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**Immersed Tunnels: Competitive tunnel technique for long (sea) crossings**

Specific topic: Immersed Tunnels

**Summary:**

Traditionally immersed tunnels are applied for river crossings and often in delta areas and in soft soil conditions. In countries like the US, Japan and the Netherlands the immersed tunnel technique is quite mature and common practice. However, over the past years there is also a growing interest for this technique in other countries. Recent tunnel projects have shown that immersed tunnels are feasible and competitive under more challenging circumstances. Immersed tunnels have been constructed successfully in water depths up to 58 m below sea level, in very poor soil conditions, with increasing lengths, increasing design lives and in offshore conditions.

Immersed tunnels are very flexible and suitable for the implementation in an urban road network, but they can also be designed to fulfil special purposes such as the crossing of a runway on an airport to reduce the construction time (Schiphol Airport, Amsterdam) or to serve as a metro platform tunnel beneath the historic Amsterdam railway stations (see figure 1).

![Figure 1: Immersed tunnel as metro platform tunnel underneath historic railway station](image)

In the nineties of last century the first steps were undertaken to apply immersed tunnels for longer crossings and under off shore conditions. In the Netherlands and Australia immersed tunnel elements were transported off shore (Sydney Harbour Crossing, Wijkertunnel and Piet Heintunnel) but still immersed under “in land” waterway conditions. The Øresund Link in Denmark was the first major tunnel crossing in which the immersed tunnel technique was applied off shore, although the conditions were still relatively favourable. However, in some fields new developments were necessary to make the immersed tunnel feasible and competitive. In any case this project was a major step forward for the immersed tunnel technique. It appeared that in more recent projects step by step new challenging conditions were faced, at the same time increasing the field of application of the immersed tunnel technique. In the Busan Geoje Fixed Link in South Korea (figure 2), tunnel elements were transported and immersed under adverse off shore conditions. In addition the foundation design had to accommodate very poor soil conditions using large scale soil treatment.

Today in Europe and China long immersed tunnels with total lengths over 5 km and even approaching 20 km (Fehmernbelt Link Denmark, figure 3) are being designed and considered competitive to bored
tunnels and even bridges. This is especially the case for multiple lane road tunnels or for tunnels in which road and rail traffic is combined, resulting in relatively wide tunnels. But, where in the past most attention was paid to the traditional civil engineering issues, in nowadays major (sea) crossings special design approaches are required and therefore a focus on multi disciplinary issues.

In long crossings tunnel safety becomes a very important issue, quite often not covered by codes and standards. That means that state of the art and project specific tunnel safety concepts (including ventilation design) have to be developed, that have to be discussed and agreed with the local authorities. Also the availability of such a link has become important, considering the investments that have to be done for the realization and operation. This means that efficient operation and maintenance strategies have to be developed to ensure these primary links remain operational during inspection and maintenance, with greater emphasis on adequate design solutions and material selection. Obviously a tunnel already has an advantage in relation to a bridge due to the fact that driving conditions are more sheltered regarding adverse weather circumstances.

Although more issues have to be addressed in long (sea) crossings, the traditional civil engineering issues often include major challenges. Especially in the long to very long crossings special attention has to be paid to the construction schedule to enable construction in an acceptable period of time. E.g. use is made of the factory based construction methodology for the tunnel elements that was developed for the Drogden tunnel (approx. 3.5 km) in the Øresund Link. In addition in long links more variable ground conditions may be encountered. In recent projects soil treatment methods were developed to accommodate adequate foundation conditions for the immersed tunnel elements, still resulting in competitive design concepts.

In immersed tunnel projects significant dredging operations need to be carried out. Of special importance are the inevitable environmental issues related to these dredging operations. But equally important is that these environmental issues are addressed and placed in the right perspective. For the Fehmernbelt tunnel special attention is paid to this issue in prescribing the use of dredging equipment limiting the environmental impact and the identification of compensation measures that have been included in the design. Land reclamations are realized with the surplus of dredged materials and designated as nature protected area and for recreation purposes.

Fig 2. Busan Geoje South Korea  
Fig 3. Fehmernbelt Link, Denmark

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Immersed Tunnels: Competitive tunnel technique for long (sea) crossings

Introduction

The rapid expansion of global economy has increased the need for a good quality (international) transport network. Natural boundaries and obstructions such as sea straits, large estuaries and in land water ways can increase costs and time for transportation. In many cases the realization of a fixed link can improve the conditions for transport and relieve the existing road network.

Traditionally large (sea) crossings are carried out by means of the apparent most economic option: by means of a bridge. If a tunnel option is considered, at first glance the bored tunnel seems favourite, most of the time from a perspective of being familiar with the technique. The last decade new developments and innovations have lead to the revival of the immersed tunnel as a competitive alternative for large fixed links. The Øresund Link between Denmark and Sweden gave the immersed tunnel technique the first boost towards revival, rapidly followed by other major links in which the immersed tunnel technique is applied on a large scale. The last impressive example is the Fehmernbelt Link, the link between Denmark and Germany comprising an immersed tunnel of almost 19 km.

In this paper the developments over the last decade are described and explanations are given for the fact that an immersed tunnel can be competitive in many fixed link projects. Some of the major projects are briefly described to illustrate the potentials of the immersed tunnel for major strait crossings. In addition an example is given for a special application of the immersed tunnel technique in the Amsterdam metro.
General description of the immersed tunnel technique

Immersed tunnels consist of large pre-cast concrete or concrete-filled steel tunnel elements fabricated in the dry and installed under water. More than a hundred immersed tunnels have been built worldwide to provide road or rail connections. Tunnel elements are fabricated in convenient lengths on shipways, in dry docks, or in improvised floodable basins, sealed with bulkheads at each end, and then floated out. They have been towed successfully over great distances. Arrived at the project location additional outfitting may be required at a pier close by.

