PROJECT

FEHMARNBELT: A NEW GREEN LINK BETWEEN GERMANY AND DENMARK

An aerial view of the Fehmarnbelt's site on the island of Fehmarn in Germany, situated adjacent to the Puttgarden ferry harbour.

Photo Jan Kofod Winther Femern AS

To be built in northern Europe and connect Scandinavia with Germany, the Fehmarnbelt will be the world's longest immersed tunnel. The infrastructure will close a major gap in the European transport network, reduce the risk of shipping collisions, energy consumption and create a new region in Europe, while also fostering the development of new nature and recreational landscapes by Working with Nature concepts.

The Fehmarnbelt Fixed Link is a joint Danish and German transport infrastructure project across the Fehmarnbelt.

Presentation of the project

The Fehmarnbelt Fixed Link – the proposed eastern route between Germany and Denmark – has been planned for a long time in an effort to create a rapid connection between the two countries with a faster and shorter link (see Figure 1). It will also close a major gap in the Scandinavian-Mediterranean corridor which is part of the European transport network. Once opened, the journey for freight trains between Hamburg and Scandinavia will reduce by 160 kilometres.

The Fehmarnbelt Fixed Link is a joint Danish and German transport infrastructure project across the Fehmarnbelt. Denmark is responsible for the planning, construction and operation of the Fehmarn Fixed Link. To carry out this task, the government of Denmark has established the company Femern A/S which is 100% owned by the Danish State and represented by the Danish Ministry of Transport. The initial feasibility studies of the project were already conducted in the mid-1990s and eventually followed by the Danish-German treaty signed in 2008. The project was given the go-ahead in Denmark in 2015 and approved by Germany in 2019. The

FIGURE 1

The upcoming Fehmarnbelt Fixed Link will be the eastern alternative to the western route from Hamburg over Funen and Zealand. The new green link will save time as well as energy.

project includes an immersed tunnel that will run for 18 kilometres under the Fehmarnbelt and connect Puttgarden (Fehmarn island, Germany) to Rødby (Lolland island, Denmark). The maximum water depth will be about 30 metres and the tunnel has an estimated total construction cost of EUR 7 billion.

The conceptual design of the link and its land reclamation was developed with the support of both environmental consultants DHI and COWI, the technical consultants Ramboll-Arup-TEC and the landscape architects Schønherr.

The Fixed Link is a combined road and railway connection carrying two lanes of road traffic and a single, high speed rail track in each direction. When complete, it will be the third largest marine infrastructure project in southern Scandinavia. It will supplement the first one, the Great Belt Link between the Danish islands of Funen and Zealand which opened in 1998, and the second, the Øresund Link which opened in 2000 and connects Denmark's capital, Copenhagen, with Sweden's third largest city, Malmö. Ten million people will then be brought closer together, enlarging each country's growth region into one major regional centre. This will bring numerous opportunities for development, exchange of culture and business, trade and education, and so forth.

The journey to the immersed tunnel

The immersed tunnel will be constructed by placing tunnel elements in a trench dredged in the seabed (see Figure 2). The proposed methodology for trench dredging comprises mechanical dredging using Backhoe Dredgers (BHD) up to 25 metres and Grab Dredgers (GD) in deeper waters. A Trailing Suction Hopper Dredger (TSHD) will be used to rip the clay before dredging with GD. The excavated material will be loaded onto barges and transported for beneficial use to the inshore reclamation areas where it will be unloaded by small BHDs. Some 19 million m^3 of sediment will be handled.

A bedding layer of gravel will form the foundation of the elements. Each element will initially be kept in place by depositing locking fill followed by general fill. Finally, there will be a stone layer on top to protect against damage from grounded ships or dragging anchors. The protection layer and the top of the structure will stay below the existing seabed level, apart from near the shore. However, at the very nearshore area, the seabed will be raised at the coastal locations to incorporate the protection layer over a distance of approximately 500-700 metres from the proposed coastline. Here, the protection layer will be an extended armour rock layer.

Reclamation areas are planned to run along both the German and Danish coastlines to use the dredged material from the excavation of the tunnel trench. The size of the reclamation area on the German coastline has been minimised. Two larger reclaimed areas are planned on the Danish coastline. Before the reclamation takes place, containment dykes are to be constructed some 500 metres out from the coastline.

