Busan – Geoje Link: Immersed Tunnel Opening New Horizons

Wim Janssen¹, Peter de Haas ¹, Young-Hoon Yoon²

¹ Tunnel Engineering Consultants, the Netherlands: Technical Advisor to Daewoo E&C for the Busan - Geoje Fixed Link
² Daewoo E&C, Korea

ABSTRACT

The Busan – Geoje Fixed Link will provide a road connection between the metropolis of Busan and Geoje Island. The Link comprises amongst others two cable stayed bridges and an under water tunnel constructed as a concrete immersed tube tunnel. The immersed tunnel has a number of special features: its length of 3,2 km, the water depth of over 35 m, the severe marine conditions, the soft subsoil and alignment constraints. Combined with the scale of the project these features make the design and the construction of the tunnel a major challenge. It is expected that the project will open up new horizons for the use of immersed tunnel technology. This paper highlights these special features and concentrates on the civil and structural aspects only.

1. INTRODUCTION

Busan is the second largest city and a major harbour in South Korea. It is located in the southeast and bordered by the Korean Strait at the south and east side whilst at the north steep mountains arise. The city is developing rapidly; the population grew over the recent years to 3,7 million inhabitants in the city (4,6 million in the agglomeration). The density of population is 4850 inhabitants/km² which is about three-quarter of the density of Hong Kong. The options for expansion are limited due to its geographic location. The Busan – Geoje Link has to create a direct link between Geoje Island and the city of Busan with the objective to allow Busan to expand, to develop industrial areas on Geoje and to add recreational facilities within driving distance of Busan city. Geoje Island is currently connected to the mainland at the west side of the island. The two hours drive by car from Busan city to Geoje will be reduced to 45 minutes after completion of the Link. The Busan – Geoje Fixed Link will provide a road connection between Geoje Island and Gaduk Island as part of a dual carriage motorway connecting the Busan Newport region to the island of Geoje. The Link will be 8,204 km in total, crosses navigation channels and links the small island of Daejuk, Jungjuk and Jeo, which are uninhabited. The principle components of the link are an immerssion tunnel 3240 m long with two-lane traffic tubes in each direction and two cable stayed bridges with respectively one main span of 475 m and a two main spans of 230 m each.

2. THE PROJECT

2.1 Organization

The project is developed as a Public Private Partnership where GK Fixed Link Corporation has been awarded the concession to design, construct and operate the Link for a period of 40 years. The concession is based on a conceptual design for the Link. The GK Fixed Link Corporation consists of
seven Korean contractors amongst them Daewoo Engineering & Construction Co. Ltd. as the leading company of the concessionaire. The joint venture TEC/Halcrow is appointed as Technical Advisor and as such involved from the start of the project. In the joint venture Halcrow and TEC take care of the bridge and tunnel related aspects respectively. The design of the permanent works is almost completed and construction in advance of the permanent works has started.

Figure 1. Geographic location of site

Figure 2. Aerial overview of the project.
2.2 Design requirements and basic constraints

The project has to provide a fixed link from Gaduk island via Daejuk, Jungjuk and Joe island to Geoje island. The basic layout is defined by the requirements to the three navigation channels. A main channel between Gaduk and Daejuk island with a width of 1800 m and a depth of 18 m. For this navigation channel no height restriction is accepted by the Authorities and as such a tunnel has been the obvious way to cross. For the two secondary channels located between Jungjuk-Jeo island and Joe-Geoje island, a minimum width of 435 m and two times 202 m, clearance heights of 52 and 36 m respectively are required. Water depth for both secondary channels is 16 m.

The relative steep shores of Daejuk island and Gaduk island and the deep position of a bored tunnel of about 25 to 30 m below the seabed make it physically impossible to fit an alignment for a bored tunnel in between these two islands. 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 under the seabed has been a logical choice.

Figure 3. Longitudinal section of the link

2.3 Geotechnical

The geological strata vary along the tunnel alignment but top down typical consist of marine clay followed by marine sand and gravel on top of the bedrock.