Then they are towed to their final location, immersed into a prepared trench, and joined to previously placed tunnel elements. Since dredging tolerances generally do not meet the foundation design requirements, additional foundation works are required. The tunnel elements can be installed on a pre-installed gravel bed or after the immersion of the tunnel element on temporary supports, the gap between the tunnel base and the trench is filled with sand using the sand flow method. After additional foundation works have been completed, the trench around the immersed tunnel is backfilled and the water bed reinstated. The top of the tunnel should preferably be at least 1.0-1.5 m below the original bottom to allow for sufficient protective backfill. However, in a few cases where the hydraulic regime
allowed, the tunnel has been placed higher than the original water bed within an underwater protective embankment.

Fig. 5 Tunnel element at project location
(Busan Geoje, South Korea)

Figure 6: Tunnel element during immersion
(Busan Geoje, South Korea)

Immersed tunnel elements are usually floated to the site using their buoyant state. The ends of the tunnel elements are equipped with bulkheads (dam plates) across the ends to keep the inside dry, located to allow only about 1.0 m between the bulkheads of adjacent elements at an immersion joint; this space is emptied once an initial seal is obtained during the joining process. The joints are usually equipped with gaskets to create the seal with the adjacent element. They are also equipped with adjustment devices to allow placement of the elements on line and grade. The tunnel elements will be lowered into their location after adding either temporary water ballast in designated water ballast tanks. After the installation of the back fill, the ballast water will be exchanged with ballast concrete, generally installed on the tunnel base slab. Subsequently the finishing of the tunnel can take place such as road paving, tunnel installations etc.

Figure 7: Typical cross section immersed tunnel (concrete)

**Historic perspective**

Basically, there have been two traditions in immersed tunnel design: The American and the European. The difference between them focuses on the selection of the construction material; steel in the USA and concrete in Europe. Within this tradition, local economics and specific project conditions also play their role in determining the choice between steel and concrete.

The history of immersed tunnels for transportation started in 1910 with the construction of a two track railway tunnel under the Detroit River between the USA and Canada. It was 30 years before any immersed tube tunnels were built outside the USA, and during the period American engineers
developed a specific steel shell technology (single and double shell). Steel tunnels use structural steel, usually in the form of stiffened plate, working compositely with the interior concrete as the structural system or using concrete for ballast purposes. The steel immersed tunnel elements are usually fabricated in ship yards or dry docks similar to ships, launched into water and then outfitted with concrete while afloat. Steel tunnels can have an initial draft of as little as about 2.5m. This technology – largely unchanged today - is still used for almost all US immersed tunnels. There are only a few exceptions, the most recent being the Fort Channel Tunnel in Boston. Currently the construction of a new concrete immersed tunnel in West Virginia is being prepared.

![Figure 8: Launching of steel tunnel element](image1)
![Figure 9: Transport of steel tunnel element](image2)

The first concrete tunnel in Europe was the Maastunnel at Rotterdam in the Netherlands, built between 1937 and 1942. Its construction marked the start of a new tradition of using concrete for immersed tube tunnels. Concrete immersed elements are usually cast in dry docks, or specially built basins, then the basin is flooded and the elements are floated out. Concrete tunnels usually have a draft of almost the full depth. This European development has been stimulated and concentrated in the Netherlands (figure 10) and even now, no real steel immersed tunnels have been constructed in Europe. A composite steel/concrete immersed tunnel has been used for the Marmaray tunnel in Turkey, crossing the Bosporus between Asia and Europe.

![Figure 10: Immersed tunnel in Europe](image3)
![Figure 11: Marmaray Crossing, Turkey](image4)

A third focal point for immersed for immersed tunnel technology lies in Japan, where construction started in 1944 with the Aji River Crossing in Osaka. For this tunnel the single steel shell of the USA tradition was adopted and it was not until 1969 that a concrete tunnel was constructed in Japan. Since then, both steel and concrete tunnels have been built, with steel remaining in the majority.
Why and when is an immersed tunnel competitive?

Immersed tunnel do not suit every situation. However, if there is water available (to cross or to use as a transport medium) they usually present a feasible alternative to bored tunnels at a competitive price. They offer a number of advantages such as:

1. Immersed tunnels may have special advantages over bored tunnels for water crossings at some locations since they lie only a short distance below water bed level. Approaches can therefore be relatively short. Compared with high level bridges or bored tunnels, the overall length of crossing will be shorter.

![Figure 12: Comparison Link options](image)

2. Immersed tunnel do not have to be circular in cross section (such as bored tunnels). Almost any cross section can be accommodated, making immersed tunnel particular attractive for wide highways and combined road/rail tunnels.

![Figure 13: Possible cross section shapes for immersed tunnels](image)

3. Immersed tunnels can be made to suit most horizontal and vertical alignments. They can be constructed in soils that would preclude bored tunnels or make it very challenging and expensive such as the soft alluvial deposits in large river estuaries. Immersed tunnel can be designed to deal with seismic conditions.

4. Bored tunnelling is a continuous process in which any problem in the boring operation threatens to delay the whole project. Immersed tunnelling involves more operations, such as element construction, dredging and tunnel installation, which can take place concurrently or overlapping, thus resulting in a more robust project planning. Partly for this reason, an immersed tunnel is generally faster to build than a corresponding bored tunnel.
Disadvantages and prejudices
Immersed tunnels are often perceived by many, not particular familiar with the technique, as “difficult” due to the presence of marine operations and consequently the interference with navigation and the environmental impact. In reality though, the technique is less risky than bored tunnelling and the construction can often be better controlled. The marine operations pose no special difficulties but careful consideration is recommended especially with regards to shipping and environmental impact.