The cut & cover sections of the immersed tunnel passes through the shoreline reclamation areas on both the Danish and German sides.

Key requirements

One key requirement of this project is that it has to be designed and constructed in harmony with the landscape and its nature areas, thereby offering the opportunity to:

- Re-establish/re-generate some of the environmental values lost during the construction of major dykes and reclamation works in the early 1900s;
- Use the opportunity to create new landscapes;
- Incorporate the link into the landscape without visual harm; and
- Make sustainable options a requirement.

Another requirement was that the Fixed Link pose minimal navigation risks to the important

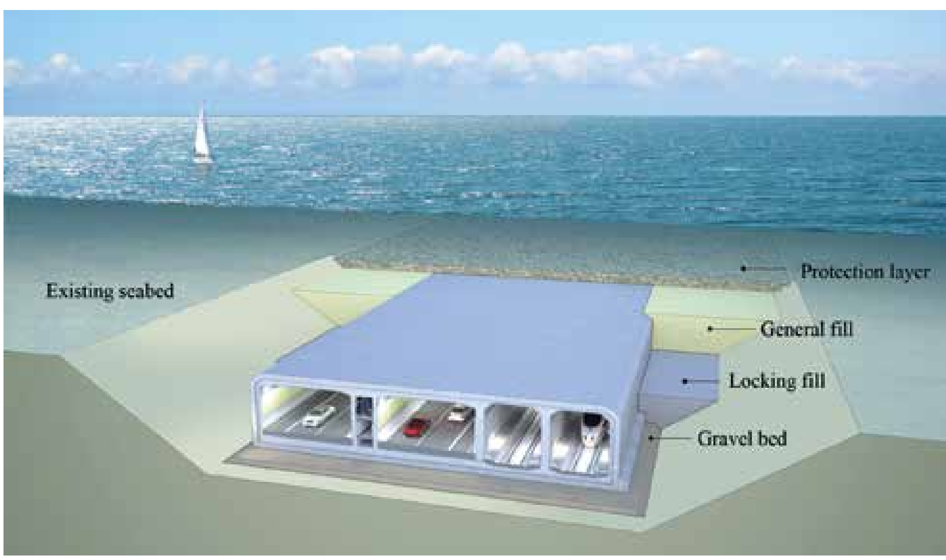

FIGURE 2

A cross section of the dredged trench with tunnel element and backfilling.

When complete, it will be the third largest marine infrastructure project in southern Scandinavia.

international navigation route connecting the North Sea and Baltic Sea. Finally, that the Fixed Link should have a minimal impact on the environment, particularly the water and salinity exchange through the project area.

Understanding the environment

To ensure the fulfilment of the above mentioned requirements, it is necessary to understand the existing environment, not only to minimise the potential impacts of the project but also to identify win-win opportunities to meet the project requirements.

A detailed two-year survey programme was undertaken using a combination of fixed measurement stations, vessel and air surveys, as well as modelling works to study the important hydraulic and ecosystem components. These included water quality, benthic flora and fauna, fish, marine mammals and seabirds. With this information, it would be possible in the first instance to identify sensitive areas. The understanding of the environment also included analysis of the potential impacts on the sensitive areas.

The effects on higher trophic levels such as birds and marine mammals were assessed based on the outcome of these simulations. Ecological modelling was used to quantify the impacts arising from spilled sediment on water quality and benthic flora. The ecological model describes the relationship between dispersed sediment spill concentrations, light availability and primary producers, between nutrients, as well as the interrelationship and interspecific competition between three distinct groups of producers: pelagic phytoplankton, benthic macroalgae and rooted vegetation.

