Opportunities for immersed tunneling

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Summary

Immersion of tunnels is one of the techniques used for crossing a waterway. In this paper a short resume is given of the traditional way of immersing a tunnel. As the demands for connections at areas with special circumstances increase innovative solutions are developed to make the immersion possible. New remote controlled systems and survey systems are used for tunnels with a greater length and depth, where6t access shafts are no longer applicable. Innovative solutions are used to immersion the Limerick tunnel in the tidal Shannon river and new techniques have been used for immersing tunnels under sea conditions. Finally the circumstances of immersing under a historic building are described.

***Keywords**: Immersed tunnel, innovations, immersion techniques, survey, bulkhead*

1. Introduction

All over the world numerous immersed tunnels have been placed in the last century. While the early immersed tunnel projects were mainly in the North West of Europe (the Netherlands, Belgium, Germany and the UK) and were confined to shallow river crossings, nowadays tunnels are immersed in sea strait crossings with a depth of 60 meters and under extreme water conditions (current, waves). The immersed tunnel is a proven and reliable technique that should be considered as a possibility for the potential connections in South East Europe.

1.1 Tunnel versus bridge crossing

Connections can be formed by a bridge or a tunnel solution. A bridge with a free passage for shipping requires a large clearance with long approaches. The main difference between bridges and a tunnels is of course the exposure of the structure as the tunnel will be placed in the subsoil.

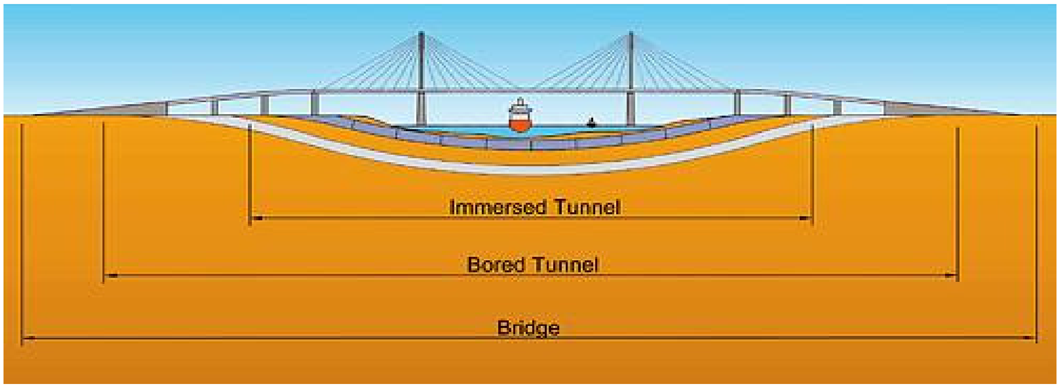


***Fig. 1** Comparison bridge – tunnel crossing*

In many situations an immersed tunnel can be the most cost-effective solution. The general properties of an immersed tunnel are:

- Little construction depth is required resulting in relative short tunnels
- Low bottom pressures are present which makes immersed tunnels suitable for soft soil situations
- Non rock or dredgable subsoil is required
- The construction of the elements is carried out in a pre-cast yard elsewhere, the sea strait is relatively short disturbed.
- Casting circumstances can be optimized to increase casting speed.
- In general the costs are lower than a bored tunnel
- The clearance for ships remains free
- No risk of closure of the crossing during severe weather
- Applicable in earthquake sensitive areas

1.2 Works performed by Mergor / Strukton Afzinktechnieken

Mergor Underwater Construction is specialized in performing the immersion design and the engineering and works for the phases of floating up, transport, immersion and sand flow (if applicable). The casting works, dredging of the trench, filling works and finalisation works are performed by others as well as the main design of the tunnel.

In the next chapters temporary phases are described in general and solutions in special circumstances are clarified based on several projects performed by Mergor in the past.

2. Immersing the traditional way

An immersed tunnel consists of a number of tunnel elements which are build in a construction dock (pre-cast yard). After completion of the elements the construction dock is flooded and the tunnel elements are floated up one by one, warped out and transported to a mooring location or directly to the immersion location. At the immersion location a trench is dredged and a gravel bed or tile foundation is prepared. The immersion of the tunnel elements will take between 24 and 72 hours depending on the local circumstances. Then the elements will be sand flowed (if required), the backfilling is place afterwards. The depth of traditional tunnels is usually in the range from 20 to 30m.

2.1 Construction of the tunnel elements

The tunnel elements are prefabricated in a construction dock. Dependent on the situation this dock can be situated near the immersion location or on some distance from the final position of the tunnel alignment. Several variants of construction docks can be applied, all depending on the circumstances at the project location. A dock specially made for fabrication of tunnel elements (fig. 2), a dock in the approach of the tunnel (fig. 3) or in a ship dock as been used for the fabrication of the tunnel elements for the Calandtunnel in the Netherlands (fig. 4).
If necessary the construction dock can be used several times to construct a batch of tunnel elements.

Fig. 2 *Construction dock in Barendrecht (Wijkertunnel)*

Fig. 3 *Construction dock in the approach of the tunnel (N57)*

Fig. 4 *Construction in a ship dock (Calandtunnel)*

In general the elements are casted in several segments of 20-25m each. By applying post tension cables these segments are bonded together, making the element able to withstand all the temporary phases as a whole. After the immersion and sand flow the post tension cables are sawn through, the segments settle to the subsoil one by one.

