A fixed and direct transport connection between Scandinavia and Central Europe has been an enduring vision for many decades. This vision is about to be realised with the construction of the Fehmarnbelt Fixed Link, an 18-kilometre-long immersed tunnel between Rødbyhavn in Denmark and Puttgarden in Germany. When it opens in 2029, the tunnel will be the longest immersed tunnel in the world combining a dual railway and motorway connection. This article provides insight into the improved dredging equipment used and the methodology specially adapted and further developed to the project's requirements.

THE FEHMARNBELT TUNNEL TRENCH DREDGING PROJECT

Project background
The Fehmarnbelt Fixed Link has been designed and planned by Femern A/S, a subsidiary of the Danish, state-owned company Sund & Bælt Holding A/S. In 2008, a state treaty was approved and signed by the Danish and German governments. Both countries agreed that Denmark would be solely responsible for financing the coast-to-coast project (and the related extension of the Danish coastlines) and therefore be the sole owner of the Fixed Link. In turn, Germany will finance and ensure the timely development of the landworks on the German side. The treaty stipulates that the link will consist of a twin-track railway and a four-lane motorway.

The toll station for the users of the Fixed Link will be located on the Danish side of the Fehmarnbelt. Femern A/S was responsible for designing and providing the basis for the official approval of the coast-to-coast section of the Fehmarnbelt Fixed Link on behalf of the Danish Ministry of Transport.

After a series of investigations between alternative solutions (an immersed tunnel, a bored tunnel, a cable-stayed bridge and a suspension bridge), Femern A/S recommended an immersed tunnel as the preferred technical solution for the Fixed Link.

The Fixed Link will fill the infrastructural gap between Scandinavia and mainland Europe by means of an efficient and high-quality transport infrastructure. In addition, the railway connection will result in the highly needed release of the Danish East-West rail connection. Freight trains from Zealand, Sweden and Norway will be able to take the direct tunnel into Germany and mainland Europe instead of the current longer route via Southern Jutland and Northern Germany (Hamburg), shortening the rail freight distance by 160 kilometres. Thus, the Fehmarnbelt Fixed Link is part of the Trans-European Transport Network (TEN-T) (Figure 1). TEN-T’s policy addresses the implementation and development of a Europe-wide network of railway lines, roads, inland waterways, maritime shipping routes, ports, airports and railroad terminals. Its ultimate objective is to enhance the efficiency of the European infrastructure so that the EU’s single market functions better and with less environmental impact. The tunnel will also offer a new strong link to the Fehmarnbelt region itself, stimulating...
growth and prosperity. Nine million people currently live in the region which extends between the cities of Hamburg, Kiel, Lübeck, Copenhagen and Malmö. The project will not only provide work for local people but will also create jobs at companies in the region, supplying the site with raw materials, goods and services.

After an international competitive bidding process, the Tunnel Dredging and Reclamation (TDR) contract was awarded to Fjellmann Belt Contractors (FBC) a joint venture between Boskalis and Van Oord. FBC started preparations in 2019 and actual operations commenced in June 2020 when the first rock was placed to start construction of the breakwaters around the Lolland work harbour in Denmark.

Geology

Figure 2 shows the geological longitudinal profile along the tunnel alignment. Both the Danish and German sides have gently sloping near-shore profiles with a maximum water depth of around 30 metres. In order to accommodate the immersed tunnel, the maximum dredging depth will be approximately 48 metres.

The soils to be dredged for the tunnel trench consist of upper layers of post glacial and late glacial deposits (gyttja, sands, silts and clays). Underlying layers are made up of glacial deposits (clay and sand) followed by a Palaeogene layer with highly plastic to extremely plastic clay. The German side is characterised by Palaeogene clays together with some clay-till and the central basin (the central part of the geological cross section along the tunnel alignment) by gyttja, sands, silt and clays. Thin deposits of hard clay-till dominate the Danish side. In total eight separate units are distinguished in the geological longitudinal profile of the tunnel trench.

