A Case Study of Subsea Shield TBM Tunnel Design: Istanbul Strait Road Tunnel Crossing Project

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1. Introduction

Recently, Shield TBM has been increasingly applied to constructing shallow tunnels in urban area, riverbed tunnels and subsea tunnels under poor ground conditions. Notwithstanding increase in shield TBM road tunnel, the subsea tunnel, diameter of which is over 8.0m, is very specific construction case as yet.

Therefore, There are many attempt and study to extend diameter of the tunnel with shield TBM. As part of this effort, Jeong (2002) [4] performed and introduced the shield TBM method to Korea. In addition, Jeon, et al (2003) [3] suggested the important items to be considered for performing shield TBM. Kim, et. al (2007) [1] also suggested the important item to be considered for selecting type of tunnel, and introduced improved shield TBM method to Korea considering experiences of riverbed tunnel through Han river (located in Seoul). Shin (2006) [2] introduced generally the trend and technology of subsea tunnels in the world.

The following chapters describe general informations of shield TBM method and key items to be considered in conceptual design "Istanbul Strait Road Tunnel Crossing Project". The key items, which should be considered for applying the shield TBM method to this project, are geological comlexity, high water pressure, aseismatic design and the like.

This paper is written with reference to conceptual design of Istanbul Strait Road Tunnel Crossing Project. Therefore, the design contents may be changed at the stage of detail design.

2. Project Overview

Recently, traffic volume between European side and Asian side has greatly increased because of explosive growth of population and development of economy in Istanbul. Therefore, Istanbul city requires an extensive transportation infrastructure, and for this purpose, a plan was made for expansion of the road system underground (Istanbul Strait Road Tunnel Crossing Project). In December 2008, TKJV(Turkey-Korea Joint Venture) including SK and several Korea companies accepted the order of large infrastructure project estimated at a billion US dollar and titled "Istanbul Strait Road Tunnel Crossing Project". This project is a historic event that connects between Asia and Europe with 3.34 km long subsea tunnel. This project is planned as BOT(Build, Operate and Transfer). In addition, It will be performed by Sambo engineering as the main design company.

SK and Sambo engineering make up a design team and currently perform design. The preliminary and detail design is performed for 18 months starting on September 2009. The project consist of 3 parts, and important structures are shield TBM, NATM, Open-cut tunnel and ventilation shaft in part 2. The length of shield TBM tunnel is planned as 3.34 km long and double deck type considering the geologic conditions, hydraulic conditions and feasibility in this project site.

NATM tunnel is linked to Shield TBM tunnel at the shaft and the double deck type tunnel is altered to twin tunnel type at that point.
In this project, one of the principal considerations is the earthquake. Turkey is located in an area occurring earthquakes over 7. And Istanbul is adjacent to the North Anatolian Fault. On account of the last point, the aseismatic design shall be performed against earthquake over 7.5. In addition, improvement of ground will be applied to this design against liquefaction. Figure 1 shows a schematic of Istanbul Strait Road Tunnel Crossing Project.

Figure 1. Istanbul Strait Road Tunnel Crossing Project Route Layout

In the beginning of design, priority items to be considered are to determine the type of tunnel and TBM equipment.

The application of tunnel type and TBM type is now under consideration. The alternative of tunnel type is double deck type and twin tunnel type. In addition, the alternative of TBM equipment type is EPB (earth pressure balanced) and slurry shield.

2.1 Selection of Tunnel Configuration

The double deck type of the tunnel is converted to twin tunnels at the shaft in conceptual design. The conversion of tunnel shape shall be determined considering characteristic of site conditions such as geological properties, hydraulic conditions, aseismatic properties, dimension of cross-section, cost effectiveness and so on. In addition, the ventilation and prevention against disaster is also important items in the long subsea tunnel. The following (1)-(4) sections describe the process of the selecting the tunnel configuration considering important items.

(1) Considerations of geological, hydraulic properties and severe earthquake occurrence

Shield TBM tunnel in this project passes through composite stratum composed of bedrock and soft ground. The maximum water level is 52m, minimum overburden is about 25m and maximum water pressure is 8 bar. In addition, there are frequently strong seismic activities (magnitude 7.5). As mentioned specific items, all of them shall be considered for safety of tunnel.

