

Immersed Tunnels: Experience and Recent Developments

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1. General

In 1993 the Immersed and Floating Tunnels Working group of the International Tunnelling association, of which I am an active member, published the first State of the Art report, followed by a second edition in 1997. Over the years we collected data for a catalogue concerning Immersed Tunnels. It resulted finally in two catalogues, one for Immersed Service Tunnels and one for Immersed Transportation Tunnels. Although not many information is available about service tunnels, it appeared that the first Immersed Service Tunnel was built in 1893, the Sewer Culvert under Boston harbour with diameter 2.75 m, and the first Immersed Transportation Tunnel was built in 1910, the Detroit River Tunnel.

Today we have identified 41 Immersed Service Tunnels and 113 Immersed Transportation (traffic and rail) Tunnels. This presentation will focus on the transportation category only. The following table shows the number of tunnels built during this century.

1910	1920	1930	1940	1950	1960	1970	1980	1990	2000
3	2	1	4	7	21	21	19	25	10+

Up till now 113 tunnels are built or under construction. This means during the last decades an average in the world of about $96/40 = 2.4$ per year. Although this market of Immersed Tunnels is small, it is of interest for the HBG companies, due to the available experience and experts.

Number of Immersed Tunnels in the different countries:

27	USA
26	Netherlands
20	Japan
7	Germany
6	Hong Kong
5	France
3	Belgium, Denmark
2	Canada, China, Sweden, United Kingdom
1	Argentina, Australia, Cuba, Ireland, Greece, Spain, Taiwan, Russia

All these tunnels are still in operation. They are a safe and durable way to cross a river or canal. Only some of them have been partly closed for a short period for maintenance and upgrading of traffic equipment. One Immersed Tunnel has recently been removed after only 26 years in operation, because the tunnel was planned too high and obstructed the shipping channel.

At this moment serious plans and designs are made for at least 15 more Immersed Tunnels for the next decade.

The working companies of the HBG group became involved in the technology of Immersed Tunnels in 1960. HBG companies were involved in the actual construction of 19 tunnels in the Netherlands, Germany, United Kingdom, Ireland and the USA, and DMC was involved on at least 18 other projects for consultancy, study or conceptual design. In total an involvement in about 30% of all Immersed Transportation Tunnels.

2. Differences between Types of Immersed Tunnels

Although Immersed Tunnels have the same purpose, several types exist. All these types are feasible and need to be considered for each new tunnel project. The main differences are:

2.1 Total Immersed length

At some projects only one element is present: Aquaduct Alphen in the Netherlands, while at others up to 58 elements are present: the Bay Area Rapid transit Tunnel in San Francisco.

2.2 Element length

The element length varies between 45 m till 268 m. The usual length is between 100 m and 125m with a tendency in the last years to 150 m to 175 m.

2.3 Cross-section

Figure 1 presents the typical difference in cross-section between concrete and steel tunnels.

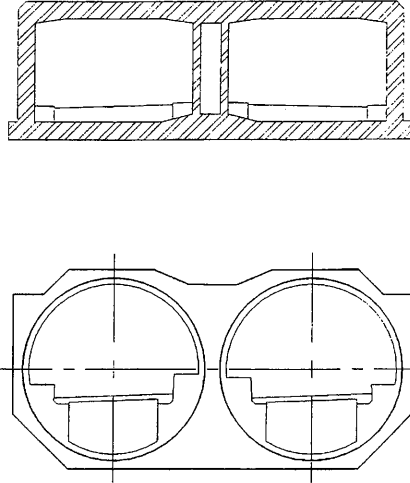


Figure 1: Concrete and Steel cross-section

2.4 Watertightness

The aspect of watertightness has been solved successful in different ways, which are characteristic for the design philosophy. The watertightness need to be secured at two points:

- the main body. The different solutions will be explained hereafter.
- the joints. Joints are in general or welded or are provided with a GINA/Omega closure.

It need to be mentioned that all tunnels have minor leakage which is fully acceptable. This leakage depends sometimes on the season. Experience has learned, that when leakage occurs it is often near the joints (directly behind the support structure of the rubber seal) and not in the body of the tunnel.

2.4.1 Steel

In the USA the tunnels are provided with a membrane. The function between structural and watertightness has been separated. The "steel" tunnel as they are called, has a steel membrane for watertightness. The composite of concrete ring plus steel membrane is the structural part.

