Drill and Blast Method for South Korea’s Longest Twin-Tube Subsea Road Tunnel

S.C. Lee¹, K.C. Ahn¹, S.K. Lee¹, H.L. Nam², Y.H. Suh², S.Y. Lee³, Y.J. Park³, S.M. Kim³ ¹TESO Engineering Co., Ltd., Seoul, S. Korea, ²Hyundai Engineering & Construction Co., Ltd., Seoul, S. Korea ³The University of Suwon, Suwon, S. Korea

1 Introduction

Because of increasing traffic volume and reducing shipping hours, there are not only investments to an inland traffic network but also to fixed-link from the shore to the island and to the peninsula. The strait crossing can help reduce travel time, manage more effectively tourist growth and promote further development in the area. But construction of artificial structures on the sea will raise problems like disturbance of marine life, interference with sea lane, and so on. Therefore, decision of the structure type for strait crossing should be carefully considered.

This paper addresses the basic design of South Korea’s longest twin-tube subsea road tunnel linked between Boryeong and Taean, as generally shown in Figure 1.1.

2 Tomography and Geological Conditions

After rough geological analysis using a geological mapping and satellite imaging during a pre-investigation program, we carried out exploration of Multi-Beam Echo Sound, refraction seismic profiling, vertical drillings from barges, and so on to determine the seabed tomography and geological conditions.
As seen Figure 2.1, there are complex tomography and geological characteristic sections such as open-cut session at tunnel starting point, a passing section under radar base, a weak zone (fault, rupture, etc.) on the sea, a rock type boundary section, a shallow overburden section at a land area of tunnel ending point. The geology of tunnel is mainly Precambrian metamorphic rock, penetrated granite at the Mesozoic Jurassic and Cretaceous period. Especially as a result of ground survey examination, metamorphic rock was made-up of schist and phyllite depending on the degree of metamorphic, and was penetrated by a number of mesozoic acidic dikes.

Five lineaments, which intersect in the main route, were analyzed by DEM (Digital Elevation Model) analysis on the land and the seabed and four faults and two geological abnormal sections were found. Among the rest, F-1 (over-thrust), F-2 (fault), F-3 (fault), L-2 (geology abnormal section) and F-4 (fault) had a little effect on the tunnel crown. In particular, F-2 (fault) was developed into ruptured fault zone about 40m, therefore a detailed construction will be required, likewise at L-1 (rock type boundary section), there is a need of a fitting water-proof method by reason of under the seabed (See Figure 2.2).

3 Structure Types

Between Daecheong port and Wonsando Island, inflow section of Chunsu Bay, was a main route and anchorage for large ships. Because of the Fisheries Resources Protection Area, migratory bird lands, fisheries and beaches are also located near the area, the conservation of the ocean ecosystem was essential. Therefore, when selecting the structure type passing through the sea between Daecheon port and Wonsando Island, we had to completely analyze traffic flows, interference problems with marine transport and impacts on the ocean ecosystem by constructing the structure, then decide the structure type.

Table 3.1 Comparing the Structure Type Crossing Chunsu Bay

<table>
<thead>
<tr>
<th></th>
<th>Subsea Tunnel</th>
<th>Approach Bridge + Suspension Bridge</th>
<th>Approach Bridge + Man-made Island + Subsea Tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Outline</strong></td>
<td>2-lane, Twin-tube tunnel</td>
<td>2-way 2-lane bridge</td>
<td>Approach Bridge</td>
</tr>
<tr>
<td></td>
<td>Length : 6.9km(subsea 5.1km)</td>
<td>Approach Bridge : 4.3km(Width 12.2m)</td>
<td>3.3km(two-way, two-lane)</td>
</tr>
<tr>
<td></td>
<td>Cross section : Width 12.0m, Height 8m</td>
<td>Suspension Bridge : 1.1km(Width 14.0m)</td>
<td>Man-made island : 0.75km</td>
</tr>
<tr>
<td><strong>Interference</strong></td>
<td>Eliminate the Interference by passing through subsea</td>
<td>Require a excess span length at the Main Route</td>
<td>Necessary the movement of Anchorage</td>
</tr>
<tr>
<td><strong>Environment</strong></td>
<td>Minimize an effect to ocean environment</td>
<td>Occur the ocean environment pollution during construction and operation</td>
<td>Change the ocean current by artificial shelter</td>
</tr>
<tr>
<td></td>
<td>Also minimize a pollution effect during operation</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Economic</strong></td>
<td>Minimize the Movement/ Compensation expenditures</td>
<td>Exceed the Movement/ Compensation expenditures</td>
<td>Exceed the Movement/ Compensation expenditures</td>
</tr>
</tbody>
</table>
As seen Table 3.1, compared with the strengths and weaknesses of each structure type, a subsea tunnel was selected because it eliminated interference with marine transport, minimized impacts to ocean environment and ensured the passage of vehicles at all kinds of inclement weather.