In case of subsea twin tunnels passing through soft ground, the emergency passage between 2 tunnels may cause the lack of structural stability, and therefore, may be damaged easily by
leakage and earthquake. However, double deck type tunnel has advantages of safety because there are not structural discontinuity of tunnel such as emergency passage. In addition, the construction of emergency passage is hard and expensive work, and therefore, the double deck type tunnel has advantages of the constructability and the cost effectiveness. In conclusion, the double deck shield TBM tunnel is selected in conceptual design as mentioned advantages. Table 1 shows the comparison of section specification.

(2) Section Specification
The diameter of cross-section of twin tunnels shall accomodate the required clearance of which minimum width and segment thickness are 8.25m and 0.55m respectively. The total area of the cross-section of the double deck tunnel is less up to 31% than twin tunnel with implement of identical structural clearance.

<table>
<thead>
<tr>
<th>Single Double Deck Tunnel</th>
<th>Single Twin Tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Outside diameter/ thickness of segment: 12,500mm / 550mm</td>
<td>• Outside diameter/ thickness of segment: 10,030mm / 550mm</td>
</tr>
<tr>
<td>• Excavation section area: 122.7m²</td>
<td>• Excavation section area: 80.1m²×2EA(=160.2m²)</td>
</tr>
<tr>
<td>• Maximum utilization of excavated space</td>
<td>• Excessive dead zone is formed on the top of clearance</td>
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</tbody>
</table>

(3) Constructability
The doble deck type tunnel has advantage of structural safety for omitting additional emergency passage structure but it has concurrently disadvantage in view of the maintenance of alignment consistency. The double deck type tunnel shall be altered to twin tunnel type at the shaft for connecting with existing road on ground. Therefore, double deck type tunnel needs more effort and care.

In case of twin tunnels, it is easier to maintain consistency of the alignment than double deck type tunnel due to the difference of tunnel section types. Notwithstanding advantage of alignment consistency and constructability, the twin tunnels increase the cost because it needs 2 set TBM equipment as well as area of worksite on ground. In addition, the twin tunnels also increase in the size of shafts which is used for start and end points of Shield TBM.

(4) Cost-effectiveness
In case of the twin tunnel, it needs 2 set shield TBM equipment due to limitation of construction time. Although the double deck type tunnel increases in construction cost due to adding deck plate into tunnel, total cost is 16% lower than twin tunnel.

In conclusion, double deck tunnel is superior to twin tunnel for safety due to aseismatic activity, seawater inflow as well as cost-effectiveness.

2.2 Selection of shield TBM equipment
The tunnel face supporting, muck handling and cutter wearing method shall be considered for selecting tunnel equipment[8].
(1) Face supporting method
In case of slurry shield TBM, the highpressure slurry is injected for balancing of tunnel face against water pressure. In case of the EPB shield TBM, thrust force of TBM is directly used for balancing of tunnel face against water pressure as 2~3 bar.

(2) Muck handling
The sludge pipe conveys and discharges muck with slurry. The transport pumps are installed at certain intervals to provide superior muck conveying pressure. Slurry movement through the sludge pipe provides superior working condition in tunnel. Muck discharging with muck car and conveyor belt requires considerable amount of power and time due to steep slope and long distance.

(3) Cutter wearing
In case of the slurry shield TBM, the disk cutter is weared less than EPB shield TBM since slurry in the chamber serves to reduce friction like lubricating oil. Therefore, slurry TBM provides better durability than EPB shield TBM type.

In conclusion, Slurry shield TBM provides superior stability and workability than EPB shield TBM. The slurry TBM can be applied to high water pressure condition of which maximum water pressure is up to 0.8 bar. The time cycle of cutter replacements in case of slurry TBM is shorter than EPB shield TBM. In conceptual design, the slurry shield TBM is selected for advantages of application to this project as mentioned before.

3. Key items for design of shield TBM tunnel
This chapter will introduce in detail about contents reflected on the conceptual design against geological complexity, high water pressure, aseismatic design in detail.

3.1 Cutterhead design in consideration of geological complexity
As shown in Figure 2, The alignment of tunnel passes through rock layer in Europe side shore via Bosporus weak soil layer and reaches rock layer in Asia side shore. The rock layers in Europe and Asia have many fracture and joint and consist of sandy silt and mudstone.