2.2 Auxiliary items temporary phases

To be able to perform the temporary phases several auxiliary items are installed during the construction of the elements such as bulkheads, a gina-gasket, ballast tanks and piping system, bollards, suspension points, temporary supports, an access tower and an alignment tower.

To make a tunnel element buoyant, the ends of the tunnel element are closed off by bulkheads, a concrete or steel wall which is supported by vertical beams. In the past often concrete bulkheads were used. A disadvantage of this concrete bulkhead is the labor-intensive removal of the bulkhead accompanied with a lot of noise and dust. Therefore Mergor developed the steel bulkhead alternative which has been used for several projects (fig. 5). This bulkhead is easily removable and the conditions for personnel are far more favourable compared to the removal of the concrete bulkhead. In case of several casting batches the steel bulkheads can be re-used.

Fig. 5 *Steel bulkhead (Roertunnel, Netherlands)*

Fig. 6 *Gina-profile (Roertunnel, Netherlands)*

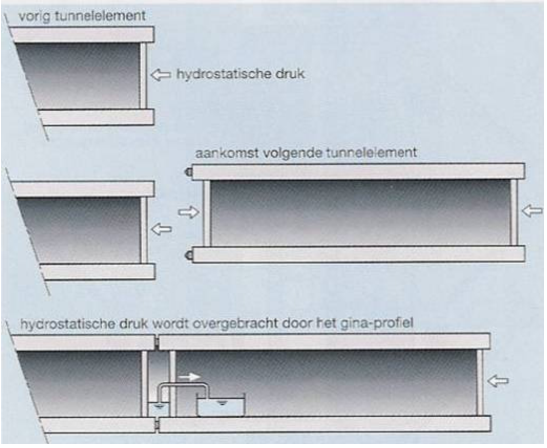


Fig. 7 *Emptying immersion joint*

The Gina-gasket is a rubber seal and forms a watertight connection between the tunnel elements. The Gina-gasket is connected to the steel end frame, an I-shaped beam present around the circumference at the front of the tunnel element (fig. 6). At the end of the immersion the two elements are positioned in front of each other and pulled against each other with jacks on top. Now immersion joint is closed of and the water between the bulkheads can be removed (fig. 7). The water pressure is transferred from the bulkhead to the gina gasket forming a water tight connection. As the immersion joint is finalized an Omega gasket is installed which forms a second water barrier.

The ballast tanks in the tunnel element are used to adjust the buoyancy (fig. 8). In the construction dock and during and after immersion the ballast tanks are filled to get negative buoyancy. In between the tunnel element is made afloat by removing the water from the tanks.

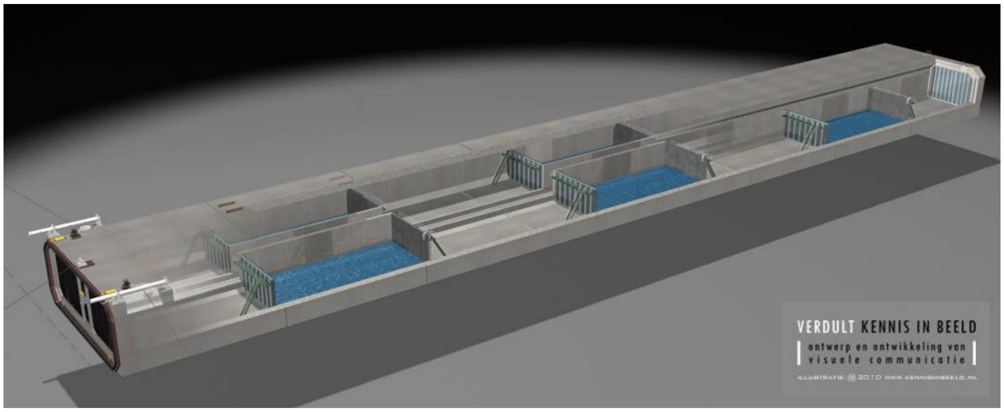


Fig. 8 *Ballast tanks (BGFL, South Korea)*

2.3 Floatation

As soon as the construction of the tunnel elements is finished, the dock is inundated. Commonly the tunnel elements are kept in place by filling the ballast tanks in the tunnel element with water. After the dock is filled the tunnel elements are floated one by one by emptying the ballast tanks (fig. 9). Alternatively the tunnel elements can be floated during flooding of the dock. The elements are usually warped out of the dock by use of a winching system and in case of open water, taken over by tug boats.

The tunnel element can be moored in the construction dock (in case relevant) or at a mooring location close by. Here the preparations for transport and immersion will take place.

Fig. 9 *TE's after inundation (Limerick)*

2.4 Transport

For a tunnel element built in the approaches of the tunnel alignment transportation will be done with winches together with a guidance system. With a construction dock further away from the final location tug boats will be used to get the tunnel elements at the immersion location.

Fig. 10 *Transport in a waterway (NS-line, Amsterdam)*

Fig. 11 *Passage of a bridge (Calandtunnel)*

During transport several circumstances have to taken into account such as depth of the water way, tidal graphs, wind and swell waves, current speed and passage of bridges or other constructions. The transport is carried out in cooperation with the navigational authorities.

2.5 Immersion

As the element arrives at the immersion location the trench is dredged. The ballast tanks are filled with water to provide the overweight required for a controlled immersion operation. This load is temporary beared by the immersion system which is connected to the suspension points on the roof. Depending on the circumstances and properties of the project different systems can be used. In case the immersion is performed between sheet pile walls a traverse beam with winches can be placed on top (fig. 12). At open water situation with relative low suspension forces and low wave conditions the cross beams can be placed on pontoons (fig 12).