The simulation of a realistic construction scenario for the entire construction period and of the permanent operation period of the link demonstrated that the Fixed Link could be built with only minor temporary and permanent impacts. A thorough understanding of the ecological aspects and coastal processes was important in order to identify options to regenerate the environment as well as to define sustainable coastal protection options. Understanding of the environment was a key element for the subsequent stages of the project and for selection of the preferred solution: the immersed tunnel that would provide the option of the beneficial use of

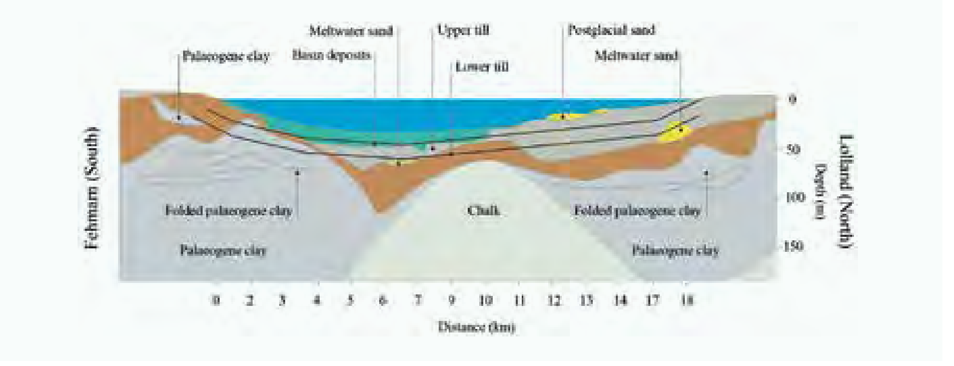

FIGURE 3

The geology of the Fehmarnbelt.

dredged material to regenerate the landscape. Some characteristic elements of the Fehmarnbelt area are described below.

Geology

The landscape of the area was shaped by ice masses mainly during the last Ice Age. Since the final retreat of glaciers from the southwestern Baltic area, the Fehmarnbelt has been characterised by highly variable sedimentary processes and environments when the outflow from the Baltic Sea to Kattegat through the Great Belt and Øresund changed position several times. The present day topography and bathymetry was formed by the last Ice Age, which ended about 10,000 Before Present [B.P.], with varying water levels in the period.

The upper subsoils in the Fehmarnbelt consist mainly of glacial meltwater sand covered by clays and topped by post glacial marine sand, gyttja and peat. Beneath these layers are mostly glacial tills – also called boulder clay or moraine clay – of different types with local pockets of meltwater sand and silt (see Figure 3). Deeper layers consist of chalk and paleogene clay that are older than the Quaternary period.

Hydrography

The Fehmarnbelt is part of the transition area between the central Baltic Sea and the North Sea. The flow and stratification in the Fehmarnbelt is highly related to water exchange between the North Sea and the central Baltic Sea. The upper water strata in the Fehmarnbelt consists of brackish water from the central Baltic Sea which, close to the surface, flows through the Belt Sea and continues up into Kattegat. A layer of water with higher salinity from the North Sea forms a lower layer.

Environment and Nature

The Fehmarnbelt is a very dynamic area in terms of water exchange and sediment transport, which forms different types of seabed substrate and forms, as well as coastal features such as cliffs and beaches.

In the shallow areas, the benthic flora is dominated by different flora communities determined by the water depth (light penetration) and substrates (mud, sand, hard bottom). Red algae communities (Fursellaria, Phycodrys, Delesseria species) are replaced in less shallow water by brown algae (Fucus Sp). In water depths over 20 metres, algae communities are rare. In wave-protected lagoons and bays, red algae are replaced by eelgrass. Blue mussels dominate along the Danish coast and are succeeded by amphipods (Bathyoireia and mussel communities (Corbula, Artcica species) in deeper water.

In terms of fish, the Fehmarnbelt is an important route for migrating cod, herring and silver eel as well as a spawning area for a number of fish species including cod and flatfish in general. In the Fehmarnbelt area, three species of marine mammals occur regularly: the harbour porpoise, the harbour seal and the grey seal. The harbour porpoise uses the Fehmarnbelt as a transport corridor whereas the seals do not, although seal haul-out sites are located over

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20 kilometres away, both west and east of the alignment.

Birds are a special issue as the Fehmarnbelt is an important migration route for both north-south and east-west migration. Many species of water birds use the areas during either winter or summer. For that reason, a number of protected habitats and bird areas have been designated. These are called Natura 2000 areas according to EU legislation (see Figure 4).

Human activity

Archaeological investigations conducted by the client reveal that the proposed alignment has been a human migration corridor over the last 6,000 years. DNA tests of archaeological finds of goat remains show that ancient human migration from central Europe to Scandinavia used the Fehmarnbelt as the main transport corridor. Today, the Fehmarnbelt is one of the heaviest trafficked waters in the world because it is the main entrance to the Baltic Sea. Ferries between Puttgarden and Rødbyhavn contributed with 35,000 crossings in 2013.