![Figure 2. Profile of the shield TBM tunnel section](image)

The central part of the Istanbul strait is weak abyssal sediment which is composed of silt, clay, sand, gravel and the mixtures and its minimum overburden is about 25m(TKJV, 2008) [6]. The detailed plan is needed in case of a cutterhead design and disc cutter replacement.

(1) Cutterhead design
Shape and features of the cutterhead must be determined based on detail study of the geological and project conditions.
To ensure smooth muck flow into the cutterhead chamber, cutterhead has an opening ratio of approximately 31%. For easy tunnel alignment control, especially when in curvature, copy cutters are applied in perimeter of cutterhead. For rock section disc cutter shall be applied and for soft ground section bit cutter and special knife edge bit shall be applied.

(2) Replacement of Cutter

As excavation cutter attached to the front side of shield machine wears out, excavation efficiency is reduced. Therefore, cutter wearing status needs to be monitored continuously during excavation and cutter replaced adequately. It depends on specific ground conditions, but cutter bit needs to be usually replaced after excavating 200~500m of bed rock or 2000m of ordinary soil ground. Disc cutters are expected to be replaced about 10 times in the rock section of the Istanbul strait shield TBM tunnel. If necessary, disc cutters need to be replaced by bit cutters in order to facilitate excavation through soil layer and to prevent partial side wear of disc cutter before starting excavation of soil.

In order to change cutter consumed in soft ground under high water pressure the stability of working face has to be ensured by performing ground reinforcement. In addition, reinforcement work should be performed at critical region expected with ground investigation.

Although freezing method is safest for tunnel face stability, it is expensive for construction cost and time. As freezing method is not adequate, chemical grouting method is applied. The replacement of cutter in high pressure on tunnel face is planned by using slide guider instead of replacement by diver.

3.2 Equipment improvement and segment design under high water pressure

Shield TBM tunnel passes through maximum water level of 52m, minimum overburden of about 25m and high water pressure of 8 bar(Fig. 2). Shield TBM equipment, segment thickness, segment joint waterproofing against high water pressure are key items to perform the project successfully.

To pass the high pressure section of 8 bar, a layer of the emergency water stop seal is applied between the 3 layers of tail seal. Also, back fill system is applied simultaneously injection system.

(1) Thickness and width of segment

Thickness and width of a segment directly influences the structural stability, productivity and workability for tunneling. Therefore, they shall be determined with consideration of construction cases and numerical analysis. The figure 3 show the relation between segments outer diameter and width, and between segments outer diameter and thickness based on the construction cases.

![Figure 3. Relation between segment outer diameter, width and thickness](image)

(a) Segment outer diameter vs width  (b) Segment outer diameter vs thickness

The segment width of 2,000mm is widely adopted value in Europe to reduce the number of segment pieces and the coalescence length, and to raise the water-tightness (No.4 Elbe tunnel in Germany and Lyon expressway tunnel in France). In order to evaluate the structural stability of that segment thickness, structural analysis has been performed. In the structural analysis,
conventional method which considers consistent ring without consideration of segment joint (between segments and between rings) and 2 ring beam-spring model which considers the segment joint as a rotational spring and the ring joint as a shear spring are used. The segment thickness of 550mm determined as the result of the structural analysis is considered to be stable enough. Figure 4 shows cross-section of the shield TBM tunnel in conceptual design.

Figure 4. Cross-section of the shield TBM tunnel in conceptual design

(2) Waterproofing for Segment Joint
According to the survey performed in Japan, 57% of segment water leakage occurs in the joint. There are two typical joint waterproofing methods; rubber water stop method and gasket method. The rubber water stop is based on the expansion pressure using the absorption characteristics and the elastic reaction force which exists under the dry condition. The gasket stops water with the contacting pressure of the elastic reaction force. The rubber gasket is widely used segment waterproofing method. It’s stress relaxation behavior and the long-term durability are fairly reviewed and assessed. The recently developed complex rubber gasket is combined with the rubber water stop. Therefore, in consideration of long-term waterproof capability of the Istanbul strait shield TBM tunnel, the complex gasket is adopted. The appropriateness of the method shall be evaluated through the basic material characteristics test, gasket compression stress test, and water pressure-resistance test with regard to offset and gap. Table 2 shows concept of segment joint waterproofing.

