the Netherlands. COWI A/S was contracted in 2014 by Energinet.dk to map the corridor in the challenging Wadden Sea environment between Esbjerg and Fanø.
The survey covered a 6.2 km long and 200 m wide cable route corridor specified by Energinet.dk. The purpose of this survey was to provide detailed geological and geographical data to support the plan for design, installation and protection of the cable.
Three surveys were carried out: a geotechnical survey at eight positions using a drill rig drilling from a barge, a geophysical survey using a small boat and an airborne survey using two drones.
The seafloor mapping was accomplished by multi beam echo sounder data (MBES) with backscatter and single beam data (SB) combined with detailed photogrammetry from the drone survey.
On the geotechnical positions, boreholes and Swedish Dynamic Probing were carried out to a maximum of 6 m below the seafloor. Samples were taken for laboratory test results. The barge could work floating in water but also be manoeuvred during high tide to land on the mud flats. Thereby data were acquired on positions otherwise not reachable. The geophysical survey included a seismic pinger survey and the results were utilized trough integrated interpretation of the seismic data and geotechnical results.
The three surveys combined have allowed mapping of the seabed and mapping of the geometry and geotechnical properties of sub-bottom layering in the corridor. The interpretation identified 12 different layer boundaries in a very active and variable geological setting of mud and tidal flats gyttjas, sandy channel fills and recent prograding sediments.

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Keywords: Boreholes, probing, seismic, drone, bathymetry

1 INTRODUCTION

In collaboration with the Dutch TSO TenneT, Energinet.dk plans to establish a 320-350 km long HVDC cable with converter stations in Endrup near Esbjerg and Eemshaven in the Netherlands. The connection is called COBRAcable (www.energinet.dk). The cable will cross the Island of Fanø. In 2014 COWI carried out a cable route survey for Energinet.DK in the Wadden Sea from Esbjerg to Fanø (Figure 1).

The survey mapped a 6.2 km long and 200 m wide corridor with vessel, barge and drone to provide coverage of seabed and the shallow sub-bottom.
The conditions in the Wadden Sea is challenging as neither onshore nor offshore standard methods will cover the entire area. Furthermore, soft mudflats and tidal schemes add complexity to the survey conditions. The tidal difference in the area during time of acquisition was up to 2 m.

Figure 1. Overview of the survey area: A 200m corridor centred at a straight line.

2 METHODS

2.1 Mapping of seabed

In order to map the seabed a combination of vessel survey with multibeam ecco sounder (MBES) and single beam ecco sounder (SBES) along with airborne photogrammetry (Ortho-photos) was suggested. During planning it was impossible to predict precisely the coverage of each method.

In planning the tidal scheme was taken into account in order to cover the full corridor. Ortho-photo coverage utilized low tide and day light were as both MBES and SBES took advantage of high tides.

A GNSS base station was set up at the southern end of Esbjerg Harbour for the geophysical survey in order to deliver RTK corrections during the survey. The GNSS position accuracy during the geophysical survey was approximately 3 cm horizontal and vertical.

The DTM accuracy from the airborne survey is approximately 10 cm.

Vessel Survey

The 15 ft Finnspeed "Nellebjørn" (Figure 2) with draft of 0.9 m, was used for the geophysical and hydrographic survey. The following equipment was used for the bathymetric survey:

- R2 Sonic 2020 multibeam ecco sounder with TruePix back-scatter sonar output.
- Atlas Deso 15 Single beam ecco sounder
- Navisuite Software

SBES data were acquired using a 210 KHz transducer mounted over the side of the survey vessel. A GPS antenna was mounted on top to the transducer setup. SBES data and GNSS RTK data was time stamped during acquisition for post-processing purposes. The survey lines were designed with 10m spacing parallel to the survey area centre line. Data were acquired from a minimum water depth of 0.78 m LAT (0.50 m relative to MLWS).