Immersed tunnels may have potential disadvantages in term of environmental disturbance to the water body bed. They may have impact on fish habitats, ecology, current, and turbidity of the water. Trench excavation in any waterway is an environmentally sensitive issue. Once the environmental conditions have been set by the planning and permitting process, care should be taken to meet these conditions. However, dredging technology has improved considerably in recent years, and it is now possible to remove a wide variety of dredged material without adverse effects of the waterway. Special requirements to handle the disposal of dredged materials are usually specified. Contaminated materials must be disposed of in special spoil containment facilities, while uncontaminated materials, if suitable, can be reused for backfill. The increase in dredging and disposal costs over the past three decades due primarily to continually tightening environmental restrictions present significant challenges to the disposal of unwanted material. In recent projects more and more attention is paid to the reuse of dredged material in the project as much as possible. Unique solutions were developed for various projects including: the use of the dredged materials to construct a manmade island such as for the Second Hampton Road Tunnel in Virginia or the Øresund Link in Denmark or to reclaim a capped confined disposal facility as a modern container terminal such as the case of the Fort McHenry Tunnel in Baltimore.

The most common method of excavation for immersed tunnels is the use of a clamshell dredger. Sealed buckets should be used for contaminated materials and/or to reduce turbidity in environmentally sensitive areas. Cutter suction dredgers have also been used and are able to remove most materials other than hard rock. Blasting may be required in certain areas, though it is highly environmentally undesirable.

Furthermore, impacts on navigation in all navigable waterways should be considered and often permitting would be required. Although it is sometimes assumed that immersed tunnelling would be impractical on busy water ways, such tunnels have been successfully built in some exceptionally busy water ways without undue problems. Obviously a good communication with the Port Authorities is essential.

Projects
In the following projects that are presented demonstrate the recent developments in immersed tunnels as competitive construction technique for major sea crossings.
Øresund Link, Denmark

Introduction
The Øresund Link, the first major sea crossing using the immersed tunnel technique, is a tunnel and bridge connection between Denmark and Sweden. This 16.7 km long link is a direct traffic and train connection between Copenhagen and Malmö. The tunnel is located at the western side of the Link, with the tunnel entrance next to Copenhagen airport. The transition between the tunnel and the bridge is accommodated by means of a large artificial island approx 4 km long and south of Saltholm. At the Denmark shore a significant land reclamation extending 430 m in the sea was established. The Øresund Link promoted the immersed tunnel technique as a serious option for sea crossing.

The immersed part of the tunnel has a length of 3500 m and runs under the Drodgen Channel. The tunnel is divided into 20 elements, each 176m long; each element is made up of 8 segments of 22m each. The tunnel includes two railway tubes, two motorway tubes and an escape gallery. The outer dimensions of the cross section are 8.5m by 41.7 m.

Innovative concepts
The Øresund Link is special and in a number of ways extending the possibilities for the immersed tunnel technique for major sea crossings. The size of the tunnel project, the tight construction schedule and the environmental conditions urged for new innovative concepts to be introduced:

1. A new factory production method for tunnel elements was developed using full section casting which resulted in high quality concrete works in a tight but feasible construction schedule. Concrete immersed tunnels are traditionally constructed by preparing a large (often temporary) excavation in which the tunnel elements are constructed (e.g. fig. 2). The excavation has to be below the water level, so that it can be flooded once the tunnel elements are complete, to allow them to be floated out to their final location. For a tunnel like the Øresund this method would have involved a huge excavation and extensive water level lowering for a period of years. A basin large enough for all elements would be too expensive; the re-use of a smaller facility for more separate batches was possible but appeared disadvantageous for the progress and the continuity of the project. A new and unique construction method was developed. It comprises a factory construction
of all tunnel concrete without resorting to a large excavation, casting the tunnel elements in a single 30 hour concrete pour, full off line prefabrication of the reinforcement cages and transportation of completed tunnel elements some 300 m, sliding over skidding beams into the basin. Then a sliding gate is close between the factory and the element. Water is impounded within the dock to about 10m above sea level, allowing the tunnel element to float. It is then winched into deep water of the basin and lowered into the sea using the same principle as a ship lock. Whilst the completed element is being immersed in this way, the factory is able to continue with the construction of further tunnel elements.

Figure 16. Aerial view factory and reinforcement prefabrication

Together with factory facility development a full section casting was studied in order to limit early age stresses, particularly those associated with thermal effects. Traditional construction of tunnel elements, in which the tunnel cross section is cast in three stages involves this early age stress issue, since the first cast base slab constraints the later cast wall concrete, resulting in tension stresses in the walls that can cause through section cracking, resulting in leakage. These are normally mitigated by cooling the concrete during the hardening process of the concrete using cats in water pipes. The construction method chosen for the Øresund tunnel largely avoids this problem by casting each tunnel segment in a single pour (2600 m³ in about 30 hours) in which artificial cooling was not required. However, careful consideration was still needed for early age stress management. This included concrete mixture selection, pour sequence, ambient temperature control in the factory, selective insulation of the concrete and timing of all aspects of the production of a segment (pour, strip and jack sequence).

2. For the foundation of the tunnel elements the concept of a gravel bed installed in individual berms was developed and applied with great success resulting in very accurate installation tolerances.

Several options for the foundation construction were studied. A sand flow foundation was found less suitable for the off shore conditions and a screeded gravel bed, of the type traditionally used for steel tunnels, was rejected since normally achievable level tolerances on such a bed would introduce unacceptable stresses into the relatively wide concrete box.

Figure 17 Multi purpose pontoon for gravel bed installation
Special equipment was developed to meet the design requirements for gravel bed installation. The basic principle for placing the bed is to feed the gravel down a pipe directly into position on the trench floor. The lower end of the pipe is equipped with a screeding plate, leaving the level the top of the gravel at the correct level as it is placed. The process is continuous and there is no secondary screeding operation. The feeder pipe is mounted on a multi purpose pontoon, fixed temporarily in position by spuds. The system appeared capable delivering an overall level accuracy of ±25 mm from the design line throughout. This is achieved by a laser levelling system linked to hydraulic cylinders on the feeder pipe.

