An Immersed Tunnel, better than a Long Span Bridge?

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Summary

Traditionally long span bridges are applied for river crossings and often in delta areas and in soft soil conditions. As an alternative to a bridge, in countries like the US, Japan and the Netherlands many of these fixed links have been constructed as a tunnel with the immersed tunnel technique. In these countries this 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 to a long span bridge 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.

Keywords: Immersed Tunnel, competitive.

1. 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.

When crossing water ways the most apparent options seem to be a bridge or a bored tunnel, often simply from a perspective of being most familiar with them. However, undeniably the immersed tunnel is a tunnel technique sometimes underestimated that can provide economic, high quality and competitive solutions to cross water ways. Especially when crossing water ways in an urban environment or when high air clearance of deep navigation channels are required, like in main ports.

The last decade new developments and innovations have stretched the limits for the immersed tunnel as a competitive alternative for large fixed links. The Øresund Link between Denmark and Sweden (Fig. 1) 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.

Fig. 1: Major sea crossing Øresund Link between Denmark and Sweden

In this paper the pros and cons of immersed tunnels are discussed and explanations are given for the fact that an immersed tunnel can be competitive to a long span bridge in many fixed link projects. Some striking examples are briefly described to illustrate the above and the potentials of the immersed tunnel for major strait crossings.

2. 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 world wide 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. (Fig.2)

Fig. 2: Tunnel elements in casting basin, in flooded casting basin and during offshore transport (Piet Heintunnel, The Netherlands)

Then they are towed to their final location, immersed into a prepared trench, and joined to previously placed tunnel elements (Fig.3). Since dredging tolerances generally do not meet the foundation design requirements, additional foundation works are required. The tunnel elements can be founded either on a gravel bed prepared prior to immersion or on a sand bed that is installed under the immersed element still resting on temporary supports, using the sand flow method. Afterwards 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. 3: Tunnel element at project location and 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 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 rubber gaskets to create the seal with the adjacent element. The tunnel elements will be lowered into their location after adding 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

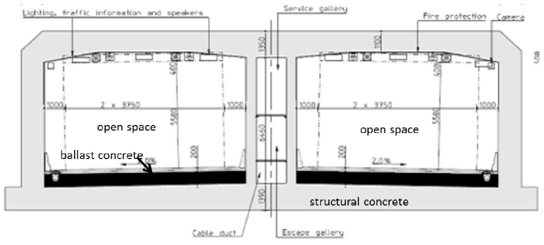

Fig. 4: Typical cross section immersed tunnel (structural concrete, open space and ballast concrete)

installed on the tunnel base slab (Fig.4). Subsequently the finishing of the tunnel can take place such as road paving, tunnel installations etc.

3. 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. The American engineers developed a specific steel shell technology (single and double shell). Steel tunnels use structural steel 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 (Fig.5). Steel tunnels can have an initial draft of as little as about 2.5m and are transported while afloat or sitting on a barge (Fig.6). 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 and the 3rd Hampton Roads Crossing in West Virginia.

Fig. 5: Launching of steel tunnel element

Fig. 6: Transport of steel tunnel element (Ted Williams tunnel, Boston, US)

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. They usually have a draft of almost the full depth. This European development has been stimulated and concentrated in the Netherlands (Fig.7) 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 (Fig 8).

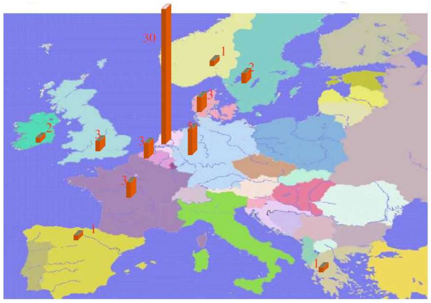

Fig. 7: Immersed tunnels in Europe

Fig. 8: Marmaray Crossing, Turkey

A third focal point for immersed for immersed tunnel technology lies in Japan, where construction started in 1944 (Aji River Crossing, Osaka). For this tunnel the single steel shell of the USA tradetion 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. Since the last two decades the composite steel concrete immersed tunnel was further developed in Japan.