Fig. 12 *Cross beam on sheet pile wall (Limerick)*

Fig. 13 *Cross beam on pontoons (Limerick)*

The immersion can also be performed by using a sheerleg (fig. 14) or in case the forces are higher and the circumstances become more severe a specialized pontoon is constructed equiped with all the winches required (fig. 15). For the BGFL project each pontoon contained 7 winches, besides the suspension, also mooring and contraction (positioning) winches were present on the pontoon.

Fig. 14 Floating sheerleg and pontoons (Wijkertunnel)

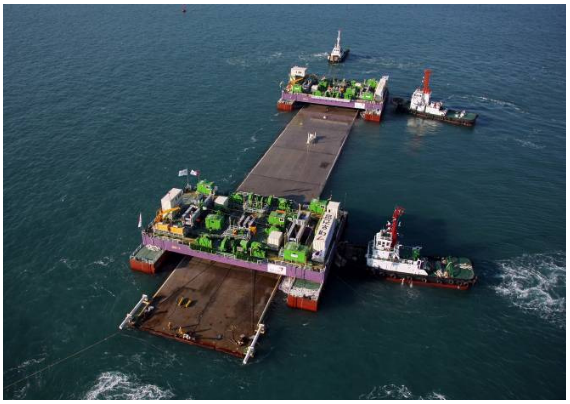


Fig. 15 Immersion with pontoons (BGFL, Korea)

3. Special circumstances

As the demands for connections at areas with special circumstances increase innovative solutions are developed to make the immersion possible. With these solutions tunnels are installed at locations with a long length (up to 3,2 km), large depth (>50m), severe water conditions (currents and swell waves) and underneath a 19th century old building.

3.1 Immersing at greater depths and large tunnel lengths (BGFL – South Korea)

The tunnel for the Busan-Geoje Fixed Link (BGFL) consists of 18 tunnel elements each with a length of 180m and a maximum depth of 48m. The tunnel elements are constructed in a temporary precast yard about 40 km from the immersion area. The immersion of the tunnel element has been performed under sea conditions with both wind waves and swell waves.

During immersion a tunnel element is usually accessible by use of the access shaft on top of the element. This shaft together with the alignment tower is also used for survey from the shore. As result of the large depth and distance from the shore the access shaft and alignment tower are no longer feasible. Several innovative techniques were developed to perform a safe and successful immersion in these circumstances.

3.1.1Central operation

As no access shaft is present, all equipment inside the tunnel element is remotely controlled or monitored from one of the immersion pontoons. For example, the valves of the ballast tanks are equipped with actuators and are operated from the control unit on the secondary immersion pontoon (fig. 16 & 17). Water levels inside the ballast tanks are monitored by using level transmitters. Dome cameras are installed inside the tunnel element to check the ballast tanks and bulkheads during the immersion process. They are also used to track people inside during the immersion preparations.

Fig. 16 Central operation from the command unit

All the data from these systems and the immersion survey system are directed through an umbilical, running from the secondary bulkhead to the umbilical winch on the secondary immersion pontoon. Furthermore, all winches on the immersion pontoons are centrally controlled from two consoles in the command unit. In this command unit, all the relevant data is presented on screens and computers, varying from the immersion survey and ballast water data, forces in the immersion winches, up to the latest wave and weather forecast data. With this information and the control systems, the immersion commander has a good and clear overview of the situation. This makes it possible for him to direct the immersion process from the command centre and to succeed in the immersion operation.

Fig. 17 *Actuator on valve ballast tank (BGFL,Korea)*

3.1.2Survey

The survey of an immersion operation is usually carried out by a Tachometric System consisting of three Total Stations on shore, measuring four prisms mounted on the access shaft and the alignment tower. This system functions appropriate up to a depth of 30m and to a distance of 800m. For deeper and/or longer tunnels an alternative survey is necessary. Such a system has been developed for the tunnel of de Busan Geoje Fixed Link in Busan, Korea.

The system used in Korea 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.

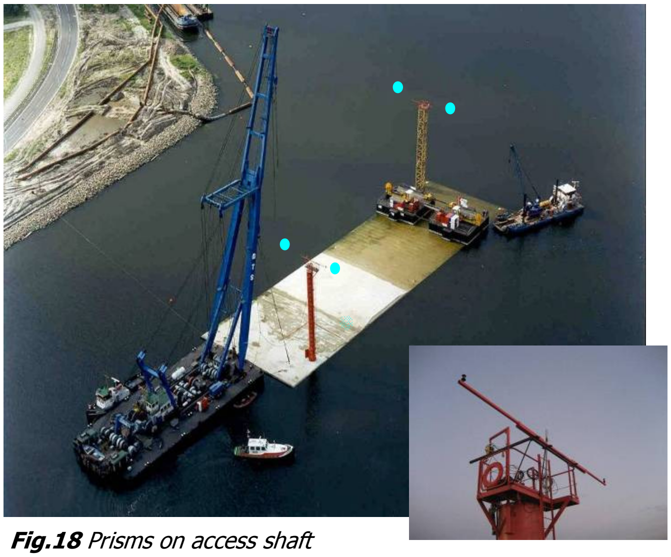


Fig.18 *Prisms on access shaft*

For the first phase in the immersion a taut wire system (fig. 19) has been designed. The taut wire is an instrument running a tensioned steel wire up and down on a drum. The taut wire unit is attached to the primary bulkhead of the tunnel element; the wire is connected to the secondary side of the previously immersed tunnel element. The taut wire reads the length of the wire, as well as the angles of the arm guiding the wire. Information about the secondary side, related to the primary side, is provided by a gyrocompass.