Environmental issues were considered to be of utmost importance. Special dredging methods were applied reducing the spillage of dredged material to a minimum. Continuous monitoring was carried out during the dredging operations to make sure the environment spillage requirements were met. At the same time dredged material was used to create the artificial islands.

In addition the blockage effect or flow restriction of the new link on the hydraulic condition of the Øresund had to be minimized (close to zero). This resulted in a design in which the artificial island was situated in the lee of Salthom, the natural island in the Oresund and by using compensation dredging of about 2.3 million m³.
Busan Geoje Crossing, South Korea

Introduction
Since 2010 a Fixed Link is connecting the south eastern part of South Korea between Busan, the country's second largest city, and Geoje Island a road connection. The Link comprises amongst others two cable stayed bridges and a concrete immersed tube tunnel, comprising 18 tunnel elements with a length of 180m. The immersed tunnel is one of the longest (3.2 km) and deepest (maximum water depth of 48 m) in the world.

Figure 20. Location of the project

In the main navigational channel between Daejuk island and Gaduk island no limit in height was acceptable; therefore a tunnel was the only possible solution. Initially a bored tunnel was studied as well. But the relative steep shores of the islands island and the deep position of a bored tunnel of about 25 to 30 m below the seabed made it physically impossible to fit an alignment for a bored tunnel in between these two islands and connect it with the adjacent bridge alignment. The gradient of the alignment would be too great and slopes too long for driving comfort and safety. For this reason the crossing by an immersed tunnel with its’ position just below the seabed was a logical choice.

Extreme design conditions
The project had to deal with a lot of challenging boundary conditions:
1. The geotechnical conditions at the project location are not very favorable. Marine clay forms the seabed along the tunnel alignment except the shore areas where outcrops of bedrock and shallow sand and gravel layers are found. The thickness of the marine clay exceeds 20m along most of the alignment and locally reaches a thickness of 30m, and this layer will form the foundation of the tunnel.

Figure 21. Indicative Geotechnical profile
2. The site is exposed to the Pacific Ocean via the Korean Strait and the East China Sea at the south. This affects the marine conditions on site. The exposed location at the end of an estuary in a typhoon area results in significant wave heights up to 8m and currents up to 2 m/s. Offshore conditions involve current, wind waves and swell waves which make the transport and immersion of the tunnel element delicate stages.

3. Seismic conditions; according to the Korean “Research on Earthquake Design Standard” the Busan Geoje Fixed Link is classified as an aseismic grade I structure with regard to the importance level. The seismicity of South Korea is mainly governed by the Tsushima offshore and the Yangsan onshore fault systems located in the depression between the Pohang Bay and Busan. However, only few major events have been recorded on those faults. This explains why, on a large scale basis, seismic hazard analysis leads to low hazards for Korea. Nevertheless a two-level earthquake hazard design approach has been developed. The two levels are the operating design earthquake (ODE) and the maximum design earthquake (MDE).

**Production of tunnel elements**

The construction of the tunnel elements is carried out in a temporary precast yard on the western side of the Jinhae Bay, about 40 km from the immersion area. The casting of the tunnel elements is carried out in two batches of four and two batches of five tunnel elements. The first 16 tunnel elements are 180 m long, 10 m high, 26 m wide and weigh about 48,000 tons. The tunnel elements are closed off with steel, reusable bulkhead panels on both ends.

![Figure 22. Tunnel elements production and temporary mooring location](image-url)

After finishing each batch, the precast yard is flooded and the dock door is removed. The tunnel elements are floated up and trimmed one by one. Once the tunnel element has been transported through the dock gate, four tug boats are used to transport the tunnel element to the nearby mooring location, where a maximum of six tunnel elements at a time can be stored. The tunnel elements are stored in floating conditions. Due to the sheltered area of the mooring location, the tunnel elements are not affected by swell waves and can be stored there throughout the year, even in the typhoon season.

The high water pressure of over 40 m on the concrete segmental tunnels is nearly twice as high as for more common immersed tunnel projects. The stringent water tightness requirements which are set for this project are:

- The cross section is designed in such a way that there is always a sufficient compressive zone.
- The concrete is casted in one continues pour, which reduces the risk of early age cracking (through section cracks).
- At the segment joints a second watertight barrier is installed. Next to the injectable waterstop an small size omega profile is installed. This was also the reduce the risk for leakage due to a seismic event.

**Offshore Transport and Immersion**

Offshore conditions involve current, wind waves and swell waves. Especially the swell waves are dominant in the design of the immersion system. Swell waves are long-crested, uniformly symmetrical...
waves that have travelled outside the area of their origin. Swell waves travel vast areas of the ocean and they become grouped by their wavelength. Because swell waves have relative large wave length (>>50m) the long lined tunnel elements are more susceptible for these types of waves.

The experience of performing the immersion operations under these offshore conditions is unique and a mayor challenge for the Busan Geoje Fixed Link project. It required newly designed innovative solutions which can deal with these conditions.

An important consequence of the offshore conditions for the Busan Geoje Fixed Link project is the presence of large hydrodynamic loads during the immersion process (mainly from swell waves), while the tunnel element is suspended to the immersion pontoons. To create a more controlled situation the immersion contractor Mergor developed an alternative system, the External Positioning System (EPS). With this system the tunnel element is placed on a gravel bed on a safe distance of the previously immersed tunnel element. With this underwater jacking system the tunnel element is lifted and moved forward in a fully controlled situation. After emptying the immersion chamber, horizontal jacks can be used to re-align the tunnel element.