Table 2. Segment joint waterproofing

<table>
<thead>
<tr>
<th>Segment Connection Part</th>
<th>Connection Bolt</th>
<th>Connection Caulking Waterproof</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complex Gasket(2 lines)</td>
<td>packing rubber</td>
<td>One component sealant applied</td>
</tr>
<tr>
<td>Excellent Durability</td>
<td>Inserting packing of ring shape</td>
<td>Excellent in adhesive force and durability</td>
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<td></td>
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- Complex Gasket(2 lines)
- Excellent Durability
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- Packing through clamping force of bolt
- One component sealant applied
- Excellent in adhesive force and durability
3.3 Aseismic design

In Turkey, earthquakes occurred frequently due to activity of the North Anatolian Fault. Especially, 7 or more severe earthquakes occurred along this aseismic belt from 1939 to 1999 (Jung, 1999) [5].

Turkish earthquake experts estimate that earthquake might occur in the same region at the average interval of 450 ± 220 years. According to Parson's calculation of Aseismatic Activity Probability, it can be estimated that a severe earthquake of magnitude 7 or greater has 32 ± 12% of occurrence within 10 years and 62 ± 15% of occurrence within 30 years. There is a risk of damage due to a large deformation caused by earthquake in the bedrock/soft layer boundary and the ventilation shaft/tunnel joint. The relative stiffness causes the relative displacement and the segment damage so that it needs to be analyze. Therefore, flexible segments are installed to absorb deformation (in each shaft-tunnel joint and each layer boundary).

The flexible segment used in Aqua line in Tokyo bay is applied for the region in which there is a possibility of relative replacement due to aseismatic activity (NIKKEI Construction, 1997) [7]. The flexible segment can deform up to 6cm in the horizontal direction and up to 14~15cm in the vertical direction (Fig. 5). The fiber reinforced rubber (elastic washer) is inserted between bolts and segments at the layer boundaries and the points where the layer changes. A flexible washer can absorb deformation of up to 5mm.

Flexible segment is disposed to joint between ventilation shaft and tunnel, boundary between the bed rock and the soft ground to be able to absorb relative displacement. Installation in situation of flexible segment is as Figure 5.

![Figure 5. Structure of Flexible Segment and Installation Diagram](image)

4. Conclusion

The items to be considered in design of the shield TBM tunnel are introduced based on Istanbul Strait Road Tunnel Crossing Project. The following five (5) items summarize the principal contents of this study.

1. The items to be considered for applying shield TBM type are method of stability of the tunnel face, muck removal process, durability of cutter. As all items mentioned before, slurry TBM is superior to EPB shield TBM in case of high water pressure condition.

2. The items to be considered for selecting the type of tunnel are construction site condition, dimension of cross section, feasibility, fire protection and cost effectiveness. As a result of study with the items, the double deck tunnel type is superior to twin tunnel in case of both safety and cost effectiveness under high water pressure.

3. As a result of investigation of the composite soil layers, shield TBM should pass through both weak soil and rock layer. Therefore, the cutter should be changed according to the strength of soil and rock. In case of passing through weak soil layer, shield TBM shall be equipped with bit cutter and special knife edge. In case of shield TBM passing through rock layer, shield TBM shall be equipped with disc cutter. The intervention at the cutterhead should be performed up to 10 times. However, it is hard to change cutter in
transition zone applying high water pressure. Improvement of ground is needed and the chemical grouting method is applied in conceptual design.

(4) The selecting type of shield TBM equipment, dimension of segment and waterproof at segment joint are important items under high water pressure. As a result of investigation, slurry shield TBM is selected because it can secure stability of tunnel face against 8bar water pressure. One layer of the emergency water stop seal is applied between the 3 layers of tail seal. The thickness and width are 550mm and 2.0m respectively according to the case study and the structural analysis was performed in order to evaluate the structural stability. The complex gasket is adopted for waterproofing at the joint of segments.

(5) The aseismatic design focus on the case history of Turkey and relative deformation induced by relative stiffness. Flexible segments are installed to absorb deformation (in each shaft-tunnel joint and each layer boundary). The fiber reinforced rubber (elastic washer) is inserted between bolts and segments at the layer boundaries and the points where the layer changes. A flexible washer can absorb deformation of up to 5mm.

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