Project design to benefit navigation and nature

The conceptual design was developed by a multidisciplinary team consisting of engineers, architects, biologists, environmental engineers and so forth. The design was based on the project objectives defined in early stages of the project and the understanding of the existing environment. These, together with extensive stakeholder engagement, worked towards a design that meets the stakeholder objectives and identifies win-win opportunities. Three options initially proposed for the link (see Figure 5) include:

- a cable-stayed bridge,
- a bored tunnel and
- an immersed tunnel.

The immersed tunnel was identified as the preferred option in the light of engineering, environmental, navigational and economic considerations. A tunnel provides safe navigation conditions since it avoids potential damage and associated oil spill resulting from ship collisions with piers and other obstacles.

With respect to the landscape, the impacts of a tunnel and bridge solution differ. As opposed to the tunnel, which is submerged, a cable-stayed bridge has a clear visual impact on the entire area. On the environmental scale,

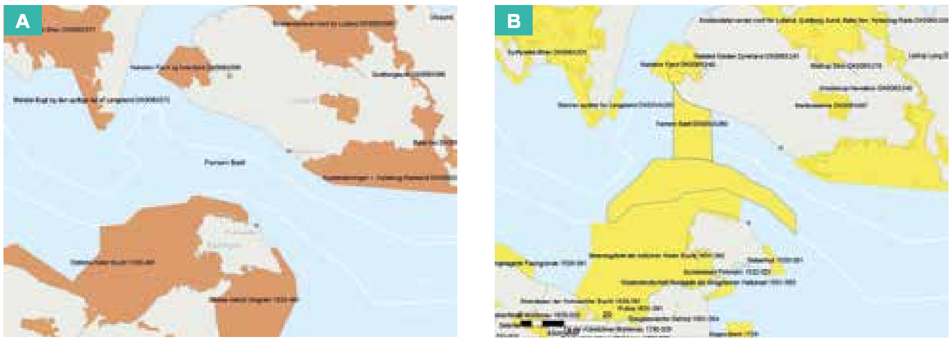

FIGURE 4

Nature 2000 areas in Germany and Denmark for birds shown in orange (A) and habitats shown in yellow (B).

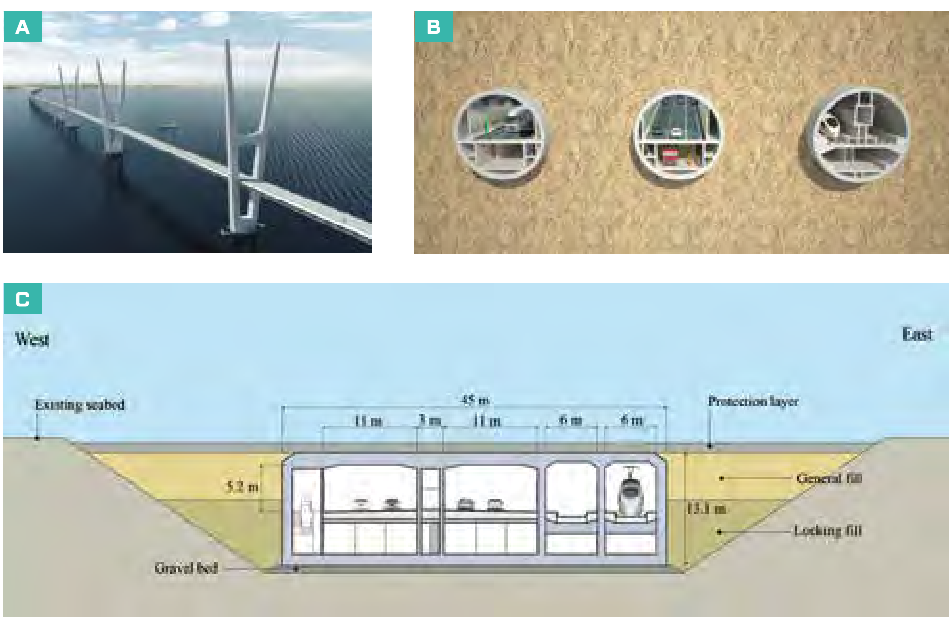

FIGURE 5

The cable-stayed bridge with two main spans of 724 metres and a navigation clearance above the sea of at least 66 metres (A). A cross section of the bored tunnel consists of three tubes. The railway tube has an internal diameter of 15.2 metres while the two road tubes' diameter are 14.2 metres (B). The immersed tunnel consists of 79 standard elements (approximately 9x42x217 metres) and up to ten special elements (approximately 13x45x39 metres) (C).