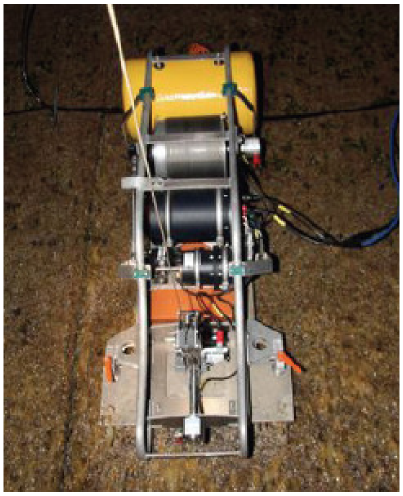


Fig. 19 *Taut wire system*

A USBL system is used as a backup of the taut wire. This acoustic survey system consists of a transducer and several transponders. The transducer, mounted on the primary side of a tunnel element, transmits an acoustic signal. This signal is received by the transponders that are mounted at known positions on the previously immersed tunnel element. The transponders reply to the transmitted signal with their own acoustic tone which is then received back at the transducer. After correcting the sound velocity differences and other variables, the angles and distances from the received replies are recalculated to the tunnel element's position.

In the final phase of the immersion process, the Gina gasket is pulled against the steel end frame to obtain the initial water tightness, necessary to empty the immersion joint. For this phase, distance sensors (fig. 20) have been developed to provide accurate measurements. With their range of approximately 25 cm, the four distance sensors are extended just before the moment the Gina profile touches the previously immersed tunnel element. The millimetre accurate readings of these sensors are used in several ways. The reading of the stroke is a direct indication of the distance. Using the four distance sensors at the corners of the primary bulkhead, a conclusion can be drawn about the position of the secondary end from the differences in the readings of the sensors.

Fig. 20 *Distance sensor*

3.2 Immersing in a tidal river (Limerick – Ireland)

3.2.1 Introduction

The immersed part of the Shannon tunnel consists of 5 tunnel elements, each 100 m in length. All five tunnel elements are constructed at the same time in a casting basin situated in the Northern Approach (fig. 21). The tunnel elements are fitted with temporary bulkheads to enable them to float, and subsequently to be immersed in a pre-dredged trench. After immersion, the tunnel is backfilled with sand and a rock protection layer.

Fig. 21 *Overview Shannon tunnel (Limerick, Ireland)*

All the elements are built in one phase, element 1 located nearest to the river Shannon, element 5 is furthest away from the river (fig. 22). When construction of the elements is completed, the basin is flooded. The tunnel elements are kept on the bottom of the casting basing by filling the ballast tanks. When the tidal window is favourable, tunnel element 1 is floated up and then transported to the temporary mooring site between the coffer dams at the southern end of the northern approach. The immersion trench (the final location where the elements are placed) is cleared and examined.

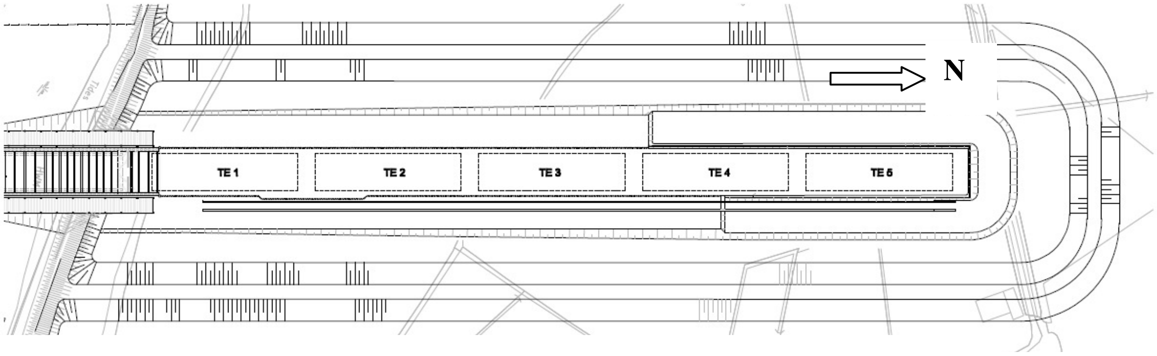


Fig. 22 *Elements built in casting basin (length approx. 700m)*

After this the elements are immersed at a rate of one element per week, depending on the tidal window and other related construction work. Immediately after immersion, the sand flowing procedure under the element will take place. Finally the locking and backfill are placed.

Two main challanges had to be solved for this project. The first one was the high current flow in the river Shannon, the second one were the large tidal differences, which varied between +4.05m ODMH and -3.2m ODMH. During low tide part of the last tunnel element (TE5) protruded above the water surface which led to a specially phased immersion operation for this tunnel element.

3.2.2Current flow

Because of the current forces on the tunnel element a transversal winching system is applied for the tunnel elements. The used system is shown in figure 23.