Marine clay is forming the seabed along the immersed tunnel alignment except in the near shore areas where outcrops of bedrock and shallow sand and gravel layers are found. The thickness of the marine clay exceeds 20 m along most of the immersed tunnel alignment. Most of the immersed tunnel will consequently be founded in this layer.

The marine clay comprises normally consolidated to slightly over-consolidated soft structured clays. These clays have been deposited during the Holocene epoch. The major part of the marine clay, from seabed down, is "very soft to soft" and of "very high plasticity" to "extremely high plasticity". The marine clay plasticity index ranges from 56% to 85% with an average of 68%. The range of saturated unit weights of marine clay is 13.9 to 15.4k N/m$^3$, with a mean value of 14.6k N/m$^3$.

2.4 Marine conditions

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. An impression is given below by the 10000 years return period hydrological conditions for the south wave direction. The maximum design wave height Hs is
9.20 m and the corresponding mean wave period $T_m$ is 15 sec. The principle wave direction due to typhoons is South.

The current is mainly influenced by the tide, which is a typically semi-diurnal type with a spring tide range of 1.60 m with a maximum current of 0.80 m/sec at the tunnel alignment.
The waves on site comprise three main components:
- Locally generated wind waves, mainly from the northwest and northeast during the winter season;
- Deep water generated wind waves, mainly from the South and South east, during the summer season;
- Deep water swell waves, mainly from the South and South east.
During construction of the marine works the swell waves with a $H_s$ of more then 0.50 m and a period of $> 6$ seconds have to be taken into account. In the summer season most of the time waves exceeds these values.

2.5 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 explain why, on a large scale basis, seismic hazard analyses lead to low hazards for Korea. The closest fault to the project site is the Yangsan onshore fault and the decisive (characteristic) earthquake will be an event on the Yangsan Fault at a distance of 5-10 km to the east of the project site and with a moment magnitude of 5.7-6.

A two-level earthquake hazard design approach has been adopted. The two earthquake hazard levels are the operating design earthquake (ODE) and the maximum design earthquake (MDE). In respect of strength the MDE is regarded as Ultimate Limit State, but in order to survive seismic loads (prevention of major failure and maintaining safety) the MDE is regarded as service limit state, with the requirements that all joints shall remain watertight and rebar stress does not exceed yield strength $f_{yk}$.

3. THE TUNNEL’s SPECIAL FEATURES

In a number of ways the immersed tunnel part of the Busan – Geoje Link is special and imposes a number of challenges.
- The alignment constraints impose a position above seabed at both outer ends of the alignment;
- It is after the Øresund Link between Denmark and Sweden the longest immersed concrete tunnel in the world;
- The tunnel trench reaches to a depth of about 50 m below mean water level;
- The site is exposed to severe marine conditions;
- The subsoil is characterised by its extreme weakness.
And in addition to this the construction method by an immersed tunnel is an unknown phenomenon in South Korea.

3.1 Tunnel alignment

From the deepest point the alignment climbs over about 95 m to the highest elevation of the cable stayed bridge over the main navigation channel. Maximum gradient is 4.73%, a little less compared to the gradient towards the east portal at Gaduk island which is 5%. Both exceed the maximum design gradient under standard conditions of 4%. The gradient at the west side of the tunnel alignment conflicts with the design objective to place the tunnel under the seabed. Due to a local depression in the seabed at about 350 meters east of the western portal the underside of the tunnel structure is positioned about 8 m above the original seabed.

The preliminary soil investigations indicated a minimum thickness of the soft marine clay at the location of the depression allowing an acceptable soil improvement and raise of the seabed in order to
bury the tunnel. More detailed soil investigations during design showed an extension of the marine clay under the depressed seabed. As a modification of the vertical alignment to a deeper position, resulting in a gradient of 6% was not an option for the Authorities an extensive study has been carried out in order to explore the technical options to overcome the problem. From a number of alternatives varying from sand compaction piles, soil replacement, preloading and deep cement mixing the latter has been selected as technical most appropriate and economical acceptable method. The areas with DCM piles will be extended over a considerable distance at both sides of the tunnel in order to support the sub-sea embankment which raises about 16 m above the original seabed and has to protect the tunnel against stranding ships and erosion.

