Wind coursing through the Seabed  
- Marmaray Project -  

Takashi Imaishi  
i) General Manager, Department of Construction Engineering, Taisei Corporation, 1-18-214, Matsuba-cho, Kashiwa-city  
277-0827, Japan  

ABSTRACT  

The project of railway tunnel construction across the Bosphorus Strait in Istanbul, Turkey is known as one of the  
most interesting projects that connects Asia with Europe, and consists of tunnels constructed in three different  
methods: immersion, TBM and NATM.  

Istanbul is the largest city in Turkey with a population of over 15 million. And this city is divided by Bosphorus  
Strait. With only two east-west bridges connecting European side and it Asian side, this resulted in chronic  
congestion with increased air pollution. To relieve these problems, construction work on a subway tunnel under the  
strait was begun in 2004 under an EPC (Engineering, Procurement, and Construction) turnkey contract with Japanese  
financial backing. This concept was imagined 150 years ago in Turkey and we can see from the design drawing  
illustrated by a civil engineer in 1860.  

Keywords:  
Marmaray Project, immersed tunnel method, TBM, F-PAS, Archaeological Survey  

1 INTRODUCTION  

This was a major national project to construct a  
seabed tunnel crossing the Bosphorus Strait and  
connect Europe and Asia with a railway. About 150  
years ago during the Ottoman Turkish Era the Turkish  
popule of the time wished for such a tunnel and even  
got as far as preparation of design drawings, but it  
was not realized. In 1998 the Turkish Government  
requested a yen loan for this project, in 2004 an alliance  
of Taisei Corporation and 2 Turkish companies was  
awarded the contract, in August of that year work  
commenced, and in October 2013 operation  
commenced.  

2 TO ISTANBUL  

In Japan Turkey is classified as a Middle and Near  
East country, but the Turkish Government classifies  
itsel as a European country, and geographically it is  
located on the Near East side of the Middle East. It is a  
place where historically many peoples and cultures  
have thrived, such as the Greeks, Ancient Rome, the  
Eastern Roman Empire, the Ottoman Turkish Empire,  
etc., so the country is very much the intersection point  
of eastern and western cultures.  

To this day I still remember my surprise when in  
January 2005 I first arrived at Atatürk International  
Airport in Turkey's largest city, Istanbul, in order to be  
responsible for the shield tunnel construction on this  

The modern airport building, the fine expressway  
from the airport to the city and the traffic congestion,  
the groups of high rise buildings rising like a forest in  
the main urban area, I could have mistaken this for a  
city in the EU, as I had imagined a landscape of  
minarets and Jami Mosques as is often seen when the  
world heritage city Istanbul is introduced in Japan, and  
I was not used to hearing the Turkish language.  

3 OUTLINE OF THE CONSTRUCTION  

This is a project (referred to as the Marmaray  
Project) to construct an underground railway tunnel  
across the Strait with the objective of relieving traffic  
congestion and reducing atmospheric pollution caused  
by the congestion in the city of Istanbul, Republic of  
Turkey, which has a population which is virtually the  
same as that of Metropolitan Tokyo (about 15 million).  
Fig. 1 shows the location of the Bosphorus Strait, and  
Fig. 2 shows a plan of the route alignment. In this  
construction, three different tunneling methods were  
adopted: immersed tube tunneling, shield tunneling,  
and NATM tunneling. Technically the project had a  
high degree of difficulty, including the world's deepest  
immersion operations, and the world's first direct  
connection below the seabed between the immersed  
tunnel and the shield tunnel. The contract was an EPC  
contract that included the construction of a total of 13.6
km of twin tunnel, of which 1.4 km across the Strait was immersed tunnel, and the remainder on the land was shield tunnel, evacuation tunnel that connected four stations and the twin tunnels every 200 m, crossover tunnel for lines in both directions, building and services construction, and laying of the main tracks. This article is focused on the shield tunnel which comprises about 80% of the total line, and introduces the special element technologies adopted, and fusion with the culture of the historical city of Istanbul.