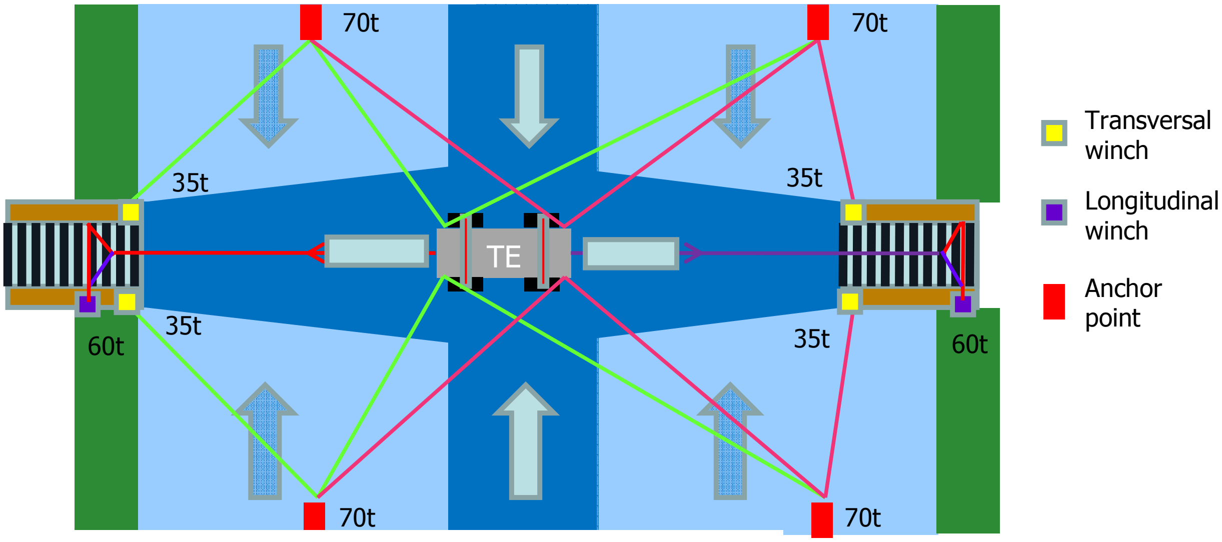


Fig. 23 *Transversal winching system (Limerick)*

The transversal winches are not located on the banks. Because of possible environmental issues, the transversal winches are located at the front of the platforms. The wires run through the anchor points in the river to the tunnel element.

3.2.3Tunnel element 5

For tunnel element 5 (TE5) several challenges and risks must be overcome to make the immersion of this element possible. The main risk is the short time frame in which TE5 is to be floated, transported and immersed at its final location. Due to the large transport distance and the tidal differences (approx. 3m water level difference in 6hrs) a temporary immersion site is to be established (fig. 24).

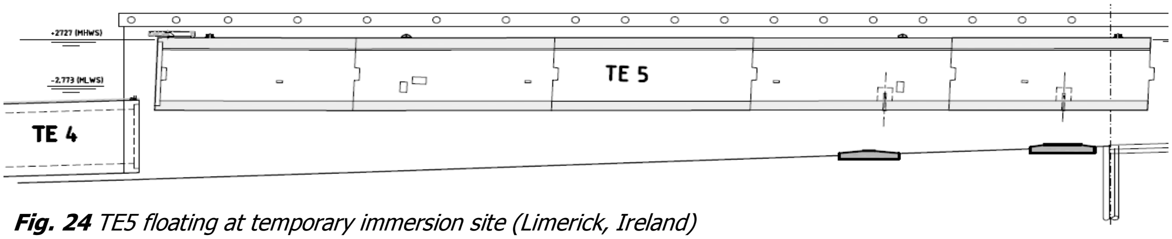


Fig. 24 *TE5 floating at temporary immersion site (Limerick, Ireland)*

After the transport of element 5 to the temporary immersion site (approx. 1.5m from final position), the two rear hydraulically coupled support pins are extracted to a length of approx. 0.90m under the floor slab. When the water level decreases, these pins are set on concrete support pads (fig. 25).

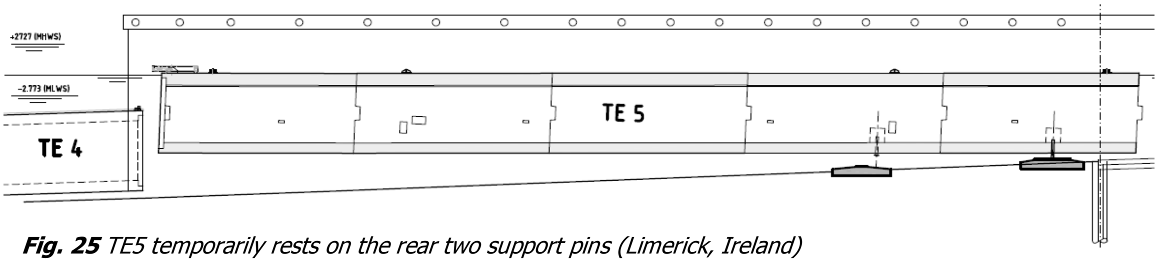


Fig. 25 *TE5 temporarily rests on the rear two support pins (Limerick, Ireland)*

Further depression of the water level will cause the primary end of TE5 to submerge. The secondary end of the element will now protrude out of the water. Extra vertical load is introduced to the rear pins during this phase and will last up to the moment that the element returns to its horizontal trimmed position. Thereafter the element floats up with the incoming tide, and the process can be repeated if necessary.

When final immersion has taken place, all four hydraulically coupled support pins are extracted to approx. 0.6m under the floor slab, the element is placed at the required angle, and manoeuvred towards TE4 (within the range of the primary pin and catch). All these actions are carried out during high tide. Further completion of TE5 can commence once the element is placed on the four pads and the immersion joint has been pumped dry. Figure 26 shows the element resting on the four support pins and pads, and the primary supports.