FIGURE 6

Design proposal for a land reclamation area on Lolland in Denmark.

the bridge would entail permanent barrier effects, for example on the hydrographical conditions of the Baltic Sea and bird migration in the area. The impact assessment on the surrounding Natura 2000 areas proved that the tunnel produces significantly fewer environmental conflicts than the bridge.

One reason for deselecting the bored tunnel solution was the uncertain time horizon for the possible re-usage of the bored material for land reclamation purposes, due to its slow dewatering process. Other reasons were that the bored tunnel had a larger (environmental) footprint on Fehmarn and significantly higher greenhouse gas emissions.

The immersed tunnel provided a 'win-win' solution because the 19 million m^3 of dredged sea-bed material from the tunnel trench would provide an opportunity for beneficial use. This was seen as a great and feasible opportunity to create new landscapes and re-establish some of the historical features that were lost due to coastal protection and flood mitigation works carried out in the past.

New reclamation areas add nature and recreational values

The new landscape will be shaped as a streamlined area along the existing coast to an extent similar to that of the existing Rødbyhavn harbour. This will ensure that there will be no additional blocking of the flow through the strait.

The new landscape (see Figure 6) will extend approximately 3 kilometres west of the harbour and 3.5 kilometres east of the harbour. The extent of the area is decided mainly by the volume of the surplus sediment that can be absorbed by the landscape. The western part of the reclamation area is designed with the purpose of serving recreational values whereas the eastern part – although it accommodates the tunnel portal – is designed for serving nature values.

These new features will introduce positive aspects by supplying new natural, environmental and recreational values and will partially rehabilitate an area that has suffered severely from past engineering flood protection projects. The use of this surplus sediment will allow the re-creation of features such as those discussed below.

The landscape

The new landscapes will connect the tunnel portals to the adjacent coastal areas. This will be achieved in a gradual and harmonious way, thus minimising the visual aspects via a green transition zone. On the German side the natural elevation forms a kind of hill, which on one hand will hide the portal structure from the hinterland, and on the other hand secure the tunnel portal against raising sea level and minimising the scour protection mound. In contrast to a more traditional design, the elevated landscape would probably have been removed and replaced by a rubble revetment mound. Finally, the passengers are allowed to overlook their journey across the sea.

Protected areas

The existing dyke on Lolland – which runs along the coast line – is not influenced by the new reclamation areas in front and will consequently still protect the low-lying hinterland. The reclaimed areas will be designed with different perimeter types

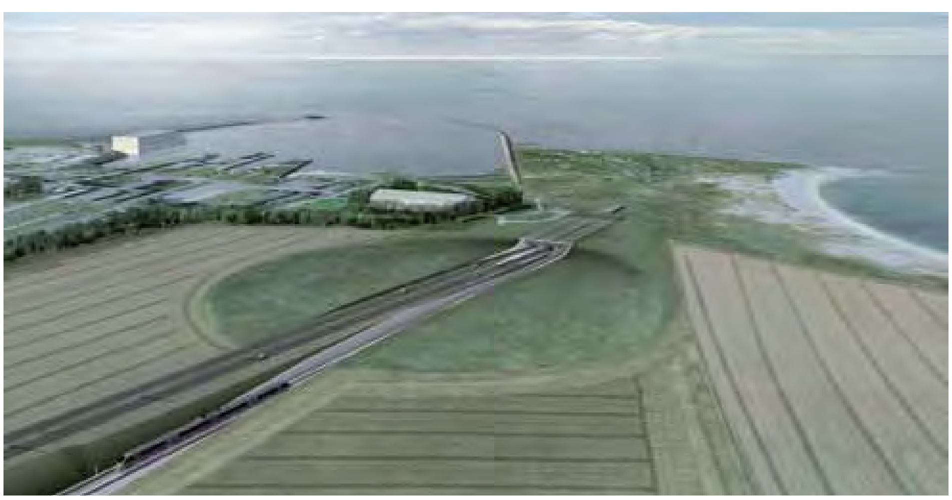

FIGURE 7

At the tunnel portal in Fehmarn, the elevated landscape was retained. No larger revetment was necessary like on the Danish side.