![Figure 23. External Positioning System](image1)

The survey of an immersion operation is traditionally carried out with alignment towers with measuring prisms and total stations on the shore line. Due to the long distance and the great depth a new underwater survey system has been developed. The new system consists of a combination of new and existing techniques, with an increasing accuracy from the transport phase up to the joining of the tunnel elements. New measuring techniques are a GPS system on the immersion pontoons during transport, a taut wire system which reads the position between the primary side of the tunnel element and the previously immersed tunnel element, an acoustic survey system which consists of a transducer and several transponders, and distance sensors which are mounted on the bulkheads and touches the previously immersed tunnel element after the tunnel element is positioned on its foundation.

![Figure 24. Immersion of tunnel element](image2)
Foundation of the tunnel

The slightly over-consolidated soft clay has a very high plasticity and consists of internal chalk compounds, which acts relatively stiff under low stresses. For the Busan Geoje Fixed link project the typhoon and the seismic conditions result in a high density backfill material on top of the soft marine clay, which results in high bedding pressures. When the chalk compounds in the clay are broken due to higher stresses the clay will behave extremely soft. These soft soil conditions results in differential settlements which are too high, therefore the soil needs to be improved. For this project a soil treatment of Deep Cement Mixed piles was used to mitigate these large settlements and to avoid the opening of joints. The CDM piles extend to just above the bed rock.

Figure 25. Typical cross section of immersed tunnel with CDM ground treatment

Close to island the tunnel protrudes above the sea bed (see also figure 21) to meet alignment requirements in relation to the adjacent bridge sections. This results in a high additional surcharge load on sea bed level. Taking into account the soft soils and the fact that the rock level is varying at this location it was decided to improve and uniform the soil properties by means of sand compaction piles in combination with a preload that represented the final situation.

Figure 26. Sand compaction piles, typical cross section and installation
Hongkong Zhuhai Macao Link, China

Introduction
Currently, one of the world's most challenging infrastructure projects, the Hongkong Zhuhai Macao Bridge Link (HZMB) is under construction. The main project covers the offshore section of the HZMB Link of approx. 30km, crossing the Pearl River Estuary from the border with Hong Kong to Macao and Zhuhai (Mainland China). The Link comprises various bridges, artificial islands and tunnels. The Link will accommodate a dual carriageway with 3 traffic lanes in each direction. To allow the passage of sea going vessels major cable stayed bridges will be included in the Design of the Link. The crossing of the main shipping channels at the eastern side of the Pearl River Estuary will be realised using a 6.75km long tunnel, of which approx. 6km will be immersed. The transition from the bridges to the tunnel will be realised with artificial islands with a length of 625m each.

Challenges in the design
Especially the tunnel part is extending the possibilities of immersed tunnelling for the near future. The tunnel will be placed at a very deep level, and consequently has to accommodate large water and ground loads. The varying soft soil conditions and adverse marine environment, the offshore conditions for transport and immersion and last but not least the 120 years design life in adverse marine conditions meant that a number of design challenges had to be properly addressed.

This is also the case for the artificial islands that form the transition between the bridges and the tunnel. The islands are constructed in very soft soil conditions and required special construction techniques that were developed by the contractor. A special point of attention was the blockage effect / flow restriction due to the realization of the islands and that was required to stay below the 5%. The shaping of the islands appeared to be important.

Tunnel Design
The tunnel structure design was faced with a set of challenging design requirements and boundary conditions:
1. The three lane road design requires large spans for the traffic tubes of 14.55m.
2. The tunnel is placed at a deep level of 29 m below the lowest design sea level, to allow the future passage of 300.000 tons oil tankers in two navigation channels with a total width of 2.810m. Since
the navigation channels will only be dredged in the future the immersion trench is allowed to fill with sedimentation up to the existing sea bed level, which means a ground cover that can exceed 20 m.

3. The geotechnical conditions are relatively poor and variable. The seabed level in this area varies between -8m and -15m. Holocene soft deposits of a thickness from 10-25 m are found below the seabed and overlying Late Pleistocene (over consolidated clays, sands and gravel) with a thickness that varies between 37m and 102m (locally). Underneath the Pleistocene deposits rock / granite is encountered.

Figure 28. Indicative geotechnical profile

Indicative analyses which included soil structure interaction had shown that direct foundation of the tunnel element in the soft layers was only possible when ground treatment was introduced. In this way the settlements and differential settlements can be limited and therefore the internal design forces in the tunnel. In addition ground treatment is applied to promote smooth transition from one tunnel part (e.g. piled cut and cover tunnel at the islands) to the other (e.g. immersed tunnel). Replacement of soft layers by gravel is applied where the soft layers are thin. On other locations where the thickness of the soft layer is large, sand compaction piles are applied. The replacement ratio varies from 70% to 40%.

The fact that the tunnel element must be able to float during transport and immersion stages implies that there are limitations to the structural dimensions as they determine most of the weight of the (floating) tunnel. For the cross section design the conventional reinforced concrete option was compared with an option with post tensioning in transverse direction (in roof and base slab). Finally it was concluded that the conventional reinforced option was still preferred when considering costs, risks and the execution of the works.

Figure 29. Typical Cross Section Immersed Tunnel (outer dimensions approx 11.5m * 38 m)

Based upon the various studies, it was concluded that the segmental tunnel was more economical and capable to accommodate the adverse geotechnical and surcharge conditions and impact of the accidental load cases.

**Offshore conditions:**
Since the project site is located offshore, the transport and immersion phase of the tunnel elements have to accommodate offshore conditions. The immersed part consists of 33 tunnel elements, of which most have a length of 180 m. With the cross sectional dimensions of 11.5 * 37.95 m the elements will
become the largest concrete tunnel elements in the world. The offshore transport and immersions stages are essential for the tunnel element design and challenging from a risk point of view. This amongst others includes the selection of the tunnel element production location, the design wave and wind climate conditions and many others.