2.4.2 Concrete with membrane

In Europe the tunnels are of the concrete box type. In many countries a separate membrane is required. In the past this was often a steel membrane at bottom and walls and a mastic on the roof. For many owners this sounds the best solution. However, due to the fact that the two functions structural and watertightness are separated, the experience is that the concrete in these tunnels is not fully capable to resist water leakage. At the moment there is a gap (bad weld) in the membrane, the water will flow between the membrane and concrete to a permeable location in the concrete, where it will penetrate the concrete. This water is usually easily pumped away, but the salt water will cause deterioration of the concrete. At this moment one of these tunnels (Limfjord) has taken out of used for a long period to remove the deteriorated concrete at the inside and replace it with new concrete.

Recently a plastic sprayed membrane was used on tunnels in Hong Kong, the Far East, Europe and USA. In this case the membrane cannot separate from the concrete, which avoids largely the above mentioned problem. The expectation is that leakage can now only occur when both membrane and concrete have a bad spot at the same location.

2.4.3 Concrete without membrane

In the Netherlands - and especially at RWS and HBG - concrete research in the seventies has resulted in knowledge to produce mass concrete without cracks by controlling the concrete hardening process. This has resulted very successful in the design of concrete tunnels without membrane. In fact the leakage is less than in tunnels with membrane. The technology to control the curing process of the concrete has played an important role to this concept.

2.5 Longitudinal layout of an element

Up till now the structural integrity in the longitudinal direction of an element is solved mainly in one of the following ways:

- The steel tunnels consist of one body, which is able to take all loads and bending moments.
 - The concrete tunnel with membrane consists of a continuous body with continuous reinforcement. The reinforcement has to be able to take the bending moments, which means potential cracking of concrete.
- The concrete tunnel without membrane consists of sections of about 25 m and rotating joints in between. The bending moments in these sections are minimal. During transport a temporary pre-stress system is used.

3. Foundation

The foundation of immersed tunnels is seen as one of the magic's of immersed tunnel technology. Although more and more computer programs become available which claim that calculation of settlements can be done, it is still worth to realise that in the past predictions were based on hand calculations and experience. It is one of the most important items of an immersed tunnel, but at the same moment one of the least predictable. The foundation has two relations:

- to the settlements
- to the structural behaviour of the elements

The foundation of an immersed tunnel consist of the original subsoil, which need to be appropriate, and the manmade foundation bed in the area between the underside of the element and the dredged bottom. In general two types of bed can be made for this layer of 250 to 750 mm:

- a bed prepared before the element is placed
- a bed after the element is placed.

In the first case the bed consists of gravel. This type is favourable with the Americans. In the past this bed was made by dumping gravel and screeding it in the required slope, a slow process. Interbeton has used this technology in Hampton Roads and Boston. The technological development of marine equipment, electronics, electronic/mechanical equipment, as well as positioning equipment made it possible to design and built a special pontoon with a fallpipe which corrects its level more than 60 times per second. This type of equipment can make the bed in a shorter period with less risk for disturbance. This pontoon is used for the first time on the Oresund and now (for other than foundation reasons) on the Second Benelux. HBW plays an important role on this project.

In the second case the bed was made in the past by the sand jetting method, by jetting a sand/water mixture from the side under the element, and is now usually made by the sandflow method, by jetting a sand/water mixture through cast-in pipes in the bottom of the element. The advantage of the sandflow method is, that obstructions in the river are avoided and the element can be levelled by jacks before making the foundation bed. This sandflow method is more favourable in Europe and HBW has made many of these beds.

In earthquake areas other foundation solutions are required. Often the subsoil need to be stabilised against liquefaction and a grout bag foundation is placed under the element. DMC has been involved in a tunnel project in Greece with this solution.

Whatever method is used, the discussion always comes to the point of the settlements. Analysis of settlements of tunnels built on a screedbed and on a sandflowbed has learned, that the potential settlements of the manmade beds are comparable, in the order of 10 to 100 mm. Usually the subsoil will not significantly settle, because the weight of the tunnel is mostly less than the weight of the removed soil. This is however not always the case and serious investigation is in that case required. The concept of Immersed Tunnels can fully handle this magnitude of settlements.