FIGURE 8
The portal area at Lolland is protected by a revetment.

FIGURE 9
Visualisation of the wetland in the eastern part of the land reclamation area in Denmark on Lolland. The bird island is the small island in the background of the lagoon.

dependent upon the different technical and environmental functions.

The stretch around the portal at Lolland will be scour protected. The structures are designed to minimise the visual aspects of the tunnel portal but also to protect against possible rising sea levels due to climate change.

Re-establish previous landscape

Some of the area's environmental values were lost in connection with the construction of a major dyke along the coast following a major flood event in 1872. The dyke cut off the previous shallow archipelago, Rødby Fjord and other shallow areas which were later reclaimed by the installation of a pumping station.

Artificial lagoon

Wetlands, salt meadows and grassland lost due to the construction of the new dyke will, to a certain extent, be re-established at the new land reclamation area east of Rødbyhavn (see Figure 9). Overall, it will be a 3.7-kilometre long and 0.5-kilometre wide green band featuring an artificial lagoon with two fixed openings east of the tunnel portal. The lagoon includes wetlands, a major recreational island and a small sea bird island. The vegetation in the nature and wetland areas will be allowed to develop naturally which will enhance the biodiversity of this environment.

Cliffs

The ferry harbour, Rødbyhavn, was constructed over a century ago and extends 500 metres out from the coastline. This extension has resulted in a beach with sand dunes that has built up west of Rødbyhavn but on the eastern side of the harbour, the blocking of the littoral transport has resulted in sand erosion along approximately 3.5 kilometres of the coastline

Most of the eastern area will be filled up to a level of seven metres. Natural erosion is allowed here whereby a 'natural' cliff will form and the eroded sand will be transported eastward by the predominant littoral transport (see Figure 10). This supply of sand will help to stabilise the beaches to the east, following a smooth transition area.

Artificial beaches

On the western side of the harbour, the area with its beaches will be used for recreational and leisure activities which feature a major leisure area. The recreational and leisure value will increase with the construction of the beaches and grasslands. Three artificial beaches are planned, with one at the extreme west end of Lolland and one lagoon beach in the middle plus a paddling beach close to the harbour on the Danish side. On the German side, a grassland is planned as well as a beach east of Puttgarden harbour (see Figure 11). The beaches are designed in their equilibrium orientation by fixed structures.

Reefs

Stones and boulders on the seabed form hard substrate to which sea algae will attach and start to increase the biodiversity which gradually leads to reef formations. Many of these stones and boulders have been removed for the purpose of constructing harbours, piers, revetments and so forth over the last 100 years or more. Stones and boulders large enough to create artificial reef structures will be used for the protection layer on top of the tunnel close to the coast in shallow water where there will be no barrier effect on the water exchange. If feasible, surplus 'reef-stone' from the dredging work will be placed at the Natura 2000 area, Sagas-Bank, in order to mitigate earlier stone removal over a 25 hectare area (see Figure 12).

Stakeholder engagement to identify possible win-win opportunities

Extensive stakeholder engagement was obtained for this project already from the start. The public, professionals and NGO organisations as well as authorities were invited to comment on the project. An exhaustive range of consultations (some public) was conducted along the way. This

FIGURE 10

East of Rødbyhavn's harbour, natural erosion is allowed, forming a 'natural' cliff as the eroded sand is transported eastward by the predominant littoral transport.

Understanding and mimicking nature plays a key role in the project's vision.

included the scoping process and environmental impact assessments. There were also public plan application document exhibitions.

Cross-border project consultations were conducted in both Germany and Denmark as well as one involving all the countries around the Baltic Sea (ESPOO hearing).

The outcome of this stakeholder input has had a major influence on the whole project including the marine area and the new reclamation landscapes, the marine ecosystem's functionality, the bird migration routes, and, of course, the Fehmarnbelt as a transport corridor for other marine life between the North Sea and the Baltic Sea. They are all part of both the Danish and German plan approvals which have been granted.