The tunnel elements will be built in a construction dock located at some 10 km of the project site and during the transport and immersion stages adverse wave conditions may be encountered. For the transport and immersion design of the immersed tunnel elements the design forces during the various stages (bending and torsional moments, shear and normal forces) have to determined stages and the stability of the floating body has to be considered, where dynamic influences obviously are involved.. It was decided to develop an advanced numerical model in combination with physical model test (figure 30). By using the results of the physical model tests the numerical models can be validated and used for various parametric studies (e.g. variation in wave conditions) and alternative execution stages.

![Figure 30. Physical model test of transport and immersion phase](image)

Developing an optimal transport and immersion design means that a balance needs to be obtained between structural capacity (quality), acceptable risks and costs. Therefore a design philosophy will be applied in which use is made of a decision model based upon a wave forecast system, in which numerous wave data are collected. With these data and the weather forecast a go / no go decision can be made for every transport and immersion operation, thus limiting risks and enabling design optimizations. This approach was successfully applied at Busan Geoje in South Korea.

**Island Design**

In the HZMB Link the transition between the bridges and the immersed tunnel will be realized by means of artificial islands. The islands are approximately 625 m long and 160 m wide. At the islands also the technical service buildings for the tunnel are located. In figure 10 the general lay out of the islands is presented.

![Figure 31. Illustrations artificial islands and tunnel entrance (on island)](image)

As for the tunnel the geotechnical conditions for the construction of the artificial islands are not very favourable. Since large land reclamations and extensive back fill operations are involved the geotechnical design is quite delicate in order to meet the settlement requirements that were defined.
The design of the islands includes:
- Excavate soft top layers of mud
- Sand compaction piles to improve underlying cohesive layers
- Installation of circular steel cylinders as retaining structures
- In fill with coarse sand to be compacted
- Construct cut and cover tunnel founded on bored piles
- Formation of the sea defence walls consisting of rock layers and revetments of doloses
- Finishing works

![Figure 32. Illustrations artificial Island](image)

**Ventilation concept**

The length of the sub-sea tunnel, which stands at +6km, poses specific challenges while considering tunnel safety. Tunnel ventilation is an essential item of the tunnel safety concept when it comes to the operational phase and regarding incident control. A ventilation concept has been selected with longitudinal ventilation in the operational phase (jet fans supported by natural ventilation induced by the piston effect and enhanced by the traffic). In case of a fire a parallel smoke extraction system will be activated using a semi transverse ventilation system including a separate smoke extraction cell (located above the escape cell) combined with an additional system like foam mist fire extinguishing system or a sprinkler system.

![Figure 33. Construction of artificial island steel cylinders and preparation cut & cover tunnel](image)

![Figure 34. Ventilation principle in operation phase and during a fire](image)
Making use of previous developments
Although a lot of challenges had to be met, in this project use could be made of the experiences that were developed in other major immersed tunnel projects:
- Factory production of tunnel elements as was developed for the Øresund Link
- Full section casting as was developed for the Øresund Link and applied for the Busan Geoje Link.
- Soil treatment concepts with sand compaction piles as was used for Busan Geoje
- Offshore transport and immersion experiences as were developed for the Piet Heintunnel and Wijkertunnel in the Netherlands and the Busan Geoje Link in South Korea.

Figure 35. Construction of tunnel element factory
**Fehmernbelt Link, Denmark**

**Introduction**
The Fehmernbelt Fixed Link is planned to cross the Fehmernbelt between Rødbyhavn, 140km south of Copenhagen, and Puttgarden, located on the north coast of Germany. Based on a comprehensive comparison between a bridge and an immersed tunnel solution it has been decided that an immersed tunnel should form the basis for the continuous planning of the project including the environmental impact studies.

This project will combines records such as a length of 18.5 km and a water depth of 30 m, while crossing a busy navigational channel.

![Figure 36. Project Location and Elevation](image)

**Immersed tunnel solution**
The tunnel elements consist of a combined road and rail cross-section all at one level, contained within a concrete structure. There are two types of tunnel elements:

- **Standard elements**, which represents the main part (>95%) of the immersed tunnel section. Each standard element has a maximum length of approximately 217 m. They have the same geometric layout and are, to a high degree, interchangeable. A high degree of standardization will allow an industrialized construction method such as developed for the Øresund project.

![Figure 37. Cross section standard element](image)

- **Special elements**, about one every 1.8 km along the length of the immersed tunnel that provide space within the tunnel dedicated for mechanical and electrical equipment. The concentration of the tunnel installations and access facilities for maintenance staff in these special elements resulted in a further optimization of the standard elements. Underneath the road and rail tubes there will be access to all areas of the tunnel in order to reduce the disruption of the traffic to a minimum.
A bedding layer of gravel forms the foundation for the elements. At the sides there is a combination of locking fill and general fill, while at the top there is a protection layer which is in general 1.2 m thick, but can vary depending on the location on the alignment. The function of the locking-fill is to lock the tunnel element into position in the trench and prevent any movement from taking place due to hydraulic loads or the placement of the general-fill. The protection layer ensures against any damage from grounded ships, or falling and dragging anchors.

Environmental issues related to dredging and land reclamation
The tunnel elements are placed in a trench dredged into the seabed. Next to stringent requirements for the dredging works, an important strategy for this project has therefore been to re-use as much as possible of the dredged materials as resource for reclaiming new land in front of the shorelines of Lolland and Fehmern, respectively. Besides adding value to the environment the environmental impact is minimized by setting stringent requirements during both construction as well as the operational phase.

These areas will be landscaped into green areas. By using the dredged materials beneficially to create natural landscapes and create added environmental, natural and recreational value to the project. This is obtained with the landscape elements such as beaches, dunes, armored dikes, wetland areas and a natural cliff, which is allowed to controllably erode and thereby supply the downstream coastline with sediments.
The size of the reclamation area on the German coastline is relative small. Two larger relocations are planned on the Danish coastline on both sides of the existing harbour which will absorb the majority of the dredged material from the trench excavation.