4 BASIC INFORMATION ON THE CONSTRUCTION

The following is the basic information on the project.

(1) Client: Railways, Ports, and Airports Construction Bureau, Ministry of Transport, Maritime and Communication, Republic of Turkey
(2) Client's Representative: AVRASYA – JV (Oriental Consultants and others)
(3) Construction: Taisei, Gama, Nurol
(4) Construction started: 27th August 2004
(5) Contract amount (initial): About 102.3 billion yen JICA environmental loan
(6) Contract construction period (initial): 56 months (until 28th April 2009), likely to be extended by a factor of 2

(7) Tendering format: Two envelope format (technical tender, financial tender)
(8) Form of contract: FIDIC-Silver book EPC-Contract
(9) Risk allocation: Extensive design responsibility including unforeseeable physical conditions (ground conditions, etc.) are included in the contractor's risk
(10) Dispute adjudication committee: Dispute Adjudication Board (DAB) to be established

5 SLURRY TYPE SHIELD TUNNEL

5.1 Outline

Of the total of about 13.6 km of new double line railway construction in the "Bosphorus Strait Crossing Railway Tunnel Project", the shield method was adopted for a total length of about 10.1 km (twin tunnel), of which earth pressure balanced type TBM was adopted in soil areas with low soil cover, and slurry type TBM was adopted in rock areas at greater depths. This paper reports on slurry type TBM used for about 3.3 km × 2 on the European side and about 4.6 km × 2 on the Asian side. (Fig. 3) The standard cross-section of the shield tunnel is shown in Fig. 4.
5.2 Selection of construction method
This tunnel construction required excavation in rapidly changing ground and underground water pressure conditions of a maximum of 0.65 MPa on the European side and a maximum of 0.85 MPa on the Asian side, so it was envisaged that there were risks of collapse of the tunnel face or ingress of water under high pressure, etc. To avoid these risks and also to finally safely connect to the immersed tube elements under the Bosphorus Strait, a slurry type TBM was adopted, which is the most reliable for prevention of water ingress and which enables real-time management of the change in ground conditions.

5.3 Shield machine (TBM)
The shield machine (TBM) adopted on this project had a semi-domed cutter face, equipped with 55 No. 17 inch disc cutters.

Also, as measures to prevent wear during the long distance excavation, the front surface of the cutter face was clad with hardened weld, and the outer periphery was reinforced with wear resistant steel plate. (Photograph 2)

Photograph 2 Shield machine

A total of 4 TBMs were manufactured, 2 No. on the European side (TBM 2, TBM 3), and 2 No. on the Asian side (TBM 4, TBM 5) with the immersed tube tunnel between the European and Asian sides. This was because at the destination underneath the Strait it was not possible to recover the TBM so it was necessary to leave the machine there, and for optimization of the overall construction schedule. (Fig. 3)

The main parameters of the TBMs are as follows.
- Excavation external diameter: 7,930 mm
- External diameter of the front body of the machine: 7,890 mm
- External diameter of the rear body of the machine: 7,850 mm
- Length of the machine:
  - European side: 10,000 mm
  - Asian side: 11,000 mm
- Thrust force:
  - European side: 75,000 kN (25 No. 3,000 kN jacks)
- Cutter torque: 10,600 to 4,800 kN-m

5.4 Construction schedule
The construction schedule for each tunnel was as follows. The arrival dates are the final arrival dates, and the dates of arrival at each station on the way, movement through each station (or non-driving), and dates for restarting are not shown.