MBES data were acquired from the three channels in the survey area. The channel locations were based on the SBES data. The survey equipment was deployed from the survey vessel's moonpool. Data were acquired using a 400 MHz transducer and the survey covered 100% of the channels. Sound velocity of the water column was measured with 2-3 hours interval and for quality control a patch test was performed during the survey.

Figure 2 Survey vessel Nellebjørn.

Airborne Survey
The airborne survey was accomplished using the following equipment:

- Leica GPS (GNSS) VivaGS12,
- Ebee UAV (COWI No.1 and 2), Drones.
- Marking material for GCP's
- 10 feet boat for transportation in the survey area.

Prior to operation, a number of ground control points (GCP) were stationed at various locations in the survey area and positioned using differential GPS. The purpose was to be able to fix the resulting terrain model and orthophoto into the project coordinate system.

The operations was performed at lowest tidal conditions possible. Two un-manned aerial vehicle (UAV) teams sampled simultaneously from Fanø and Esbjerg, resulting in full areal coverage of the project trace. During the operation, sampled imagery were quality checked.

Figure 2. Picture from establishment of GPS's

2.2 Subbottom Profiling

SBP data were acquired using an Innomar SES 2000 compact narrow-beam parametric profiler on three survey lines parallel to the centre line of the cable corridor and nine lines perpendicular to the centre line. The nine perpendicular lines focused on surveying the channels. The survey equipment was deployed from the survey vessel's moonpool.

2.3 Geotechnical Positions

The shallow waters pose a challenge for heavy gear and COWI had therefore opted to use a small barge carrying a light-weight belt-mounted rig (mini-rig) with the capability to drill to 6 m depth with a 6” drill bit using an auger with casing.

The drill rig and barge had a total weight of 2500 kg. The barge had a draft of 0.4 m and was therefore manoeuvrable in the shallow waters. The barge was equipped with an outboard engine and had two retractable legs, each with a diameter of about 3". The legs were placed in the seabed to maintain the correct position and to stabilise the barge during work.

The drill rig and barge can operate in water depths from 0.5 to 5 m. During high tide it will be possible to place the drill rig on the mudflats (Figure 3). If low tide occurs during the drilling this will not affect the equipment. A small service boat was used for transport of personnel and for safety measures.

Figure 3. Picture of Barge at mud flat

In addition to the geotechnical drilling, Swedish Dynamic Probing tests (Svensk Rammesondering) were carried out from which the strength of the soils can be estimated with results equalling those of Soil Penetration Test (SPTs).

In total eight geotechnical boreholes including Swedish Dynamic Probing tests were undertaken. Furthermore, temperature measurements within the upper 100 mm of the soil were undertaken at each borehole location using a data logger and a thermometer. The data logger used was the model WTW Multi 3430 set F (IP67/68).

The relationship between the Swedish Dynamic Probing results, N_{20}, and cone resistance, q_c, is described in Bulletin 6, March 1976 by Borros AB, Swedish Geotechnical Institute. According to this reference, the relationship is assessed for granular soils; $qc = \frac{N20 + 4.45}{1.8}$

3 SEABED

In Figure 4 the resulting data coverage is shown. SBES data was surveyed first and covered both channels and mudflats in order to establish the positions of the deeper parts where MBES and SBP could be used. MBES was sailed using the highest tidal conditions possible, but only at depth greater than – 1.5 m LAT could MBES provide coverage. Airborne data were collected for the entire area. However, after processing it was clear that the photogrammetry could only work in depth range above 0 m LAT as the wet soils only gave the water surface. Therefore, in total 4 km of the 6.2 km corridor are covered mainly with single beam data.