Unit 1: Postglacial sand

Unit 2: Postglacial gyttja and freshwater peat

Unit 3: Postglacial late glacial clay and silt

Unit 4: Postglacial late glacial sand

Unit 5: Upper till

Unit 6: Meltwater deposits

Unit 7: Lower till

Unit 8: Palaeogene clay

Each unit features different characteristics when it comes to ease of dredging placement in sand reclamation or foundation of tunnel elements.

The entire UXO clearance works comprised three individual phases: surveys, identification or removal or relocation.

Unexploded ordnance and naval archaeology

The survey and removal of any potential unexploded ordnance (UXO) within the respective work areas comprised a series of activities that began in 2011. First, an initial desk study was carried out, followed by detailed surveys and a removal operation.

The desk study included searching for information in the Royal British Navy, German Navy and Royal Danish Navy archives. As a result, it became apparent that no capital dredging works would be initiated until a full survey and removal campaign had been completed. Overall, the entire UXO clearance works comprised three individual phases: surveys, identification and removal or relocation of identified UXOs.

UXO and other surveys

Survey vessels were carried out by the specialist company Heinrich Hirdes (a Boskalis subsidiary) deploying its state-of-the-art equipped fleet for the purpose. A towed magnetometer array measuring the total field amplitude was deployed within the respective work areas with a line spacing of 1.5 metres between each magnetometer array, in combination with a multibeam and side scan sonar survey. From this, the special detection criteria, a maximum towing height of the magnetometer of 4 metres above the seabed was used as the threshold.

Based on the magnetometer survey, the target list was correlated to the anomalies detected by the combined multibeam and side scan sonar survey. The survey campaign resulted in a final target list comprising 2,883 potential targets, approximately half of which were classified as potential UXOs.

UXO identification and removal campaign

Subsequent target inspections were performed by deploying a specialised tool operated from a work pontoon within the nearshore area and from survey vessel Hamara covering the offshore areas (Figure 3). The specialised tool comprises a group of instruments and equipment for the purpose, including an acoustic profiler system, the EM detection system, an imaging sonar, a dredge pump and finally an orange peel grab for the recovery of an item. The configuration allows for immediate switching between all these individual tools (Figure 4).

Relocation of identified UXOs

Further handling of identified UXOs depended on the conditions of each object as concluded by the previous investigations. Therefore, the encountered ammunition objects were classified as follows:

- Any UXO concluded as safe to transport was recovered onto the deck on the inspection vessel and subsequently handed over to the responsible authority in the Port of Kiel, Germany.
- Any UXO not safe to transport on deck was relocated by means of underwater transport facilities to another weapon storage location – again in collaboration with the German authorities. Or
- In the case of an UXO being neither safely transportable nor relocated to another area, the UXO was blasted in situ by respecting the requirements from the respective German and/or Danish authorities.

Within the Danish territory, the Royal Danish Navy monitored and assisted the campaign with the actual identification of UXO items, and took charge in the event of a removal operation, i.e. explosive ordnance disposal (EOD) in the German territory. Heinrich Hirdes operated on its own until the need for German authorities to tone down identified UXOs. As a result, an extensive set-up of requirements for mitigation measures for the removal of any UXO in the areas close and inside the Nature 2000 network of core breeding and resting sites for rare and threatened species were put in place. This is a result of extensive talks with German authorities on enhanced and underwater noise mitigations from the EOD of an UXO, such as double bubble curtains and pingers.

Based on the UXO survey campaign, 119 UXO targets were identified. Of these, 104 were classified as non-UXO targets, one as an old anchor and 10 UXO targets were relocated to a weapon storage area in Danish waters. One UXO target was cleared by the German Navy and one UXO target located in Danish waters was cleared by specialists of Heinrich Hirdes in 2022 by controlled detonation.

Naval archaeology

Detailed surveys performed in preparation of the dredging activities also included locations of known historical wrecks (Swarte Arent and Lindormen (found in 2012 during preparatory surveys) and the Danish historical vessel,
The offshore construction activities are the excavated trench below the seabed. 