4. 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 bridges or 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 (Fig.9);

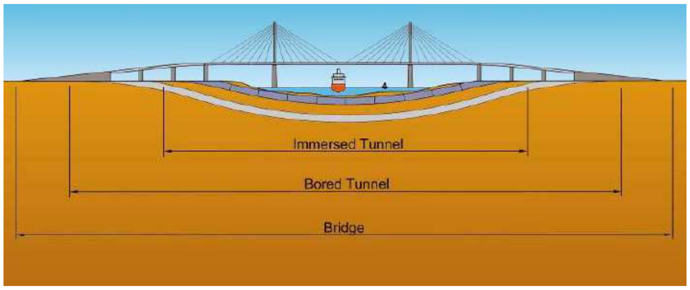

Fig. 9: Comparison Link options

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 (Fig.10);

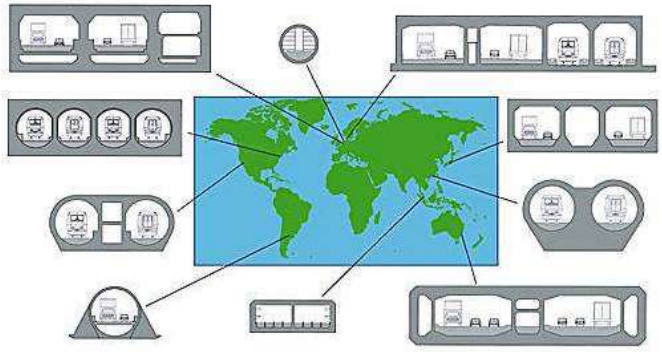

Fig.10 : Possible cross section shapes for immersed tunnels

3. Immersed tunnels will have less impact on environment (visual, noice and disruption) than high level bridges (especially when access to a port is involved air clearances of 60-70 m may be required) and their connection to the local road or rail network is generally easier to perform than for both high level bridges and bored tunnel that are located on a deeper level.

Fig.11: Illustration of impact of a high level bridge in urban and port environment

4. Hydraulic impact and blockage effects become more and more an issue in a lot of places when it comes to the realization of a crossing. Especially in river with large discharges and substantial sediment transport the presence of obstacles in the river (such as bridge piers) may result in serious scouring and sedimentation, resulting in banks or even small islands and the changing of embankments during periods of high discharge.

5. 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.
6. Bored tunnelling is a continuous process in which any problem in the boring operation threatens to delay the whole project. Immersed tunnelling involves more construction activities, 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
7. A considerable part of the design and construction works (80-90%) can be done by local design and construction companies. The involvement of international experts in both design and construction is essential but limited.

5. 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.

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.

In the following section some project examples are described in which the ultimate selection of the immersed tunnel is explained.

6. Case studies

6.1 Caland tunnel Rotterdam, the Netherlands

The Caland tunnel is a typical river crossing, located in a very busy part of the Rotterdam port, with a total length of approx. 1.500 m, accommodating 2x3 road lanes and a service / escape duct (Fig.12).

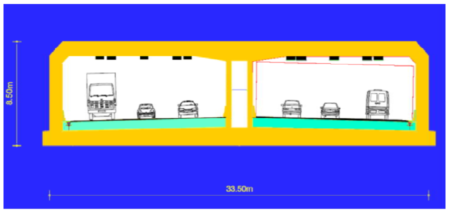

Fig.12: Typical cross section immersed tunnel

The tunnel comprises an immersed section of 700m. The tunnel was constructed to replace an existing bridge in the motorway A16 that contained a movable part that opened 8.000 times a year to allow the passage of the sea-vessels (Fig.13).