Figure 40. Lay out of land reclamation on Danish Side with in dotted red the existing shore line

**Safety Concept / Tunnel Safety**

Safety and self rescue are more prominent when tunnel length increases. The safety level is higher compared to when travelling on a motorway or railway due to the absence of adverse weather conditions, turn outs, crossings and the constant light level in the tunnel.

Figure 41. Safe driving conditions within a tunnel with high availability

However, the consequences of an accident in the tunnel may be higher, especially when fire is involved. Therefore, a great number of provisions are implemented to manage incidents in a manner that provides adequate safety.

The safety strategy has been based on three levels and three key objectives:

1. Prevention of accidents and fires through design and operation,
2. Control of incidents and self rescue of users in case of an incident. This is important because due to the length of the tunnel the response of emergency services inevitably takes time
3. Emergency response and rescue.

The primary safety objective for safety level 1 is to provide a tunnel solution that will prevent accidents and other emergency situations occurring. It has been achieved through both design and operational considerations. E.g. for the road tunnels this includes:

- Uni-directional tunnels (road and rail) – no head-on collisions
- Multiple tubes (4) for escape, rescue and fire fighting set-up
- Central gallery for safety
- Robust, concrete structure
- High reliability and availability of protection systems (Traffic information system / Drivers awareness lighting)
- Fire separated systems – services and pipe gallery
- Road and rail control rooms (24/7)

Figure 42. Traffic information and drivers’ awareness lighting

In addition to the facilities provided for normal operation and prevention there are procedures, systems and installations designed to minimize the impact of an incident (level 2). For the self rescue principle these include amongst others:
- Exit doors at 108m intervals – highly visible
- Initial road evacuation into central gallery – protected area
- Walkways and exits in rail tunnels
- Voice alarms, radio re-broadcast
- Exit signage, distance to exits signs
- Electronic messaging
- Safety and emergency lighting
- Emergency stations – every 54m

For the incident control level this includes (level 2):
- Structural fire resistance – RWS hydrocarbon curve for all critical elements
- Automatic suppression – water deluge system
- Longitudinal Ventilation System
- Emergency Stations – portable extinguishers
- Pressurized central gallery
- Uninterruptable and back up power supply
- Drainage in all tubes for capture of dangerous goods

The level of control leads to the secondary objective of minimizing the consequences of an incident and enabling self rescue to occur without immediate emergency services intervention.

Figure 43 Automatic suppression / water deluge system
As a result of the initial incident control, and particularly the use of a deluge system in the event of fire, it is expected that many incidents will be under control prior to emergency services arrival meaning that intervention should be minimal. For those scenarios requiring significant intervention, facilities for the emergency services include:
- Range of emergency communication systems – FM radio, mobile phones, emergency telephones, TETRA radio system
- Hydrant systems every 50 m, 1200l/min
- Access to tunnels at portals for first response and brigade vehicles
- Fire systems controls at portals
- Dedicated control rooms (two plus auxiliary)
- Comprehensive fire and emergency response plan

**Tunnel Ventilation**

The ventilation is designed as a longitudinal system for both the road and rail tubes. The system comprises of normally self ventilated tubes by means of the piston effect caused by traffic supported by longitudinal ventilation by jet fans from portal to portal. The ventilation system is applied for both the day to day operation as well as for emergency situations, like fire.

For the day to day operation the ventilation design of the road tubes takes into account the low number of vehicles in the opening year, the expected traffic growth in the coming years and reduced car emissions from improvement in technology. The system is capable of keeping conditions in the tunnel below internationally recognized threshold values throughout the whole lifetime of the tunnel.

![Traffic predictions and emissions](image)

The use of a longitudinal ventilation system for smoke control is based on the assumption that under normal operation, congestion inside the tunnel and downstream the fire will not occur and will even be prevented during peak hours. This is because of the tunnel’s location in a rural area, the relatively low number of vehicles, and the implementation of a dedicated intelligent traffic management system. In the event of a fire in the road tunnel the traffic in front of the fire will continue to drive through the tunnel, travelling faster than the flowing smoke layer. Upstream the area will be kept smoke free by a minimum critical air velocity from the fans preventing back layering of smoke. The traffic behind the fire will stop and the occupants of these vehicles will commence to evacuate upstream of the fire into the adjacent central gallery and road tube, via escape doors spaced at intervals of about 108m. This relatively small distance between the escape doors improves the capability for self rescue and is considered adequate even in the very rare case of a double accident scenario where car users might be trapped downstream of a fire. The likelihood of such an accident is extremely low. The longitudinal ventilation concept eliminates the need for ducts and an intermediate ventilation island, which reduces the navigational risk in the strait and the cost of the project.
North/South Metroline Amsterdam, The Netherlands

Introduction
Not only for the large (sea) crossings immersed tunnelling has strengthen her position, also for very particular circumstances immersed tunnelling can be applied as a very viable and competitive solution. This is especially illustrated at the North/South Metro Line in Amsterdam, where an immersed tunnel was applied under a historic building.

The North/South Metro Line in Amsterdam, containing eight stations and measuring 9-km in length, will connect the northern and southern suburbs with the city centre (figure 45).

Figure 45 Alignment North/South Line

The northern part of the line will be mainly on surface level; as the line approaches the IJ river, the line goes underground using traditional cut and cover techniques. An immersed tunnel will be applied for the crossing of the river. The southern part of the line will be just below surface level, also applying the traditional cut and cover techniques.

For the metro sections running under the city centre, construction is treated quite differently. As a requirement, the city centre’s design solutions were specifically tailored to protect the historic structures and limit disruptions. The design of the underground station at Amsterdam’s Central Railway Station (CS) was largely determined by local environmental constraints. The underground metro station is being built in front of, behind and also directly underneath the historic central railway station. Damage to the listed station building and obstruction of the existing traffic and passengers flows are not acceptable. Additional complications were the soft and highly variable subsoil conditions and the high ground water table.