4. Internal Corridor

HBG companies are promoting immersed tunnels all over the world. Although the basic concept is very simple and identical for each tunnel, it is important to mention, that Rules, Regulations, Requirements, Local and Personal preferences result in different tunnel designs. One aspect worth to mention is the internal corridor. It is often difficult to convince the owner that an intermediate corridor (figure 2) has large advantages. This corridor can be used as escape way and as cable corridor. This avoids placing of cables under the road deck with the consequent disturbance during replacement or placing of extra cables. An internal corridor offers also advantages related to the penetrations.

An investigation to the additional costs of this corridor has learned that this is less than 1 % of the construction costs. This is less than 1 million Euro on an average project of about 100 million Euro.

Short term construction costs are for the owner sometimes more important than long term costs. When taking into account the fact that immersed tunnels last more than 100 years, but Mechanical and Electrical equipment need to be replaced every 10 to 25 years, it shows quickly that it is worth the investment.

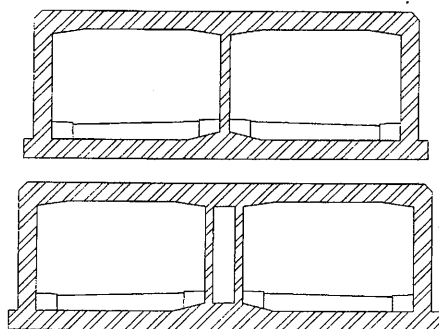


Figure 2: Cross-section with and without internal corridor

5. Entrances

It need to be realised, that the Immersed section of a tunnel project is often the most spectacular, but that the entrances at both sides are often even complicated to built. Especially for train tunnels these entrances are very long. They need not to be underestimated during the design, planning and estimating of a project.

6. Mechanical & Electrical

We are usually interested in the civil part of a tunnel project. It need to be mentioned that the Mechanical and electrical aspects as Drainage, Ventilation, Energy and Light, Communication and Road Information Systems are often more important for the user. The cost of these systems is mostly in the order of 15 to 25% of the construction costs and is increasing due to the technological development and sharper safety rules.

7. Loading cases

Immersed tunnel engineering and construction consists mainly on the art to handle the many loading cases during the construction period and permanent situation. They depend on aspects as type of tunnel, foundation, construction methods, etc. In figure 3 the main temporary situations are presented.

8. Passing ships during construction

Initially this presentation had the title Second Benelux Tunnel (figure 4 and 5). This tunnel is at this moment under construction and a number of the elements are placed. Although it is basically a well-known type, it has some specialities that have had a very important impact on the realisation. The location of the tunnel is close to an existing immersed tunnel, built in 1967. No examples are known of such a case. (In Baltimore two tunnels are placed next to each other, but they are built at the same moment). Intensive studies have been done to the stability of the existing tunnel during dredging of the trench.

The dimensions of the tunnel are very large, 45 * 140 * 9 m. For comparison, the Oresund tunnel is 42 * 175 * 8.50 m and the Drecht tunnel is 49 * 115 * 8 m. Both the width as the length of the second Benelux Tunnel requires special attention on the narrow Dutch rivers during marine works. This tunnel is located in the Nieuwe Waterweg, a location where large container ships are passing. Due to the fact that the tunnel is located in a curve in the waterway, ships need a certain minimum speed for manoeuvrability. During the construction of the First Benelux tunnel, the passing ships were smaller and there sailing speed lower. As known, the watertable around ships lowers due to the local increase of the speed of water around the ship. When sailing over a tunnel, there will be a difference in water height between both sides of the element. This gives a difference in hydrostatic pressure and a local return current, which act both horizontal as vertical on the element. As a result external forces will act on the element, which depend on the speed and sailing direction of the ship in relation to the element. The temporary ballast of the element must be able to cope with these forces. This loading case only exists during the construction period, when the trench has not yet been backfilled.

The combination of increase of ship size, large width of the elements and enlargement of element length resulted in larger than usual ship induced forces and a potential unbalance during one of the many construction stages. The main reason was the temporary gap between underside element and dredged bed. Finally the planned sandflowbed was replaced by a screedbed, to prevent this loading case of having a gap. So this tunnel will be placed on a screedbed, not because of foundation bed requirements, but because of other intermediate loading cases.