Conclusions

The Fehmarnbelt Fixed Link is an outstanding example of the application of the Working with Nature principles for large marine infrastructure projects. The construction of the project is planned to start in 2020. The main features of the project can be summarised as:

- The proposed marine and landscaping are a win-win situation discussed and proposed during the stakeholders engagement;
- 19 million m^3 of dedged material will be used to create new landscapes;
- These will add new nature, environmental and recreational services much to the public needs and requirements;
- Understanding and mimicking nature plays a key role in the project's vision; and
- The immersed tunnel avoids long-term over-water disturbance of the aquatic environment.

FIGURE 11

Aerial perspectives of the new western beach section with dunes at Lolland, east of Puttgarden harbour.

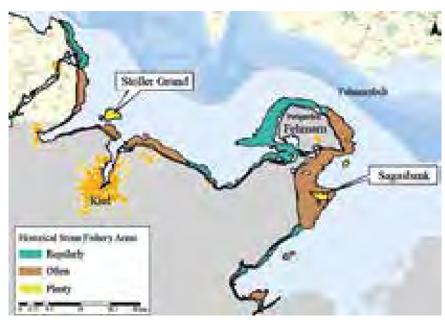

FIGURE 12

Sagasbank, Germany has suffered from intensive stone fishery and 25 hectares will be re-established.

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Summary

The proposed landscaping for the Fehmarnbelt Fixed Link – an immersed tunnel which will provide a transit connection between Germany and Denmark – is considered a 'win-win' situation by using the surplus of 19 million m^3 of dredged material generated by the project. This dredged material will be utilised to create new landscaping features that will add a positive impact to the project in the form of providing 'natural' landscape elements. Ranging from lagoons to beaches and reefs, these features will bring new natural, environmental and recreational values to the area, and rehabilitate areas which have long been blighted by engineering projects in the past.

At the 34th PIANC World Congress 2018, Femern A/S was granted the accolade of 'Supporter of Working with Nature' because of its incorporation of environmental considerations into the Fehmarnbelt Fixed Link's conceptual design.

Anders Bjørnshave
Anders Bjørnshave, M.Sc., has decades of experience in project management for large-scale construction projects around the world. As Head of the Environmental Department at Femern A/S, he conducted the vast environmental impact assessment of the Fehmarnbelt Fixed Link. He served as Chief Technical Adviser for a large environmental donor programme in Egypt and has in-depth experience of foreign investors' environmental performance and compliance in developing countries. In addition, he has years of hands-on experience in the remediation of soil and groundwater contamination from oil stations, oil depots, airfields and military bases in Europe.

Ian Sehested Hansen
Ian Sehested Hansen has over 30 years' experience in mathematical modelling in environmental hydraulics and water quality assessments as well as operational forecasting of marine hydrodynamics and water quality conditions. He has experience in estuarine/marine conditions in the tropics – especially the waters of Dubai, Hong Kong and Lake Maracaibo in Venezuela – as well as estuarine dynamics and water quality from several Danish and international projects. He serves as project manager for several large consulting and research projects including the EIA service to Femern A/S for the Fehmarnbelt Fixed Link since 2009.

Victor Magar
With more than 20 years of environmental engineering experience, Victor Magar, PhD, PE, has expertise in sediment management, hazardous waste remediation, contaminant fate and transport, contaminant transformation processes, and technology evaluation, testing, and selection. He serves as a lead civil/environmental engineer for sediment and marsh restoration projects, responsible for managing client services in contaminant assessment, monitoring, and remedy selection and implementation. He chaired PIANC Working Group 176 to develop PIANC's *A Guide for Applying Working with Nature to Navigation Infrastructure Projects* released in 2018.

Juan C. Savioli
As head of the Coastal and Marine Department of DHI Water & Environment Malaysia, Juan Savioli has over 20 years' experience in the application of numerical models in coastal and marine projects, and gained a deep understanding of the evaluation, modelling and analysis of flows, waves, and sediment transport processes. His expertise lies in coastal developments where reclamation, dredging and sedimentation processes are evaluated for their design and optimisation, and believes concepts such as Working with Nature can be applied to benefit coastal developments. He was part of PIANC's Working Group 176 which produced *A Guide for Applying Working with Nature to Navigation Infrastructure Projects*.