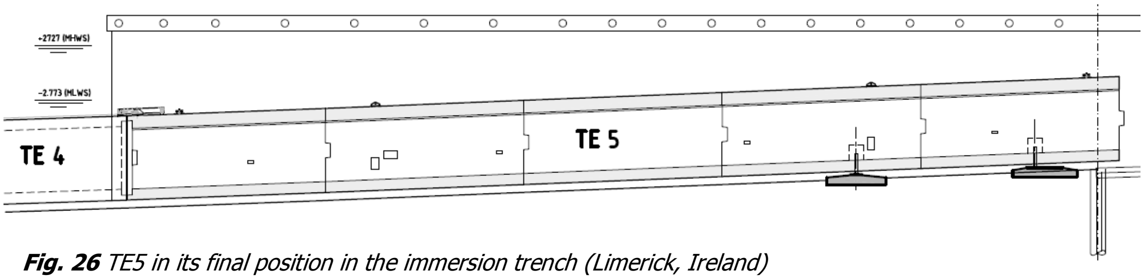


Fig. 26 *TE5 in its final position in the immersion trench (Limerick, Ireland)*

3.3 Immersion with swell waves (BGFL – South Korea)

In an open sea situation swell waves are present. As the wave lengths can be in the range of the length of the element the impact on the structure of the element or immersion system can be fatal. First the reaction of the system to waves is tested and a wave forecast system is set up as the operation takes 2 or 3 days. On the basis of this forecast system, Go / No-Go decisions are made at several moments before and during the immersion operation.

3.3.1 Model testing

An extensive hydraulic model test programme has been carried out to determine the effect of waves on the tunnel element during several stages of the immersion procedure. In a maritime laboratory, a scale model (fig. 27) of the immersion spread has been tested with several combinations of wind and swell waves. For this model test, the immersion trench is modelled together with the tunnel element, the immersion pontoons and the winch wires. The mooring and contraction

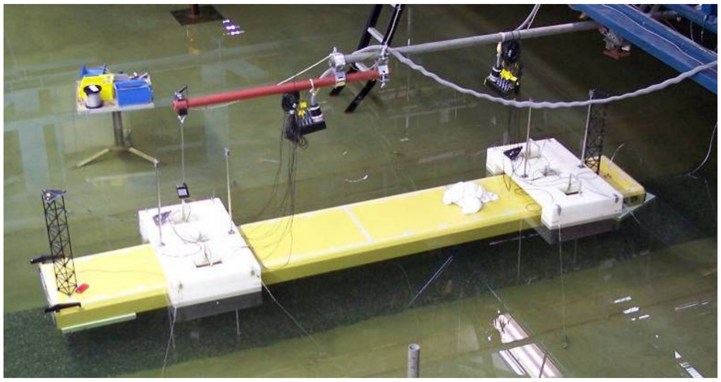
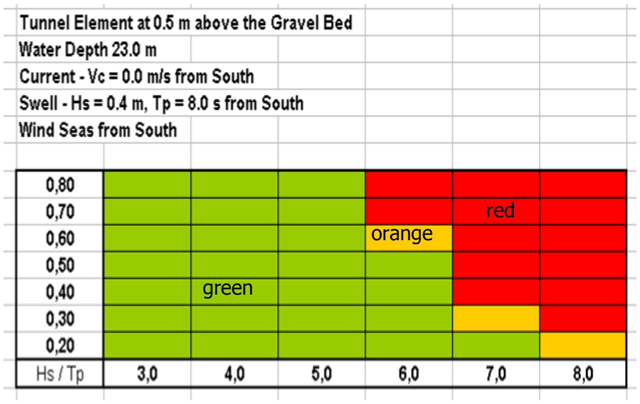


Fig. 27 *Scale model for hydraulic tests (BGFL, Korea)*

wires are modelled with a stiff string and a calibrated spring to obtain the specified stiffness of the wires in the taut situation. During the model tests, the motions of the tunnel element and immersion pontoons in all six directions of movement and the forces in the winch wires are registered.

Subsequently a numerical model is constructed in a multi-body time-domain simulation tool. This numerical model is calibrated so that it reproduces the results from the scale model tests as accurately as possible. This calibrated model is used for over 5000 simulations considering a large number of environmental conditions divided over three sets, with variation of wind wave height, wave period, wave direction and swell conditions. Current forces are also added to this numerical model. Statistical analysis results (mean value, standard deviation, minimum and maximum) are generated for each case. The results per combination of conditions are compared with the criteria value and visualised in numerous criteria tables (fig. 28). If none of the limiting values are exceeded, a green colour is shown. Exceeding of availability and failure constraints are visualised with an orange and red colour.



Tunnel Element at 0.5 m above the Gravel Bed
Water Depth 23.0 m
Current - Vc = 0.0 m/s from South
Swell - Hs = 0.4 m, Tp = 8.0 s from South
Wind Seas from South

0,80	🟩	🟩	🟩	🟥	🟥	🟥
0,70	🟩	🟩	🟩	🟥	🟥 red	🟥
0,60	🟩	🟩	🟩	🟧 orange	🟥	🟥
0,50	🟩	🟩	🟩	🟩	🟥	🟥
0,40	🟩	🟩 green	🟩	🟩	🟥	🟥
0,30	🟩	🟩	🟩	🟩	🟧	🟥
0,20	🟩	🟩	🟩	🟩	🟩	🟧
Hs / Tp	3,0	4,0	5,0	6,0	7,0	8,0

Fig. 28 *Criteria table*

3.3.2Wave forecast system

For the project location, a detailed wave forecast system has been developed based on the world wide MIKE 21 SW wave model. This new generation spectral wind and wave model is based on unstructured meshes. The model simulates the growth, decay and transformation of wind generated waves and swell in offshore and coastal areas.