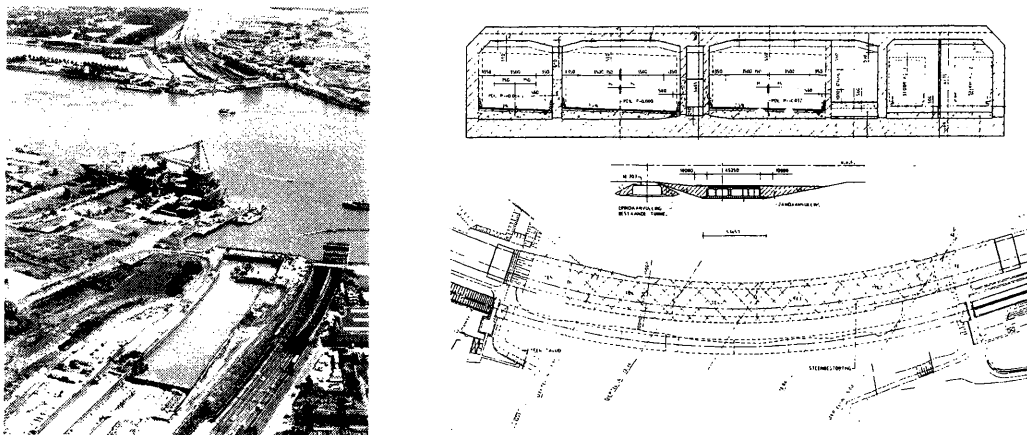


Figure 4 and 5: Second Benelux Tunnel

9. Recent Developments

During the last years many global and local alternatives have been proposed, published and sometimes executed by HBG companies and others. It is of importance to realise that it is difficult to develop new designs or construction methods which are feasible on all aspects. Often the alternative solution is valid for an isolated aspect. It has been noted that alternatives are copied without realising the ins and outs. Some examples will be given of (to my opinion in the near future) non-potential and potential improvements:

9.1 Non-Potentials

In literature and magazines often wild ideas are presented of improvements. They often end with dissatisfaction. Each project will be finally finished, but then after delays and budget overruns. Some examples:

9.1.1 Floating portals

An idea which floated around for many years was to immerse the entrances, the section without roof. Initially it sounds attractive, built the entrances as a tunnel without roof in a dock, and sink the element on the slope of the embankment. However it has numerous disadvantages, which have been realised insufficient when this idea was used by a competitor at the Lee tunnel. First, the element will have a tapered shape, which makes floating and immersing complicated. Second it is difficult to design a safe vertical stability in its final position. Immersed tunnel technology is based on fully immersed bodies. A partially immersed body has varying uplift forces due to tidal influence. That need to be secured in such a way, that vertical stability is guaranteed and settlements are controlled. The final design ended with very large side flaps, which could be loaded with soil and a double bottom with fixed tanks below and a tidal tank on top during immersion. HBW has placed this element for the main contractor and gained experience with this design.

9.1.2 Securing without Wedging

Sometimes solutions are copied without realising the technical implications and required measures. Constructing the elements in a dock in one of the entrances can be attractive. However the temporary closure between the final element and the in the dock to be built entrance is very complicated. DMC and HBW have done that properly on the Medway Tunnel, by wedging the hydrostatic pre-stress to a prepared bottom slab. A competitor who thought to copy this method to his project and using a cheaper solution by not wedging the final element, discovered what we already predicted, that the element moved backwards and downwards, when the pre-stress in the Gina joint disappeared. The tunnel finally finished after long delays, modification of the joint and additional safety measures.

9.2 Recent developments and Potentials

Difficulties in finding a dock location in the area of the tunnel project result more and more to offsite construction. As a consequence, the elements need to be transported, at least through onshore waters, but also over sea. In the past elements of 6 tunnel projects have been transported over sea. The design wave conditions were mostly moderate.

9.2.1 Transportation over sea

The steel tunnel elements of the Boston Ted Williams tunnel have been transported over the Atlantic Ocean by Interbeton, with advice of DMC. After many meetings the only feasible transportation mode for steel shell tunnels was established: as cargo on a submersible barge. This has been done 12 times successful without damage and delays.