TBM 2 (European side)
- Total excavation length: 3,068 m
- Excavation starting date: 31st December 2009
- Arrival date: 8th August 2011

TBM 3 (European side)
- Total excavation length: 3,081 m
- Excavation starting date: 1st December 2009
- Arrival date: 26th January 2011

TBM 4 (Asian side)
- Total excavation length: 4,216 m
- Excavation starting date: 26th March 2007
- Arrival date: 17th February 2010

TBM 5 (Asian side)
- Total excavation length: 4,187 m
- Excavation starting date: 24th January 2007
- Arrival date: 5th October 2010

As can be seen from the above, it was not possible to commence construction on the European side in accordance with the schedule due to the extension in the time period for the Archeological Survey at Yenikapi Station, which was the base for commencement of tunneling, so tunneling commenced about three years after commencement on the Asian side. As a result the overall schedule was greatly extended, but it was also possible to obtain time for analysis of the construction records on the Asian side and reflect this into the construction on the European side, so it was possible to greatly improve the construction efficiency on the European side which started later.
5.5 Ground encountered

The ground to be excavated did not vary greatly between the Asian side and the European side, and consisted of mainly sedimentary strata of mudstone, sandstone, and shale from about 250 million years ago, the rock strength (uniaxial compressive strength) was an average of $\text{qu} = 80 \text{ MPa}$, or medium hardness rock with many cracks.

Also, Turkey is a seismic country, so there were igneous intrusions (diabase) within the sedimentary rocks, around which clay and boulders were formed by metamorphosis due to the heat and pressure. In order for the TBM to excavate horizontally through these strata, it was necessary to excavate from the sedimentary strata through the clay or boulder strata into the igneous rock strata, and again through the clay or boulder strata back into the sedimentary rock strata and repeat this flow many times. This variation in soil strata ranged between short periods of 5 to 10 m up to long periods of 100 to 200 m, and every time it was necessary to precisely control slurry in order to stabilize the cutting face. In addition borders and fracture zone frequently occurred, so it was necessary to spend much time and effort on countermeasures against these.

6 JOINING DIFFERENT TYPES OF TUNNEL BELOW THE SEABED

6.1 Technical outline

Normally the immersed tube elements with a rectangular cross-section and the shield tunnel with a circular cross-section are joined via a shaft, but in this project the world's first direct connection between tunnels with different types of cross-section was achieved omitting the shaft, in order to greatly reduce the construction period and achieve cost reduction.

6.2 Connection procedure

In order to eliminate the vertical shaft, a steel shell sleeve pipe with the shape of a pair of glasses was installed on the ends of the immersed tube elements, to provide space for the operation of connection by the shield machine penetrating into this sleeve pipe (Fig. 5).

Although the environment for carrying out the operation of connecting the different types of tunnel was within the sleeve pipe, a maximum of 0.6 MPa of water pressure was applied to the artificial backfilling on the sea bottom, so it was necessary to provide a structure that was sufficiently waterproof. Therefore a Freezing Packing for Seal (F-PAS) mechanism was installed within the sleeve pipe as a waterproof sealing device.

Also, during the operation of producing the immersed tube elements on land, the initial connection preparation work of fitting the waterproof sealing device in advance was carried out, which contributed to reducing the amount of work on the sea bottom where the operability was poor, and improving the safety.

![Fig. 5  Sleeve pipe](image)

![Fig. 6  Waterproofing sequence](image)

The F-PAS procedure drawing and structural drawing are shown on Figs. 6 and 7 respectively. The inside of the steel shell sleeve pipe was filled with LW material (a 2 liquid ground improvement material made...
from cement, bentonite, and sodium silicate), which has the property of changing from solid to liquid after freezing and melting. Before the arrival of the shield machine, refrigerant was circulated into the waterproof seal device (an aqueous solution of calcium chloride at -25°C) to cause freezing in a doughnut-shape, and which protected the device during penetration of the shield machine. After arrival of the shield machine, the frozen portion was melted by circulation of hot water to liquefy it, and waterproof packing was activated by injecting water under pressure into a pressure tube so that there was close contact between the packing and the shield machine steel shell. At this time, in order to prevent foreign matter in the LW material that changed from solid to liquid from penetrating between the steel shell and the packing, the contact between the waterproof packing and the shield machine steel shell was increased. This is referred to as the primary waterproofing.