Fig.13: floating tunnel element arriving at site and passing under existing movable bridge

Due to the fact that the water way was relatively narrow (around 250 m) and the required air clearance was at least 50 m a high level bridge was not considered to be a serious option, due to the fact that the long approaches would be very costly and a lot more difficult to integrate in the road network. However the bored tunnel was compared in more detail, but appeared to be not competitive either. Due to the fact that a significant ground cover is required on top of the bored tunnel and much less favourable circular cross section for a 3-lane bored tunnel, the total tunnel length increased with some 50%, which was expressed in the comparative cost estimates as well (Fig.14).

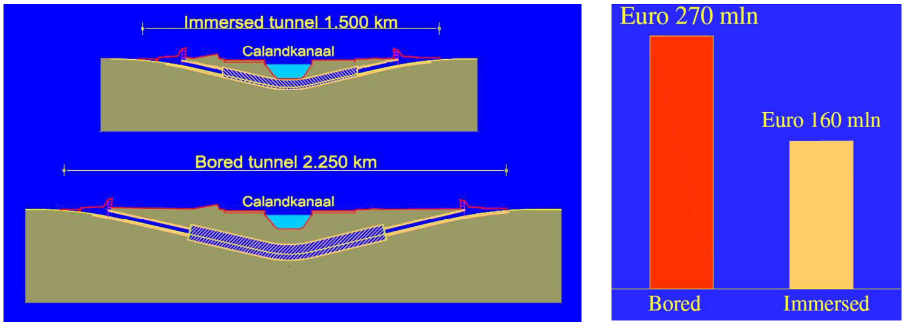

Fig.14: Comparison immersed and bored tunnel in design and costs

6.2 Hongkong Zhuhai Macao Link, China

Currently, one of the worlds' 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, at completion being the longest immersed tunnel in the world. The transition from the bridges to the tunnel will be realised with artificial islands with a length of 625m each.

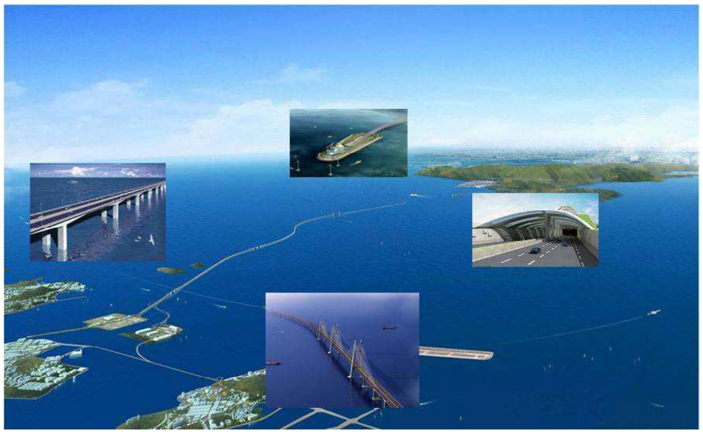

Fig.15: Project Location

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.

The selection of the immersed tunnel was made after a careful consideration of both the bridge and bored tunnel option. For the bridge option crossing of the main navigation channels with the required air clearance of over 60 m resulted in a major suspension bridge spanning both channels and with towers of over 100m in height. Since this bridge would interfere with the aviation requirements for the approach of Hong Kong International Airport the bridge option had to be rejected.