The wind and wave model covers a large area around Korea (fig. 29), with a fine mesh in the area close to the immersion location. The forecast system for Busan-Geoje Fixed Link provides twice daily hourly forecasts for a five-day horizon of the following parameters:

- Wind speed and direction
- Significant wave height, period and direction
- Swell wave height, period and direction

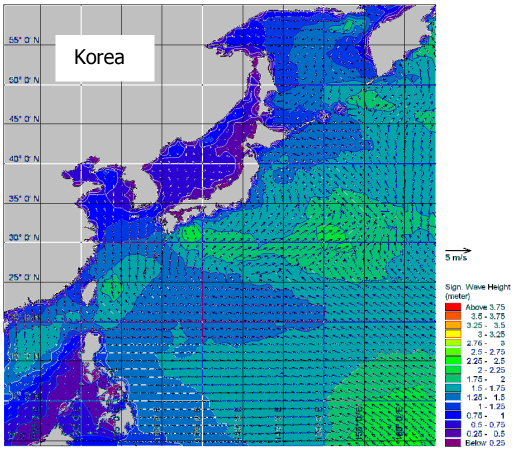


Fig. 29 *Swell wave prediction (large area)*

Since 2004, wave measurements have been taken by a wave rider station close to the tunnel location. These data sets have been used for calibration and validation of the forecast model. After the first immersion season (January 2008 – May 2008), the data was compared with the given forecasts. On basis of the differences, a "Model Response Function" was derived to give better predictions of the waves. This value is dependent on wave direction and wave height. The accuracy of forecasts has demonstrably increased in time. The forecast data is made visual in a wave prediction graph (fig. 30) and is available on the internet.

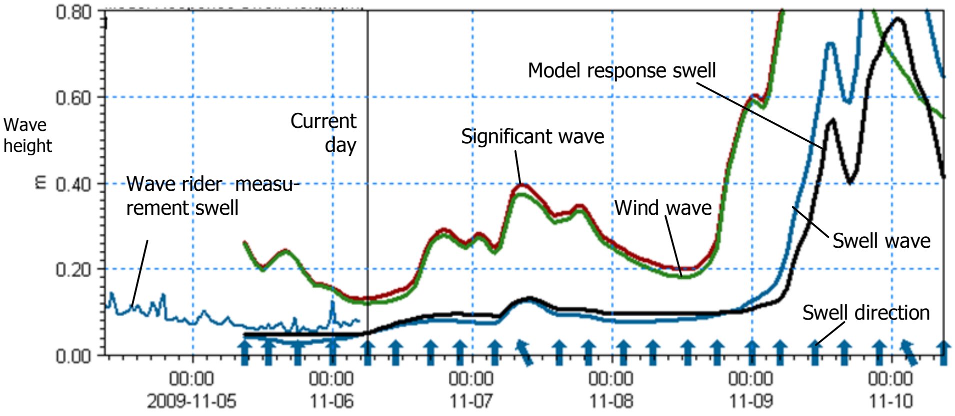


Fig. 30 *Wave prediction graph (BGFL, Korea)*

3.3.3Go / No-Go decision procedure

Before and during the transport and immersion process, several Go / No-Go decisions are taken. The main purpose of these decisions is to check whether the conditions are within the limits for all phases, from commencing transport to a fixed tunnel element on the seabed. Moreover, it is checked to see if all the necessary measurements have been taken and if everything is ready for the oncoming operation. Extensive checklists are filled out.

For each Go / No-Go decision, a decision report is made in which the wave forecasts are checked with all criteria during the total operation. With the wave forecast, a safety factor is applied based on statistics. The procedure was delayed up to nine times for one of the tunnel elements. Half of the immersion procedures have been carried out with no delay at all.

3.4 Immersion in restricted areas

An example of a project realised in a restricted area is the immersion of a tunnel element underneath Amsterdam Central Station (fig. 31). Here the metro line crosses 15 railway tracks, 6 railway platforms and the station building, a historic monument build between 1881-1889. During construction of the tunnel under Amsterdam CS the railway traffic should not be disturbed and nearly no displacements were accepted.