From the shape of the waterproof seal in the primary waterproofing, the greater the pressure in the direction in which the water pressure is applied, the greater the contact between the waterproof seal and the shield machine steel shell, ensuring a failsafe mechanism. Also, secondary waterproofing was provided by injecting waterproofing material behind the waterproof seal after activation of F-PAS. After removal of the slurry from inside the chamber of the shield machine and restoring it to atmospheric pressure, waterproofing welding was carried out on a steel plate between the shield machine steel shell and the steel shell sleeve pipe. This welding was tertiary waterproofing. After the triple waterproofing had been provided as described above, the shield machine was completely removed except for the steel shell, and the RC segments of the shield tunnel and the RC structure of the immersed tube elements were connected with reinforced concrete, to achieve complete waterproofing of the tunnel.

Fig. 7. F-PAS structural diagram

7 DEALING WITH UNSOUND BUILDINGS

A characteristic problem in Turkey which had to be dealt with directly was the problem of unsound buildings. Within the total 13.6 km length of the planned route, apart from 2.0 km under the Strait it was almost completely below residential areas. In Turkey, homes are normally passed from parents to children and then on to grandchildren, so there were many buildings that were aged and that were more than 100 years old. (Photograph 3)

Photograph 3  Example of aged building

As a result many of these buildings did not comply with the current building standard law, their strength was insufficient, and, there were also buildings that have been illegally constructed (Photograph 4). Even more surprisingly in Turkey it is reported in the media that every year several housing complexes collapse naturally resulting in many victims. In this contract, with a partial exception it was responsibility of the contractor to maintain the integrity of buildings in the area around the excavation of the tunnel. Therefore first of all a survey of the buildings in the areas of concern was carried out. The integrity of the buildings in the areas of concern was classified into six categories, and buildings in the 3 categories with the highest level of danger were resurveyed in detail. Istanbul Technical University was commissioned to evaluate the survey results and formulate measures based on the results. The main measures taken prior to construction were demolition of buildings, strengthening of buildings, temporary evacuation of the residents of buildings only during the time that tunnel excavation was in progress directly below, and monitoring of the buildings. Tunnel excavation proceeded while checking the results of these measures. As a result, it was possible to safely complete the construction without damaging any of the buildings. The most important of this whole series of operations was communication with the residents, and because this communication could not be carried out by the Japanese alone, it was necessary to rely on the efforts of the local staff. This was very much a case of "when in Rome, do as the Romans do".
8 ARCHAELOGICAL SURVEY

One of the events that occurred in the heart of the historical city of Istanbul was the Archaeological Survey which was carried out over a long period of time during the construction period. For the author who only had experience of construction within Japan and who had to deal with the unsound buildings, it was extremely stressful and demanding to cooperate with this survey which stretched out over a surprisingly long period of time and without any schedule while at the same time proceeding with the construction.

The scope of the Contractor in the Archaeological Survey in the contract was construction of temporary works. The Employer was explicitly involved in the survey, which was managed and directed by the Heritage Committee. The Contractor supplied workers for excavation surveys in accordance with the instructions and requirements of the Heritage Committee, and provided temporary storage, transport, and office facilities, etc. for the excavated artifacts.

The excavation was carried out in all the construction locations from the surface such as at the ventilation tower, station, etc. A total of 9 locations were excavated in sequence from the west, the Yedikule ventilation tower, the Yenikapi ventilation tower and station, the Sirkeci east ventilation tower and west ventilation tower, and south and north accesses, the Uskudar Station area, and the Ayrilikcesme ventilation tower.

The survey was carried out by hand excavation for each excavation and each artifact era, the excavated soil was sieved, taking care to ensure that not a single fragment of plate was overlooked. As a result preparation of the reports which required positional surveying of the excavation of the founding, measurement of shapes, and preparation of 3-D drawings, etc., required from several months to one year. These reports were submitted for discussion to the meetings of the Heritage Committee which were held once every month. Based on the results of the discussions, the Heritage Committee arrived at 3 types of conclusion: to collect the objects and bury them in another location while maintaining the records, to sort the objects and transport them to another location for storage while maintaining the records, or to preserve them in the same location while maintaining the records. In the case of excavated artifacts of high importance, careful examination was carried out which was not completed in one committee meeting, so several meetings were required in order to obtain a conclusion and in some cases required more than six months to obtain a conclusion. Therefore, the survey which commenced from November 2004 was completed in August 2012, which greatly exceeded the contract construction period of April 2009.