After fixing the structure type for subsea tunnel, we selected the tunnelling method which allow for an analyzed geology condition and an economical efficiency. The construction site is located in a variety of geological conditions from weathered rock to hard rock layers and to the complex ground including numbers of abnormal geology layers, therefore NATM, has a good countermeasure like a pre-boring and a pre-reinforcement during construction, was selected.

4 Subsea Tunnel Plan

A subsea tunnel plan should given a special attention according to the following. First, geology survey on the sea is more vulnerable than the ground. Second, because the center of tunnel is located at the lowest point, pumping of inflows are always required during operation. Last of all, the weakness of geology, made by the abnormal layers passing through the strait, was considered. Even though there is limited geological information for design, we have to locate the tunnel on the optimal geological condition and satisfy not only a stability and an economical efficiency but also minimizing maintenance expenses during operation.

4.1 Longitudinal Profile of the Tunnel

In Norway 25 subsea road tunnels have been completed since constructed the Vardø tunnel in 1981. All these tunnels are excavated in bedrock by drilling and blasting, with a strong reliance on probe drilling and pre-grouting, and with drained rock support structures. Key data of completed Norwegian subsea road tunnels were as follows; length 1.6–7.8km, maximum gradient 8~10%, maximum below sea level 56~287m and minimum rock cover 20~50m. Fjord, constructed the subsea tunnels in Norway, has a steep slope at the seabed, a deep-sea and a thick sedimentary layer. Accordingly, tunnel entrances are located away from the coastline toward the land and planned a rapid gradient of longitudinal profile. Figure 4.1(a) shows a minimum rock cover of completed Norwegian subsea tunnel, representing function of bedrock depth.

![Figure 4.1: Rock cover](image_url)

a) Rock cover of Norwegian subsea tunnel  
b) Project rock cover
The rock cover can be looked upon as including faulting rupture zones and clay gouges that of a peculiarity of a fjord. Therefore Figure 4.1(a) is a guideline, which has a high safety factor and the reference when planning subsea tunnel in Norway, considering a difficulty of survey on the sea and getting a rough geological conditions.

In this project, a vertical drilling situation was in good conditions, so it was easy to obtain almost all of geological conditions of the route. Therefore, rock cover was defined as 'depth of water + sedimentary layer', considering the maximum depth of water (about 35m), shallower than Norway. Our analysis of subsea section of the route, assuming previously mentioned, told us that an average rock cover was 40.3m and a lack section compared with a Norwegian standard was a submarine canyon, a little smaller than cases of Norway. A section of submarine canyon, distributed thin sedimentary layers and be verified that has a good bedrock, was known that has a few risks. But we have planned a pre-boring and pre-reinforcement for stability during excavation. Figure 4.2 shows a longitudinal profile considered a rock cover and a design criterion for gradient (5% on design speed 60km/h, if necessary 6%).

![Figure 4.2: Longitudinal profile of the subsea tunnel](image)

4.2 Tunnel Cross-Section

As a result of forecasting of traffic demand, AADT(Annual Average Daily Traffic) is 15,198 and two lanes are required. Therefore, tunnel was planned as a twin-bored two-lane tunnel. The cross-section was designed considering the following criteria; 3.25m width per lane, 1.0m side margin, installation of an inspector pathway both side, 1,030mm jet fan diameter.