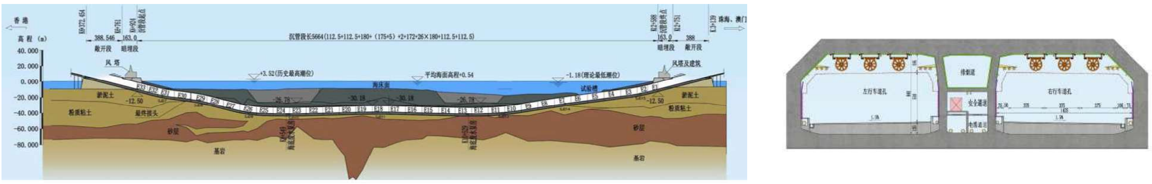

Fig.16: Longitudinal section and cross section of the immersed tunnel

The bored tunnel option was studied in detail during the conceptual design stage. The design consisted of two bored tunnels with an outer diameter of 16.9 m in order to accommodate 2 x 3 road lanes. On regular distances cross passages were included to meet safety requirements. The vertical alignment dropped from -40m for the immersed tunnel to -54m for the bored tunnel. The tunnel length increased from 6.6km for the immersed tunnel to 7.2km for the bored tunnel. The length of the artificial island increased with some 250m per island.

The main reasons to select the immersed tunnel as preferred option were costs, risks and schedule:

- The cost estimates that were carried out indicated that the bored tunnel was approx. 10-15% more expensive than the immersed tunnel. This included the additional costs for the artificial islands and maintenance and operation of the tunnel.
- From a risk point of view the immersed tunnel performed better than the bored tunnel. Especially the geotechnical risks involved with the variable ground conditions were supposed to be better manageable with the immersed tunnel. The very large diameter op 16.9 m in combination with the wide variety of soils that would be encountered (weak soils → hard rock) would be a major challenge for the Tunnel Boring Machines.
- The construction time for the bored tunnel was estimated to take 10 months longer than for the bored tunnel. In addition the planning risks (delays) were considered larger for the bored tunnel.

6.3 Fehmarnbelt Fixed Link, Denmark and Germany

The Fehmarnbelt Fixed Link will connect Scandinavia and continental Europe with a combined rail and road connection between Denmark and Germany. It is planned to cross the Fehmarnbelt between Rødbyhavn, located some 140km south of Copenhagen on the island of Lolland in Denmark, and Puttgarden located on the island of Fehmarn on the north coast of Germany. This immersed tunnel project will have a world-breaking distance of about 17.6 km, almost 5 times longer than the current record-holder. Other challenges are a water depth of 30 m, crossing of a busy navigational channel and strict environmental requirements.

Fig.17: Plan view and cross section of the immersed tunnel

In the late nineties a feasibility study was carried out for this fixed link and the Danish and German government labelled the cable stayed bridge as the preferred solution and the immersed tunnel as the best alternative. In 2009 two consultants were selected by the Client organization Fehmern A/S for a more detailed study of both solutions in an internal competitive process (Fig.18).

Fig.18:Tunnel and Bridge option in competitive process

After a comprehensive comparison between a bridge and an immersed tunnel solution, in February 2011 the Danish government concluded that the immersed tunnel became the preferred solution.

The main raisons for the selection of the immersed tunnel were:

- more or less equal in price (with the immersed tunnel being slightly lower in price)
- performing better in terms of availability due to the sheltered conditions from adverse weather and an state of the art maintenance concept
- hydraulic impact is much less considering the many piers that are involved in the bridge option
- less visual and environmental impact which was considered very important to satisfy the various stakeholders
- the possibilities for local contractors and suppliers to get involved in the project were considered much higher

Important innovations were included in the immersed tunnel design to allow for a reduction in costs and to be able to compete with the bridge option, such as (Fig.19):

- the introduction of special elements ever 1.8km for the housing of M&E installations and easy access for the maintenance staff. This allowed for an optimization of the standard cross section.
- the development of a state of the art safety concept that allowed for longitudinal ventilation for both normal operation and during fire; an expensive semi transverse ventilation system including a ventilation island could be omitted from the design.
- the re-use as much as possible of the dredged materials from the tunnel trench as resource for reclaiming new land on the shorelines of Lolland and Fehmarn, respectively. The reclaimed areas will create valuable natural and recreational resources and will act as an environmental interface between the man made landscape and the Fehmarnbelt, while still providing safety against flooding.

Fig.19:Special elements and re-use of dredged material of land reclamation

The start of the construction of the tunnel is expected to commence in 2015 and the link is scheduled to be opened for traffic in 2020.