Metrostation Central Station

Figure 46 : Aerial view Station Island

The underground station Central Station of the North/South Line is located on Station Island (figure #). Station Island is an artificial island (land reclamation) that was created at the end of the nineteenth
century in order to build the new Main Railway Station for Dutch Rail. The island was formed by filling in a channel area in the River IJ with sand.

The new metro station will be an integral part of the biggest public transport hub in the Netherlands and will provide transfer facilities between local, regional and international public transport systems. Currently over 200,000 passengers per day use the present transport amenities. Building an underground station at such a location can be seen as one of the greatest challenges of the construction of the North/South Line. The underground station consists of three parts (see figure 47):
1. Southern entrance under the Square “Voorplein” in front of CS
2. Northern entrance under De Ruijterkade
3. Platform part underneath the railway station Amsterdam CS

The top track level of the station is NAP -15.2 m (Amsterdam Ordinance Datum).

Figure 47: Plan and longitudinal section metro station CS

Platform part metro station CS as immersed tunnel
The platforms of the underground metro station are located underneath the railway station. The major challenges were the protection of the historic and listed structures of the buildings together with requirements of not disturbing the operation of the railway station and to keep the inconvenience for the passenger to a minimum. The station building was built around 1880 on an artificial island in poor soil conditions. The building is supported on some 9,000 wooden piles and considered to be highly sensitive. After extensive studies it was concluded that a platform tunnel immersed in an artificial canal underneath under the railway station was the preferred option. The main reasons for selecting this option were:
- Since the platform tunnel is constructed at another location it limits the extent of construction activities on the railway station and it results in a shorter construction schedule since construction can take place on two locations.
- For the immersed tunnel option only a limited lowering of the water table inside the artificial canal was required. This was regarded as a significant advantage since the risk of influencing the water table outside and consequently the sensitive wooden pile foundations under the buildings was minimal.

Although the design was challenging it appeared to meet the requirements in the best way.
The platform part underneath the railway station consists of the following two main parts:
- An artificial canal (immersion pit) underneath the railway station including auxiliary support structures for the buildings and supplementary relief measures to protect the structures.
- Platform tunnel, built on another location and that is immersed in the artificial canal

Figure 48: Illustration of historic station building with immersed tunnel

For the formation of the artificial canal special tailor made types of building pit walls are developed, that are not described here (see literature).

The platform tunnel was designed as an immersed tunnel element and constructed in an approach ramp (temporary utilized as construction dock) on the north bank of the IJ-river.

Figure 49: Construction of the tunnel element in the Northern IJ river crossing approach

Figure 50: Tunnel element towed out in the Northern IJ river crossing approach and ready for transport

The platform tunnel is 130 m long, 21 m wide and 8 m in height. In the final situation the tunnel is subjected to a ground cover of approx. 9 m. The tunnel is designed as a segmental tunnel, consisting of 7 segments with lengths varying from 14.5 to 21 m. The centre support of the tunnel cross section is designed as a row of columns with heavy longitudinal beams at roof and floor slab level. A continuous wall was not accepted because of social safety and surveillance during operation.

After completion of the tunnel elements the construction dock was filled with water and the elements
were floated up. Thereafter they were towed out of the construction dock and transported to and moored temporarily at a quay in the Suezhaven in the western Amsterdam Port area.

Once the immersion pit underneath the railway station is completed an open connection has to be made with the IJ-river in the north in order to be able to transport the tunnel element under the railway station. This connection is made through the deep building pit for the northern part of the metro station. The transport and immersion process can hardly be described as standard (figure # and #) and had to deal with some particular circumstances:

- the structures over the building pit that were supporting the parts of the station above the building pit were just above the groundwater table. To enable transport and immersion underneath these structures, the water table in the immersion pit had to be lowered approx. 2.5 m. For that reason a so called lock-pit had to be applied in line with the immersion pit and extending into the IJ-river. After the lock pit is closed off with a separation wall the water table within the immersion pit can be lowered. (see figure 51 and 52).
- The sandwich wall at the Station Building (southern 40m) is supported by strut layers at 4.5-m. This strut layer is an obstruction to the floating tunnel element and implies a staged immersion process as described below.

1. floating transport of tunnel trough lock pit and building pit “De Ruijterkade”

2. shift element underneath railway station at a lowered water table (2.5 m) up to struts sand which wall underneath station building

3. immersion phase 1 below level struts station building and shift to the far south end

4. immersion phase 2 (to its final position)

Figure 51: Immersion process in four stages

After the lock pit has been closed off, the water level in the lock pit / immersion pit can be lowered to about 3-m and the element can be pulled towards the station building of Amsterdam CS and the under water struts at 4.5-m. The element, hanging from flat pontoons, will be immersed to a level such that the upper side of the element is marginally below the strut framework. The element can now be shifted horizontally underwater over a distance of about 40 m in a southern direction. Then it will be immersed deeper until it reaches its’ final position. At this stage the tunnel element will be secured with hanging beams attached to the support structures over the immersion pit. After the separation wall between the immersion pit and the building pit for the north entrance has been installed, the gap between the tunnel base slab and the under water concrete slab (strut), which is approx. 0.6 m, is filled with sand, using the sand flow method. Pre installed pipes (0.3 m diameter) inside the tunnel element are used for this purpose. Finally the ground fill on top of the tunnel is installed. At the same time the concrete structure at the northern entrance is executed. When adjacent structures are completed the connections with the platform tunnel can be constructed using freezing techniques for temporary water tightness purposes.
Figure 52 and 53: Impression of operation to transport floating tunnel element under railway station
Literature:
- Immersed tunnel, a better way to cross waterways?, ITA Brochure, May 1999
- Hongkong Zhuhai Macao Bridge Link, China’s latest infrastructure challenge, J.C.W.M. de Wit, Tunnels and tunnelling, May 2011