5 Inflow Rate Guideline

The ground-water flow into tunnel effects the stability of tunnel, and the rate of inflow is reflected into the standard selection of facilities like drain pipes, sumps, sewage treatment facility and so on. Especially at the subsea tunnel, inflow rate guideline affects the cost of construction and maintenance conflicting with each other (see Figure 5.1). Therefore, the inflow rate guideline was adequately decided to consider not only the economical efficiency but tunnel stability, reduction of maintenance, and so on.
In South Korea, inflow rates generally use an excess value, 2~3 m³/min/km, in reference to experience on the Seoul Metro. But the Korea Expressway Corporation has recently applied a reduced inflow rate, 0.3 m³/min/km, to the field, reflecting actual survey on the domestic road tunnel cases.

For international land tunnels, the goal value of inflow rate was generally about 0.1m³/min/km, but if these standards apply to the subsea tunnel, an excessive construction expense was expected, so the standard of inflow rate set a range of 0.3~0.5m³/min/km. Particularly, as a result of actual survey of the Norwegian subsea tunnel, it was generally managed below an average of 0.2m³/min/km, and it had been showing signs of decrease during operation. The Seikan Tunnel, experienced a huge influx of water because of weak ground conditions and deep sea had a total discharge about 31m³/min (≒0.57m³/min/km) at an initial step of operation in 1987, but since then a total discharge has been decreased to 22m³/min(≒0.41m³/min/km) in 2002. As this is a result after increasing inflow rates following a large earthquake, it shows that an inflow into tunnel is decreased by time.

Therefore, in this project, the inflow rate guideline was set to a value about 0.5m³/min/km, considering a actual survey result of similarly tunnel construction cases, the tunnel pass through almost a bedrock.

6 Excavation and Reinforcement Design

6.1 The Advanced Prediction Method During Excavation

Because of a limited survey situation on the marine, a geological survey reliability of subsea tunnel is weaker than a land tunnel. Therefore, to overcome uncertainty of geological survey, the advanced pre-boring method was carried out aggressively to the tunnel face. Figure 6.1 shows the flow chart from the advanced pre-boring to the excavation, and there is necessity to overlap the pre-boring of tunnel face for obtaining the survey reliability.
The first step is a TSP (Tunnel Seismic Prediction). It is an advanced predicting method about 20 of transmission borehole were set to the tunnel wall and then found out the discontinuity of tunnel face by acquiring/processing/analyzing the seismic reflection wave, induced by explosion. Detective range of this method is about 200~300m, so we planned the TSP every 200m all tunnel route.

The second step, a long distance horizontal drilling (about 100m) is carried-out to an abnormal section and a weak zone predicted by a marine geological survey and a TSP, to find out their correct characteristics, locations and scales. After gathering samples above NX size, we planned a direct confirmation of geological condition and finding the inflow state into the borehole.

The third step, a probe drilling is executed to about 20~30m of advanced tunnel face. Probe drilling, performed by a drill equipped MWD (Measurement While Drilling), can obtain the information of a drilling speed, an impact pressure, a turning force, and so on, as using above, a rock strength and a crushed rock rate ahead of tunnel face will be known. Also a measurement of inflow rate or a water injection test is carried-out there, and then will be determine the pre-grouting whether it is necessary or not.

6.2 Pre-Grouting

As you seen in the flow chart of Figure 6.1, necessary of pre-grouting is determined by the volume of inflow in the probe drilling. The guideline is 0.2 l/min/m (0.5m³/min/km, if based cross section of tunnel). In cases that inflow rate of probe drilling exceeded the pre-grouting guideline, we have studied the grouting pattern. As a result of numerical analysis about the waterproof effect around tunnel section by pre-grouting range, grouting should be applied all around tunnel section about depth of 5~7m, if takes effect (see Figure 6.2).

Distance between grouting boreholes was determined, a rock section was 3~4m and a weathered rock section was 2m, considering the similarly cases of abroad. And the others determined as follows; grouting boring distance was 20~30m, grouting materials was micro-cement.

6.3 Support System

The subsea tunnel was designed to have more support system than a land tunnel for stability increase (Table 6.1). Especially to prevent the deterioration of supports by chloride invasion, it added silica-fume to shotcrete for enlarging the durability by forming the fine structures, and minimum shotcrete thickness was
limited 8cm to block the infiltration of seawater. Rockbolts are Combi-Tube, as generally used in Norwegian subsea tunnels, possibly a compact grouting injection around the bolt, so anti-corrosion was reinforced. The strength of concrete lining was set to $f_{ck}=40$MPa, high-strength concrete, by using the cement admixed blast-furnace slag, and it ensured that concrete cover was above 8cm for enlarging the chloride invasion resistance.