The Contractor applied for an extension to the construction period and contract amount due to the effect of the delay in completing the Archaeological Survey on the progress of the construction, and the construction period was extended to 29th October 2013, which was the 90th anniversary of the founding of the Republic of Turkey.

At Sirkeci Station east ventilation tower where there was excavation to about 60 m from the ground level, it was possible to get a glimpse at the survey that symbolized the historic city of Istanbul. As shown in Photograph 6, after the start of the survey first remains from the Ottoman Turkish era were discovered. Then, as the excavation proceeded relics were found from the Byzantine era, the Roman era, and earlier, the deeper the excavation the older the discoveries, and when a human skeleton from 8,500 years ago was discovered, the local media reported that the history of Istanbul had been rewritten.
9 RELIGIOUS CUSTOMS AND LOYALTY

In Turkey, there is separation between politics and religion so the precepts of Islam are not mixed with politics. Therefore, unlike other Muslim countries, in Istanbul it is possible to enjoy alcoholic drinks and tobacco, and women dye their hair and wear fashions the same as in the EU. However, for prayers on Friday which is religiously important, most of the workers go to the mosque, and during the month of Ramadan most of them fast from sunrise to sunset, and after sunset would have one meal. In the tunnel construction operations which carried on for 24 hours, it was necessary to adjust the break times on Fridays, and to adjust the shifts during the month of Ramadan. This interrupted the continuity of the operations, but this is a reality in practical civil engineering construction based in this region.

What was problematic in terms of labor management was the weak labor loyalty among the workers and local staff. This was the first time ever that the slurry shield construction method and the immersed tube construction method were applied in Turkey, so specialized and experienced workers and engineers were scarce, and it was a major problem to provide staff. The construction progressed by Japanese staff providing them with education and instruction, but the workers would resign for no good reason. As their skill level increased they would leave for other higher-paying workplaces or overseas, so in the case of important operators or engineers it was necessary to always employee several and to raise their salaries.

Things that would be unthinkable in Japan occur normally overseas. This may be just a difference in common sense or culture, and the only way to deal with it is to persevere, in accordance with the old saying "when in Rome do as the Romans do".

10 CONCLUSIONS

It is said that Turkey is a pro-Japan country. Certainly the Turkish people you meet on the street are very friendly, and are very kind to Japanese people in particular. However, this is not the case when it comes to business, as is the case when working in other overseas countries. Turkish business people were tough. I feel that the keys to success learned from many difficulties are to find the point of destination by searching for mutual benefit, by persistently strong negotiation, by repeatedly checking before saying Yes or No, etc., using genuine communication ability.

It is my wish that completing this project not only produces friendship between Japan and Turkey, but also connects Europe to Asia. What I have felt through working for 6 years overseas on this project is that we Japanese engineers, myself included, must not just rely on our technical capability and industriousness, which has been highly evaluated throughout the world, but also make continuous efforts to realize the day that we are active in the world with strong negotiation capability.

REFERENCES

1) Hidemi Ohmi, Dream Come True Project - Bosphorous Strait Crossing Railway Tunnel -, JSCE Civil Engineering, Vol. 91, No. 8, CE Report, 2006.8
3) Yosuke Taguchi et al., The Bosphorous Strait Crossing Railway Tunnel Construction, Tunnels and Underground, 2008.1
7) Takashi Imaishi, Strait Crossing Railway Tunnel Construction Connecting Europe and Asia - In the Culture Space that is Neither Arab nor European, JSCE Civil Engineering, 2014.05.