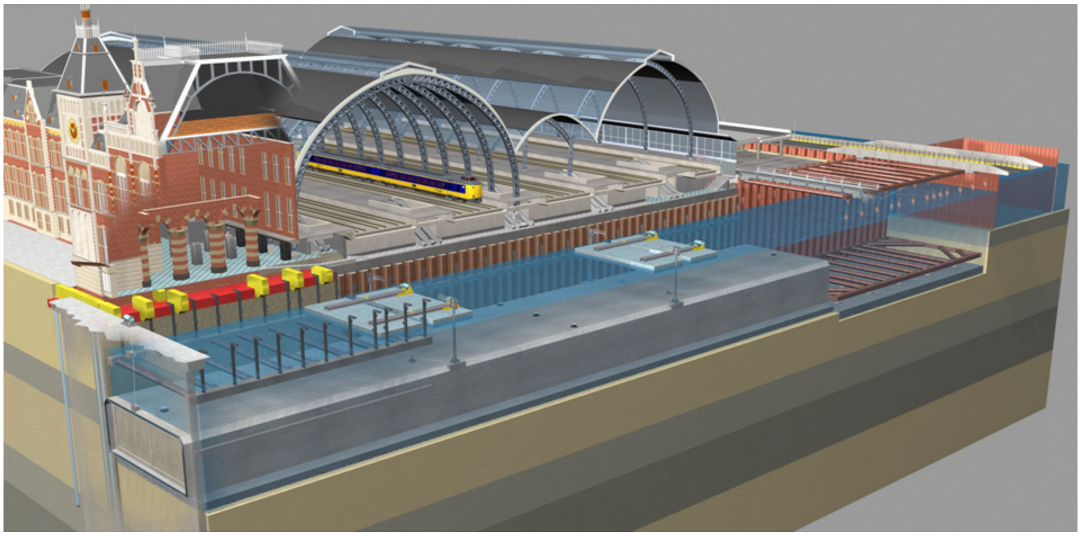


Fig. 31 *Overview tunnel element immersed underneath railway station (NS-line, Amsterdam)*

Before the immersion could take place an immersion trench was created by exchanging the wooden pile foundation of the buildings by two foundation walls with a roof slab on top. As this trench was finished the immersion process could begin.

The following challenges are present for this project:

- Little space between tunnel element and constructions above which leads to an immersion phasing with several water level lowerings, minimized dimensions of the immersion pontoons and an alternative survey system
- Little space between the tunnel element and the retaining walls. Guiding structures are needed to prevent damaging the retaining walls

The tunnel element is 136m long 21m wide and 8m high. The first obstacle to overcome is the water level of the river IJ in relation to the bottom level of the roof slab carrying the trains and passengers. Only 0.4m space is left between them. To create working space underneath the roof slab additional compartment walls are installed in the cofferdam.

Fig. 32. *TE and pontoons under roof slab (NS-line, Amsterdam)*

With the first compartment wall the water level can be lowered from -0.4m NAP to -1.5m NAP so the space between water level and the bottom side of the roof slab increases to 1.5m. Now the tunnel element can be winched under the station. The second compartment wall provides another 1.5m working space so a total of 3m is achieved. The pontoons can be transported to its final position on the tunnel deck and the wires on the suspension winches can be connected to the hoisting points on de tunnel element (fig. 32).

With the freeboard of the tunnel element of about 0.3m a working space of 2.7m between tunnel element and construction above is left. Every part of the immersion equipment should be minimized to make the immersion possible. The height of the immersion pontoons was restricted to 1.2m and small winches were used with a capacity of 7 tons and a height of 1.1m (fig. 33). To be able to bear the immersion weight of 35tons per hoisting point the suspension wire was reeved up to 12 times.

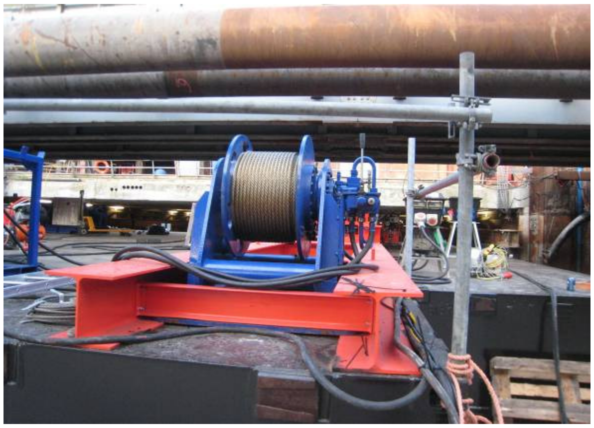


Fig. 33 *Immersion winch (NS-line, Amsterdam)*

The immersion itself has to be executed in phases as well because of struts underneath the station building (fig. 31). First the tunnel element is winched towards the struts. Than the tunnel element is immersed so it can pass below the struts and be winched towards its final position. On the deck of the tunnel element four steel beams are placed on hinges and are lying flat (fig. 34). Once in place, the beams are raise up and attached to

Fig. 34 *Suspension beams (NS-line, Amsterdam)*

brackets anchored in the floor slab. That done the tunnel element is finally suspended to the floor slab and the immersion pontoons can be removed. Subsequently the tunnel element can be ballasted in preparation of the sandflow.

For the project two access shafts are used. A primary shaft at the front end of the tunnel element and a secondary shaft at the rear. Due to the limited space the primary shaft can only be placed after the tunnel element is fully immersed. For the secondary shaft the immersion phasing is very important and restricts its dimensions. During floating the shaft is positioned between the struts of the cofferdam, after the first immersion phase it just fits underneath the floor slab and after immersion the top of the shaft is just above the water level (fig. 35).

Before immersion *After 1st immersion phase* *After immersion*

Fig. 35 *Access shaft in immersion phasing (NS-line, Amsterdam)*

During immersion only one access shaft is available for survey purposes and a traditional alignment tower can not be used because of the construction above the immersion trench. A special floatable alignment tower was developed. The alignment tower is lying flat on the deck of the tunnel element connected with a hinge. During immersion it floats and after reaching the final depth the alignment tower is fixed and can be used as a second survey point.

Another challenge for this project is the narrow space between the tunnel element and the retaining walls. Underneath the station building only 15cm are available on both sides of the tunnel. Several guiding structures were installed to prevent collisions between the tunnel element and the retaining walls.

4. Conclusion

At this moment immersed tunneling has taken a big step forward, it has overcome many challenges to enable it to be a real competitor for a bridge or a bored tunnel. Now there are proven solutions to built immersed tunnels at greater depths under conditions of current flow, sea states and tidal movements. In many cases it even will be the best cost-effective solution.