During the tender for the Oresund tunnel, under the flag of HBW and DMC, hydraulic modeltests were done to establish the transportation on its own keel of large concrete elements over the Northsea. In this case waves were expected as high as 12 m. In fact the tests were done for a range of spectra for wave heights and wave periods. It showed, that with sufficient

(temporary) pre-stress, elements can be transported through these rough sea-states. It also learned, that design codes of the classification societies need to be handled with utmost care. At this moment we are involved in a study to investigate the value of the codes for these conditions. The figures 6 and 7 show the transport of a steel and concrete tunnel over sea.

Figure 6,7: see appendix

9.2.3 Interaction between tunnel element and portal

The interaction between the tunnel element and the entrance is always complicated. DMC has solved with Interbeton this aspect very successful at the Boston Ted Williams Tunnel with the world's largest unbraced cofferdam (figure 8) and with HBW on the Medway Tunnel with the secondary closure in a 5 meter tidal river (figure 9).

Figure 8,9: see appendix

9.2.4 Industrial Production method

On the Oresund project, the contractor has chosen to built with success an Industrial Production Plant for the 20 long concrete elements.

Figure 10: see appendix

9.2.5 Submerged Floating Tunnels

In 1886 the idea was presented to built Submerged Floating Tunnels through fjords (figure 11). During the last decade numerous studies have been done to this concept in Norway, The Netherlands, Italy and Japan. In principle all aspects are conceptual solved. The situation at this moment is that when a budged is made available, the first SFT will be realised. Point of discussion is the amount of extra safety measures. A first step is made by the recent design of a railroad tunnel as an underwater bridge through the Lake Lugano (figure 12).

Figure 11,12: see appendix

10. Conclusion

Immersed tunnelling, although nearly a century old construction method, offers still a very feasible, safe and cost effective solution for underwater connections. It is an art based on experience with still potential improvements for the future.

Data and figures from different sources have been used.

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Figure 6: Steel tunnel transportation



Figure : Concrete tunnel transportation

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Figure 8: Boston Cofferdam

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Figure 9: Medway Secondary Closure

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Figure 10: Oresund Plant

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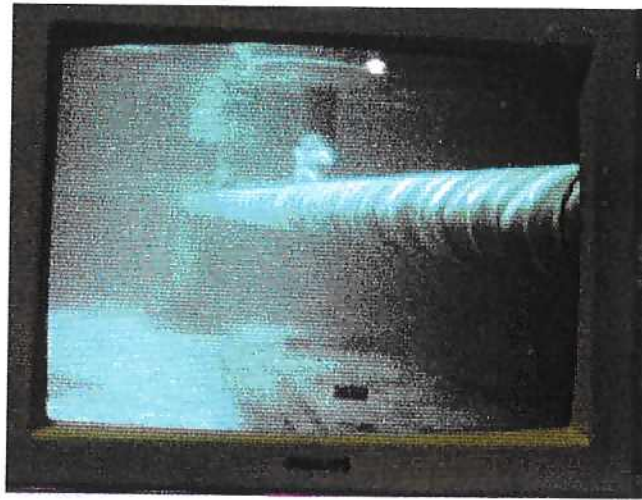


Figure 11: Submerged Floating Tunnel

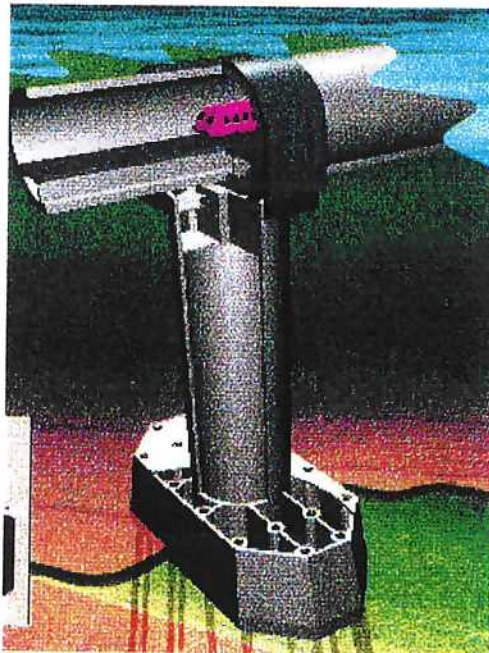


Figure 12: Lugano concept