Table 6.1 Rock Support Structures

<table>
<thead>
<tr>
<th></th>
<th>SP-1</th>
<th>SP-2</th>
<th>SP-3</th>
<th>SP-4</th>
<th>SP-5</th>
<th>SP-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outline</td>
<td><img src="image" alt="Outline" /></td>
<td><img src="image" alt="Outline" /></td>
<td><img src="image" alt="Outline" /></td>
<td><img src="image" alt="Outline" /></td>
<td><img src="image" alt="Outline" /></td>
<td><img src="image" alt="Outline" /></td>
</tr>
<tr>
<td>Q</td>
<td>Above 40</td>
<td>10~40</td>
<td>1~10</td>
<td>0.1~1</td>
<td>Below 0.1</td>
<td></td>
</tr>
<tr>
<td>Shotcrete(cm)</td>
<td>8(SFRS)</td>
<td>8(SFRS)</td>
<td>12(SFRS)</td>
<td>16(SFRS)</td>
<td>20(SFRS)</td>
<td>25(SFRS)</td>
</tr>
<tr>
<td>Rockbolt(m)</td>
<td>3.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Steel Rib</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>LG 70×20×30</td>
<td>H 100×100</td>
<td>H 150×150</td>
</tr>
<tr>
<td>Auxiliary Techniques</td>
<td>-</td>
<td>Fore polling, if necessary</td>
<td>Umbrella Arch Reinforcement</td>
<td>Umbrella Arch Reinforcement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-Grouting</td>
<td>-</td>
<td>Pre-Grouting $\Theta=360, \theta=5.0~7.0$m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete Lining</td>
<td>40cm (Reinforcement)</td>
<td>40cm (Reinforcement)</td>
<td>40cm (Reinforcement)</td>
<td>40cm (Reinforcement)</td>
<td>50cm (Reinforcement)</td>
<td>50cm (Reinforcement)</td>
</tr>
</tbody>
</table>

(Note: SFRS=Steel Fiber Reinforced Shotcrete, LG=Lattice Girder)

7 Drainage System

The minimum design level of subsea tunnel is EL. (-) 88.5m, so that if applied the waterproof type tunnel, it is expected that have high pressure above 0.8MPa to the lining. Therefore, they applied partial drainage system to subsea tunnel for reducing water pressure, and if the weak geological condition zone is met, applying the pre-grouting around the tunnel for sharing the water pressure with surrounding ground. In addition, for a smooth drainage under sea section, Induced drain material is applied, a more water-passing capacity than a normal non-woven fabric, and by using a compartment waterproof system, restricted the movement of sudden ground-water inundation (see Figure 7.1).
The subsea tunnel has to drain the inflow water by pumping, because of characteristic of longitudinal profile. The sump, collecting the inflow water, was planned reasonably, because it is related to construction expenses, safety operation of tunnel and maintenance. The main point of internal standard for sump of underground facility, like a domestic subway and all that, is as follows; design the sump to store the waters during minimum 30 min and install the spare pumps and pipes.

As some Norwegian tunnels stored the water by day and drained by night, electric charges were reduced, but inflow rate in a case like this was small, below 0.2 m$^3$/min/km. If this idea applies to a long tunnel which flows into the waters, it will affect the excess initial construction expenses and stability of Sump structures.

In this project, based on the inflow rate, 0.5 m$^3$/min/km, the sump and spare pipes/pumps that stored the water in an hour were designed.

8 Conclusions

This paper shows about the basic design of South Korea's longest twin-tube subsea road tunnel, using drill and blast, includes as follows; longitudinal profile of subsea tunnel, pre-boring method during excavation, pre-grouting, support, waterproofing design and so on. The main point of subsea tunnel design is as follows; first of all intensify the survey in the tunnel during excavation for overcoming limitation of a survey on the marine, and secondly make the system reflect its results directly in the field.

Therefore, during the detailed design step, it will be reviewed the basic design using the geological data, obtained by the additional field survey, and designed the design elements in detail for the field application.

9 References

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