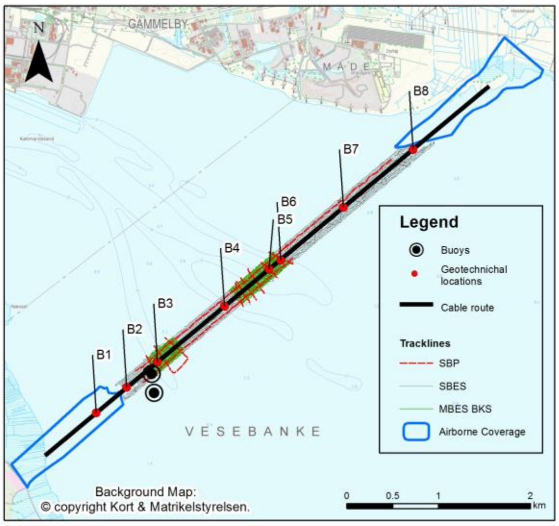

Figure 4 Data coverage.

Each method covered a part of the depth range in the area that the other methods could not reach.

Table 1. Methods used to map seabed/terrain.

Method used	Depth Range
Multibeam Ecco Sounder	-5 - -1.5 m LAT
Singlebeam Ecco Sounder	-1.5 - 0 m LAT
Airborne photogrammetry	0-4 m LAT

Each of the methods also have different resulting coverage and resolution (Table 2).

Table 2. Methods used and their resolution

Method used	Resolution horizontal/vertical to LAT
Multibeam Ecco Sounder	25x25 cm / 10 cm to LAT
Singlebeam Ecco Sounder	Lines 10 m apart / 20 cm to LAT
Airborne photogrammetry	25 x 25 cm / 10 cm to LAT

3.1 Bathymetry/DTM

Three Northwest-Southeast trending channels with water depths of more than 2 m are shown on the available nautical charts based on which the geophysical survey was planned (Figure 4). The MBES data clearly shows that one of the channels is located approximately 150 m more easterly than expected (Figure 5). The seabed in the channels have steep slopes of more than 2°

toward the centre of the channel. The deepest parts of the channels are found at -5.1 m LAT.

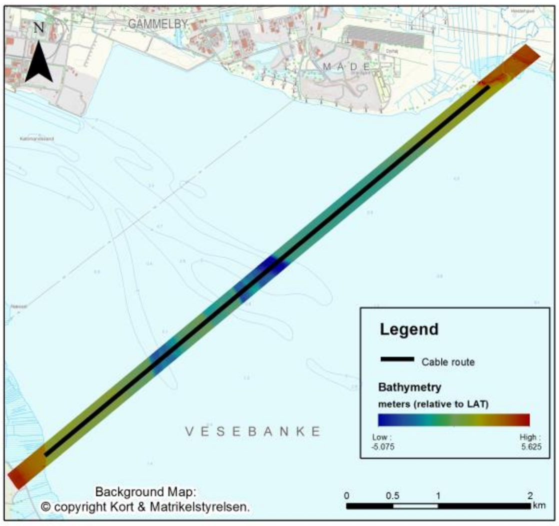

Figure 5. Bathymetry after gridding. Note that the channels marked in the nautical charts does not correspond to the channels mapped in this survey.

3.2 Seabed, texture and objects

The backscatter data acquired with the MBES data are of low to medium quality and are clearly affected by being acquired in marginal conditions. The low and varying water depth only allowed for a small beam width and have caused a lot of distortion.

In the central part of the deepest channels the data quality was reasonably good and the range large enough to allow for independent identifications of targets.

24 targets were identified in the backscatter sections. Only targets greater than 0.5 m were picked. Most of these are white spots and may have been denoted debris/boulder. The second most abundant target is parts of pipe/cable troughs or uncovered pipes.

The Airborne data were of excellent quality. Targets larger than 0.5 m were prioritized, but several targets down to 0.25 m were identified. After picking the smaller point targets, larger features e.g. oyster beds or clay outcrops were identified and digitized as polygons. 124 targets were identified from the orthophotos. Of these 30 are onshore. Offshore the most abundant target type was interpreted as boulders.