3.2 Tunnellength

The current design comprises 18 elements of about 180 m in length. The concrete cross section is 60 m² and the tunnel width is 26.5 m and the height 9.75 m. The two elements at the Daejuk island side are tapered and vary in width from 26.50 m to 28.50 m to create space for a climbing lane. In order to economize the production of the elements the principle used for the element production of the Øresund has been considered. The casting at a fixed location moving the elements by skidding was considered too complex, costly and as such not economical justified. The casting facility has been changed into a system using a moveable casting facility along the element length allowing full section casting at various locations. The choice for this construction method has been supported by the good experience with this method on a number of tunnel projects in Switzerland.

![Figure 6. Model of precast yard for fabrication of 4 tunnel elements](image)

3.3 Tunnel depth

3.3.1 Waterproofing

At the Daejuk island side of the alignment the seabed is about 35 m below mean water level, resulting in 47.5 m water to the underside of structure, increasing till about 55 m due to wave action. All concrete segmental tunnels constructed in Western Europe are in moderate water depth of about 15 m. The deepest one is the Calandtunnel in Rotterdam with 26 m water to the underside of structure. The
Bosphorus immersed tube recently under construction will have locally almost 60 m. The deep alignment has an impact on the immersion and provisions to prevent water ingress in the tunnel. In spite of the fact that the experience with concrete immersed tunnels is limited to a water depth of maximum 26 m the concept of a segmented concrete tunnel has found technical feasible. The cross section has been designed such that at least a defined part of the cross section is under compressive stress assuring a sufficient barrier against ingress of water through the concrete. The full cross section will be casted in one process avoiding horizontal construction joints. The segmental joints will be provided with a double seal. The primary deal is a modified injectable waterstop which can accommodate the water pressure under great displacements. In the Øresund Link tunnel the second seal consisted of a hydrophilic rubber placed in the joint. The expected displacements during an earthquake cannot be accommodated by this rubber and a more robust solution building in omegas (Ω) in every segment joint are considered in order to assure sufficient reliability during an earthquake under the great water depth.

3.3.2 Dredging in relation to tunnel depth
Most of the trenches for immersed tunnels are dredged with cutter suction dredger. This type of dredger can dredge only up to 30 meter water depth. For the deeper sections there are only two alternatives; grab dredgers and trailer hopper dredgers. Grab dredgers can achieve relatively low production rates only and could cause environmental problems when working with open buckets. Large hopper trailer dredgers can excavate up to 100-meter water depth and are used in Korea for mining sand for reclamation works. Due to the high operational cost these large dredgers can only operate economical if they can work continuously during a larger period of time.

3.4 Marine conditions

3.4.1 During installation
The exposed conditions of the sea are unique for the location of an immersed tunnel. This has an impact on the weather window during which marine work can take place.

The mayor challenge for the immersion operation is the swell waves, which impose large movements and forces on the tunnel element and the immersion equipment. In order to quantify these forces and movements a numerical wave model has been made of the area and 10 years wave data has been analysed. Furthermore a waverider has been installed in June 2004 south of the Jungjuk Island. Hydraulic and numerical model tests have been carried out with the tunnel element and the immersion rigs. From the tests it has been concluded that in particular swell waves larger than 0.80 m and Tp more than 6 seconds cause large movements and loads. In combination with the wave analysis it became clear that immersion during the summer season will be difficult and most likely special equipment has to be developed. For the time being it has been decided to immerse the elements in the winter season.

Another effect of the large swell waves is the relatively high uplift and horizontal loads on the elements after they are placed in the tunnel trench. Additional filling of the ballast tanks combined with placing of the foundation layer and locking fill directly after immersion are means to secure the element and will be taken into account when determining the operational window for immersion and placing of the foundation layer and backfill. A weather and wave forecasting system will be set in place to predict the wave height and period during the immersion period.