Each one will be cast in a temporary factory from 89 prefabricated tunnel elements. (Figure 6). The tunnel will be constructed at two ports in Puttgarden and Rødbyhavn nearshore location within the perimeters of the existing ferry harbour.


Offshore construction scheme

Laying close to the existing infrastructure, the alignment for the 18-kilometre-long immersed tunnel passes just east of the existing ferry harbour at Rødbyhavn. (Figure 5). In close contact with the Vikingship excavations, specific exclusion zones were established to preserve the historical wreck. Delmenhorst was discovered at a nearshore location within the perimeters of the existing ferry harbour of Rødbyhavn. It is planned that the reclaimed land will not extend beyond the breakwaters of the ferry harbour. 

Tunnel alignment between Lolland and Fehmarn. 

Dredging and reclamation works

An approximately 18-kilometre-long trench must be dredged into the seabed of the Fehmarnbelt between Lolland and Fehmarn, representing the majority of the dredging work in terms of the quantity of dredged material and the associated construction time. Excavated into the existing seabed, the trench will measure up to 90 metres wide and 16 metres deep. It is estimated that the volume of material to be dredged into to create the trench is around 14,500,000 m³ and dredging of the trench is planned to run over a period of 18 months.

Dredging processes

The dredging process comprises dredging of material from the tunnel trench, transportation of the dredged material to the reclamation areas and unloading of the excavated material into the reclamation areas. The applied dredging methodology is a combination of mechanical dredging with backhoe dredgers (BHD) and grab dredgers (GD) and hydraulic dredging and placement deploying trailing suction hopper dredgers (TSHD) Backhoe dredger will dredge the shallow parts of the tunnel trench at both the German and Danish sides of the Fehmarnbelt to a depth of approximately -25 metres. Deeper parts below this depth will be dredged by a combination of grab dredgers and trailing suction hopper dredgers. TSHD’s will make use of a special draghead for handling of the very hard clay-till combined material.
with a recirculation system that pumps water from the hopper back to the seabed in order to minimize soil cut and fine sediments into the environment and to optimise the dredging process. The mechanically-dug material is loaded into transport barges that then sail to the nearshore reclamation areas where the soil is unloaded. Both towed barges and self-propelled (split hopper barges) are deployed for the project.

Boulder removal
Boulder removal from the dredged till is an essential part of the dredging works and the progress thereof. A TSHD can remove and transport boulders up to a maximum diameter of approximately 0.3 metres as part of the normal dredging and offloading process. This limiting dimension is based on the dimension for dredge pump passage. A grid is installed in the dredging diet to prevent larger boulders from entering the pump. Larger boulders will remain on the seabed bottom but will be excised by the TSHD to enable other vessels to remove them.

It is anticipated that one boulder (larger than 0.3 metres in diameter) per 50 m² will be encountered on average, which will result in a large number of boulders reaching the barge to be removed simultaneously with the TSHD operation. The quantity of boulders left on the seabed will in turn have an effect on the production rate of the TSHD. Observation of the distribution of boulders, which may be encountered, may be encouraged and spread over the tunnel trench or found clustered in large quantities (resists).

A large number of the boulders left on the seabed after removal by a fishing net operation, deploying a medium-large size multnet. After positioning, the net is lowered from the stern of the vessel. During the subsequent towing, the resistance on the net increases gradually. This resistance is continuously monitored on board until time for recovery (Figure 8).

Sediment split management
In view of previous experiences with large-scale marine infrastructure development projects in Denmark, the proper control and management of fine sediments originating from the dredging and reclamation activities are a crucial aspect of all preparations and execution of the project. Following extensive environmental research, a total sediment split budget was defined before works began. This sediment split budget is split into smaller parts, distributed by time (months and seasons) and space (eight split monitoring areas) along the alignment of the tunnel trench, including near shore areas at Lolland and Fehmarn). Spill budgets range from negligible to an environmentally sensitive areas in the summer to several tens of thousand tonnes in less sensitive areas over winter period. Overall compliance is monitored at all these levels and totals. Contractor FBC has the responsibility to ensure compliance using extensive field monitoring and numerical modelling (Figure 9), including verification of achieved accuracies at the end of all dredging operations.