Seabed classification was established from the backscatter data and orthophotos. The outline of the beach and the intertidal zone of the shore face (Figure 6) as well as the extent of ripples was included in the classification. Seabed classification was an important part of the scope but highly challenged by lack of data coverage in the areas covered by SBES data (-1.5 – 0 m LAT). For interpretation of differences in seabed characteristics also geotechnical boreholes, bathymetric data and interpretations from the SBP data were taken into account for deciding what sediment type was expected. Six different classes were employed. These are listed in Table 3

Table 3 Summary of classification scheme

Description	Orthophoto/ Backscatter characteristic
Vegetated area/ beach	Green vegetation shows clearly on the orthophotos. Small occurrences detached from the shore are not included.
Intertidal zone	A small rise with some sand deposition. Identified on orthophotos, interpreted to represent previous land areas with present day deposition following a transgression.
Gyttja/Peat	Dark colours in orthophotos, may have some sand content. Relatively featureless in backscatter data.
Sand (small ripples)	Small ripples seen in backscatter data. Distance between crests around 0.5m.
Sand (large ripples)	Larger sand ripples observed in backscatter data and visible in the bathymetry. Distance between crests typically around 5 m.
Mixed/coarse sediments	Patches of variable backscatter intensity observed.

Figure 6 Example of seabed classification from ortho-photos showing the outline of the vegetated area/beach and intertidal zone of the shore face as black lines.

4 GEOLOGICAL MODEL

4.1 Geotechnical Data

Geological descriptions of the samples collected during the drilling campaign were carried out by a geologist according to "A guide to engineering geological soil description" by the Danish Geotechnical Society. The sediments encountered in the boreholes were postglacial sediments with the exception of two boreholes, where sediments of glacial origin were found.

A series of laboratory tests were conducted with the objective to evaluate selected properties of the sediments encountered.

Swedish dynamic probing results was used to assess the relative density of the sand deposits. The blows per 0.2 m, N_{20}, are recorded as 1 to 18, equating to very loose to medium dense soil. Based on the relationship referenced in section **Error! Reference source not found.**, this equates to a cone resistance in the order of 3-12 MPa.

Gyttja was present in all boreholes in thicknesses ranging from 0.6 m to more than 3.0 m. Peat was encountered in 2 boreholes with thicknesses of 0.3 m to an excess of 1.3 m. The peat and gyttja were deposited in marine, freshwater and brackish environments. Postglacial sand was encountered in two boreholes and described as slightly organic to very organic. The thickness of the sand layer found in the boreholes ranges from 0.2 m to 3.0 m. Clay was encountered in one borehole and described as highly plastic with organic lamina.

4.2 Subbottom Profiler Data

The SBP data were interpreted in IHS™ Kingdom® version 2015. A total of 12 different layer boundaries were identified. A very active and variable geological setting of mud and tidal flats gyttjas, sandy channel fills and recent prograding sediments was revealed.

4.3 Integrated Interpretation

The vertical scale of both the bathymetric grid and the geotechnical data were converted from depth (m) to two-way-time (TWT) (s) for interpretation. After interpretation, grids of the layer boundaries have been converted from TWT to depth. The TWT-depth relations for the conversions are given below. The interpretations are presented in alignments sheets (Figure 7).

- Seawater: 1480 m/s,
- Geological layers below seabed: 1600 m/s.

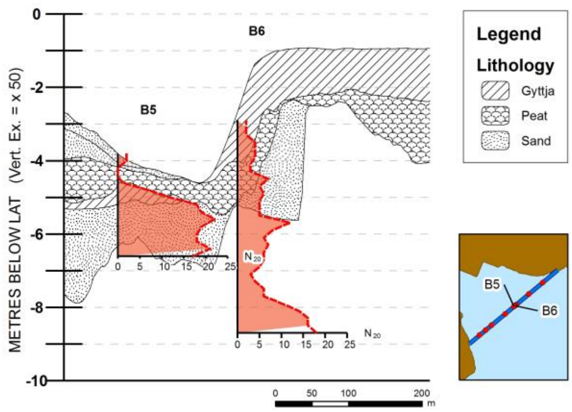

Figure 7: Snapshot from alignment sheets showing the results of the Swedish Dynamic Probing and its correlation in the integrated interpretation along the deepest channel.