3.4.2 Effect on the permanent structure
In order to investigate the effect of the large waves on the permanent tunnel structure hydraulic model test has been carried out at DHI laboratory in Denmark. For the extreme event the typhoon wave of Hs = 9.2 m has been defined. Direct after construction the backfill of rock material is very permeable but during lifetime fine clay material will penetrate, resulting in a more impermeable behaviour of the backfill and rock protection. Both horizontal and vertical forces were investigated and it was found that both increase when the grain sizes decreases. These forces are however dynamic; change in
direction and intensity cause small movements of the tunnel element itself allowing balance of water pressure around the tunnel.

Where the tunnel top protrudes above the original seabed large waves will have an impact on the stability of the rock-protection of the tunnel. Hydraulic model test have shown that pre-cast artificial rock elements of more then 30 tons were needed. In order to reduce the weight and thickness of the protection layer Core-loc™ blocks have been chosen for the most affected part of the tunnel (the first three elements on the Gaduk side).

On both ends of the tunnel existing islands are extended artificially to allow construction of the transition zone between the immersed tunnel and the approaches. To protect these reclaimed extensions, normally Tetrapods are used in Korea. Hydraulic model test performed at the Korean hydraulic institute Kordi showed that Tetrapods with a weight of 50, 60 and 70 tons are needed.

3.5 Subsoil conditions and tunnel foundation

In the alignment the Marine clay is the dominant soil type. The thickness of the Marine clay deposits varies but usually exceeds 30 m and is located directly below the foundation level of the tunnel. The very soft marine clay and the very high plasticity in combination with the low saturated unit weights, the low rate of over-consolidation and the structured nature of the soil have been crucial for the foundation method finally chosen.

Normally the aggregate of the weight of the immersed tunnel, the backfill and rock protection is less than the weight of the excavated trench material. Due to this and under the assumption that the original soil does not settle, theoretically no settlement will occur as the weight of the tunnel is less than the weight of the original soil. On the basis of the above normally immersed tunnel are not provided with a piled foundation. There are just a very small number of immersed tunnels which are by the author’s knowledge founded on piles. The IJ tunnel in Amsterdam, the Rotterdam metro, a part of the Zeeburgertunnel in Amsterdam and the Chang Hong tunnel in Ningbo China are founded on piles for various reasons.

The Busan situation is special in this respect. The backfilled material which needs to be of a certain weight in order to lock in the tunnel horizontally has a higher unit weight compared to the original marine clay. This results in an increase of the effective stress under the backfill and associated settlements of the backfill and the tunnel. The increase of effective stress could well be in the range of the over consolidation level, implying the risk of increased settlements because of the less stiff soil behaviour (ration between re-compression and compression index is almost 14). In addition to this the magnitude of settlement will vary along the alignment due to variations in soil characteristics and amount of backfill. The latter depend on the accuracy of trench dredging which is low because of the extreme depth of the tunnel trench and the severe marine conditions.

Figure 7. Plaxis model of tunnel and trench section

The segmental concrete tunnel has the ability to adjust to differential settlements. But too large joint opening shall be avoided. For this reason it has been decided to improve the marine clay by Deep Cement Mixing piles DCM. By this method cement is injected direct into the clay and in situ round columns of a clay/cement mixture are made. The diameter of the columns depends on the equipment used. For offshore works normally 4 columns are made at the same time forming a square of 1,80
meter by 1,80 meter. This soil improvement method removes the cause of the subsoil settlement and brings this aspect back into the existing range of experience.

The use of DCM piles also reduces the difference in subsoil stiffness at the locations where the tunnel alignment changes from marine clay into the outcrops of bedrock at the both ends of the tunnel alignment. And as such reduces the differential settlement over these parts.

Figure 8. Offshore equipment for making piles up to 70 meter depth

4. CONCLUSION

The tunnel section of the Busan-Geoje Link is special for many reasons. The article above has introduced the project and highlights these special features. They go far beyond today’s common practise within concrete immersed tunnel technology. Not all of the special design aspects have been identified in full depth at the start of the project but awareness developed ongoing the design process. This has been a challenge to all involved. At the moment this paper was written not all design issues have been solved completely but the most essential design decisions have been made. It is expected that completion of the Link will open new horizons for the use of immersed tunnel techniques in deep water, severe marine and difficult geological conditions.