In practice, FBC modelled potential sediment spill originating from different soil units and different dredging and reclamation methods in detail. By verifying applied parameters for the modelling through extensive field monitoring of dredge plumes and sediment concentrations at the permanent works boundaries, the modelling is validated (Figure 10). Results of this modelling and monitoring are published online.

Reclamation works
Reclamation works are executed on both the German and Danish sides of the Fehmarnbelt. The largest share of the dredged material will be placed at the Danish side in newly constructed land reclamations. A smaller part of the dredged material will be placed at the German side in specific stockpiles onshore.

The reclamation areas on both sides consist of bunds constructed of mechanically-dug upper till, quarry run, filter layers and armour layers. The reclamation basins are specifically designed for the purpose of receiving the dredged material from the tunnel trench, which is placed both mechanically by direct offloading from barges or dump trucks and hydraulically by pumping ashore material from hopper dredgers. All reclamation areas are initially accessible for direct placement from transport barges by leaving parts of the reclamation bunds open for marine access.

Some reclamation areas are subsequently closed off in preparation of hydraulic placement of material, for which spilt boulders are constructed to manage process water and contained fines sediments. Other reclamation areas can be closed off when transport barges no longer have access due to reduced water depths as a consequence of material placement. Those areas are subsequently filled to final design levels using dump trucks that are loaded at several temporal or more permanent offloading quays receiving the transport barges.

Specific placement methods, planning and execution depend on several criteria, which are all considered in detail during the design and work preparation stage. Each geotechnical unit dredged in the trench features specific specific strength and other characteristics, making it more or less suitable for placement at certain locations (see Figure 12).

• Unit 2 (gyttja, commonly found at higher levels in the tunnel trench) has relatively low strength after dredging and needs to be covered at all times to avoid the material oxidizing. It is therefore placed as fill material in the lower parts of the reclamation areas.
• Unit 5 (upper till, found at low levels in the tunnel trench) has significant strength when dredged mechanically and transported carefully and can be used for bund construction or construction of the erosion cliff featured at the Eastern extreme of the reclamation areas at Lolland and
• Unit 3 and Unit 8 (silty clays and Paleogene clays) are dredged mechanically or manually and mainly placed as fill material in view of anticipated lower strength after dredging.
Hydraulically dredged material (unit 5 upper till, unit 4 sandy clay and unit 7 brown clay) are found at upper levels in the tunnel trench and therefore dredged in later stages of the trench excavation process. These are placed at higher levels in the reclamation areas as fill or surface covering material only. Please note these are general guidelines only based on actual monitored material characteristics, other placement locations or purposes were selected. In general, there is a shortage of dredged material of sufficient strength to construct bunds and stockpiles on shore. Therefore, careful monitoring of actual behaviour of dredged material, management of transport processes towards all available placement locations and selection of most suitable material is a key success factor in the entire land reclamation process.

Selection of dredging equipment

The dredging of the tunnel trench requires a small fleet of dredging equipment. Both the geometry of the tunnel trench (depth of the seabed, excavation depth of the trench including deeper special elements) and the geology of the material to be excavated require specific dredgers to be deployed. Additional requirements related to beneficial use of dredged material in the reclamation areas also need to be taken into consideration when selecting the appropriate dredging equipment.

Firstly, the tunnel trench excavation scope is divided into mechanical dredged parts and hydraulically dredged parts. Hydraulic dredging by TSHD’s generally features higher production rates and is therefore considered more cost efficient, although higher levels in the reclamation areas (relevant for placement in the embankment areas) and the need for highly adaptive management of dredging and reclamation activities, which are implemented in close consultation between Femern A/S and the contractor FBC. The technical developments already deployed in the works, such as the draining buckets for the backhoe dredgers and the newly constructed grab dredgers, perform according to expectations. Other innovative systems, like recirculation of process water, will only be put to the test in the near future.