Layers interpreted are all deposited in upper or lower tidal environments, with the shallower part dominated by salt marsh deposits and mud flats, while the deeper parts are good examples of an active tidal channel system (Figure 8). The varying facies of the different layers indicate that sea water level has fluctuated during deposition. The character of the upper layers indicates that the water level has been rising relative to the land (transgression). The lower boundary of the Post Glacial deposits could not be interpreted since seismic penetration did not reach the depths where borehole information have records of it in the shallowest waters (Figure 7).

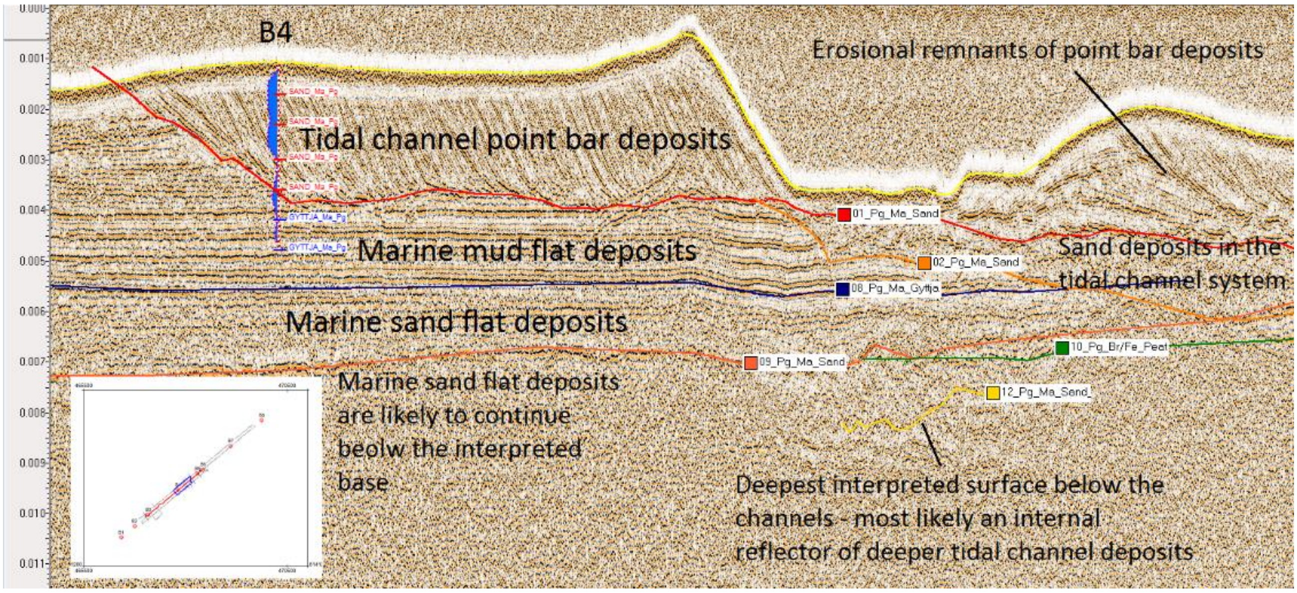

Figure 8. Arbitrary section of SBP profiles with geotechnical data. This section illustrates the stratigraphic layers within the active tidal channel around borehole B4. A series of sand and mud flat deposits is covered by the active tidal channel system with migrating point bar sand deposits.

5 REFERENCES

Bulletin 6, March 1976 by Borros AB, Swedish Geotechnical Institute

A guide to engineering geological soil description.