The grab dredgers deployed for tunnel trench dredging are purpose-built for the project. To preserve as much as possible the strength of upper till during dredging and transport (Figure 12), a view of beneficial use of upper till for bund construction, several draining dredging buckets were developed for the different backhoe dredgers deployed. Strength of upper till depends to a large extent on the moisture content. Reduction of moisture content or avoidance of increase of moisture content of the upper till therefore of utmost importance. To achieve this, several retardation buckets and general purpose draining buckets were designed and constructed.

Conclusions

After half a year of work on the excavation of the tunnel trench, experience has shown that the dredging and reclamation process is as challenging as ever anticipated. Governed by strict environmental requirements, curbsome CTV/CTV challenges and the local climate conditions, the works can be seen as progressing according to schedule.

At the same time, the tunnel trench deposits to be excavated sometimes deviate from original estimates, which were based on extensive soil investigation campaigns, laboratory research efforts and geological modeling. This resulted in a detailed soil model describing predicted distribution of soil units and related characteristics as in-situ strength and remoulded strength (relevant for placement in the embankment areas). These small but sometimes relevant deviations from predictions result in the need for highly adaptive management of dredging and reclamation activities, which are implemented in close consultation between Femern A/S and the contractor FBC.

In spite of the large fleet of existing dredgers, the project was required to avoid build-up of residual loads in the hopper consisting of boulders that are dredged but not pumped ashore. As previously explained, all boulders encountered smaller than 3.0 metres in diameter are dredged and pumped into the hopper. However, boulders larger than 3.0 metres are unlikely to be pumped ashore while unloading, leading to build-up of residual loads over time. To avoid this, a system of boulder catching on deck of the TSHD has been developed, in which boulders sized between 0.2 and 3.0 metres are selected, removed and transported to shore for beneficial use.

The grab dredgers deployed for tunnel trench dredging are purpose-built for the project. Using existing sea going multi-purpose grab dredgers and newly built grabs for specific geological units and purposes will be selected. In general, there is a shortage of dredged material of sufficient strength to construct bunds and stockpiles on shore. Therefore, careful monitoring of actual behaviour of dredged material, management of transport processes towards all available placement locations and selection of most suitable material is a key success factor in the entire land reclamation process.

Several technical developments took place before actual deployment for tunnel trench excavation.

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Summary

This article describes the general background and need for the Fehmarnbelt Fixed Link project, an 18-kilometre-long immersed tunnel between Denmark (Rødbyhavn) and Germany (Puttgarden) – filling the infrastructural gap with a combined motorway and rail connection – and German coastlines.

It first gives a general overview by showing the tunnel alignment and the surrounding areas, including portal and ramp structures, the tunnel element factory and the reclamation areas along both the Danish and German coastlines.

More detailed description of local conditions and soil types within the reclamation areas.

The challenges of dredging hard till formations containing a large number of big boulders, the construction of containment dykes around the reclamation areas and the construction of the work harbour breakwaters, basin and access channel.

Further, the article comprises detailed descriptions of the extensive UXO and naval archaeology investigations, which were carried out starting with a comprehensive desk study followed by multiple surveys up to detection, wreck protection and UXO clearance.

It also includes work waste management.

With an MSc in Hydraulic and Coastal Engineering from the Danish Technical University and more than 40 years’ experience, Claus Iversen has worked as a superintendent for contract director for various large-scale marine related infrastructure projects in Denmark and abroad. Major assignments have included dredging and excavation projects for the Great Belt Link, followed by the tunnel trench dredging and reclamation for the Øresund Fixed Link from 2005–2008. Claus was responsible for the superintendence of the construction of the deepest immersed tunnel in the world under the Bosphorus in Istanbul, Turkey. From 2008–2013, working for Femern A/S as construction manager (marine works), he was involved in the preparation and permits application for the construction of the Fehmarnbelt Fixed Link project. In between, Claus has worked as an expert consultant to UNDP in Vietnam, to FAD in South Africa and to the Danish International Development Agency (DANIDA) in Sri Lanka and Egypt.

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