Bosphorus Crossing Update, Istanbul, Turkey

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1.0 Introduction

The Bosphorus Project is a 76km long $US 3.5 billion metro and freight railway providing the first rail connection between Europe and Asia. The major structures include a 1.4km immersed tube tunnel, 19.6km of TBM bored tunnels, 2.4km of cut & cover tunnels, 3 underground stations, and 37 surface stations. This paper updates construction progress on Contract BC1, covering the immersed tube tunnel, bored TBM tunnels, and cut and cover stations in central Istanbul (Figure 1).

Istanbul has a rich history. The city has been the capital of great empires, so is full of historic buildings. With a population over 12 million, Istanbul is the largest city in Turkey. It sits on both sides of the Bosphorus – European and Asian. The idea of a railway tunnel under the Bosphorus was first proposed in 1860 as an underwater bridge by the Ottoman Sultan Abdul Mecit. Engineering studies in the mid 1980s were refined from 1996 to 1998. These studies confirmed that the project would greatly improve the Istanbul transportation network by helping to ease traffic congestion in the city. Population was growing at an unprecedented rate, having quadrupled since the 1980s studies.

Traffic congestion is a significant problem in Istanbul. The only way to cross the Bosphorus Strait is by ferry or one of two highway bridges. Rush hour commuters are faced with long delays, particularly on the bridges. The existing metro system carries 10,000 passengers per hour but lacks connectivity, leaving most commuters with no other transport options. The new railway is expected to carry 65,000 passengers per hour with multiple connections to existing metro and bus lines.

The Client is the Ministry of Transport and Communications, Republic of Turkey. The Engineer is Avrasyaconsult, a joint venture of Oriental Consultants Co. Ltd of Japan, Yuksel Proje Uluslararasi A.S. of Turkey and Japan Railway Technical Services of Japan, with Parsons Brinckerhoff and others as associate partners.

Financing is provided by the Japanese International Co-operation Agency (JICA), the European Investment Bank, the Council of Europe Development Bank and the Republic of Turkey. Project cost is US$ 3.5 billion, with construction from 2004 – 2013.

Avrasyaconsult acts as the Employer’s Representative for the FIDIC two party contracts. The project is divided into three design-and-build contracts:

- Contract BC1 – All tunnels and 3 underground stations – Taisei (Japan), Gama - Nurol (Turkey)
- Contract CR1 – Surface railway & stations – Alstom (France), Dogus (Turkey), Marubeni (Japan)
- Contract CR2 – Rolling stock – Hyundai (Korea)
2.0 Project Scope and Benefits

The total project scope (all contracts) consists of the following elements:

- 76 km triple track (except tunnels)
- Third track for inter-city and freight
- 3 depots and 2 workshops
- Operations control centre
- 44 ten-car passenger trains
- 19.6 km of twin bored tunnel
- 2.4 km of cut & cover tunnel
- 1.4 km immersed tube tunnel
- 3 major underground stations
- 37 surface stations

The major railway systems consist of:

- 25 kV AC traction power system
- Continuously welded rail
- Modern control and coms systems
- “Step free” access at all stations
- ERTMS Level 1 with moving block signaling
- Railway systems in accordance with NFPA 130
- Tunnel ventilation to cater for 100 MW freight train fire (possible largest in the world)

Archaeological excavations at cut & cover stations have delayed the project for more than two years. Yenikapi Station is located at an ancient shoreline for the port of Constantinople, one of the busiest ports in Byzantium. Archeological finds cover the Ottoman, Byzantine, Roman and Greek historical periods, and include 10 sunken boats, walls, pottery, chapels, cisterns, and baths. Archaeological preservation involved 210,000 cubic meters of hand excavation at Yenikapi Station.

The project challenges require the best technologies available from the international tunnelling industry:

- Deepest immersed tube tunnel in the world (58m depth)
- One of the world’s busiest waterways (average 6 ships per hour)
- Immersed tube tunnel placement in strong currents (up to 3m/sec)
- Different work cultures and expectations
- Largest archaeological excavations in Europe (estimated direct cost $30 Million)
- Design to the highest international earthquake standards
- Designing all life safety systems for a 100 MW freight train fire

The expected project benefits are significant:

- Train journeys increased from 3% to 27% of all passenger journeys in Istanbul
- Direct connection (including freight) between Turkey and Europe
- Economic benefit of US$600 million per year
- New modern stations & fully air-conditioned rolling stock
- Seamless interchanges with new tram and existing metro systems
- Traffic congestion and resulting vehicle pollution will be significantly reduced
- No permanent impacts on the Bosphorus’ rich aquatic habitat
- The spectacular views over the Bosphorus and Istanbul’s historic skyline will be preserved

The Asian tunnel portals are shown in Figure 2, illustrating typical ground support measures required to facilitate tunnelling in a dense urban environment.
Figure 3 – Contract BC1 Bosphorus Tunnels and Stations

Figure 4 – Contract BC1 Geological Long Section Showing Tunnelling Conditions
The limits of Contract BC1 are shown in Figure 3. A geological section showing tunnelling conditions for Contract BC1 is shown in Figure 4.

Ground investigations for design of tunnels were carried out in three phases:

- Design 1985–87: 20 marine boreholes, 37 land boreholes, SPT, geophysics, bathymetric
- Pre-tender 2002–03: 7 marine boreholes with CPT, 26 land boreholes, geophysics on alignment
- Contractor 2004: Maximum hole spacing 200m in soft ground, 300m in hard rock, 50m at stations

### 3.0 Immersed Tube Tunnel

The 1.4km immersed tube tunnel consists of 11 elements formed in a dry casting basin and floated to the site. The tunnel is rectangular in cross section, consisting of a two-cell structural concrete box with one track in each cell (Figure 5).

Tunnel immersion is by catamaran barge in a 10m deep trench on the sea floor. Once installed, the tunnel is backfilled with grout and engineering fill with 2m minimum cover.

Immersed tube elements consist of:

- 7mm thick watertight steel shell
- Reinforcement 300 kg/m³
- C40 concrete
- 15.3m wide x 8.75m high
- 135m length maximum
- 17,200 tonnes per element

The fabrication yard and casting basin is in a shipyard 40km south of the city. The lower half of tunnel units are cast in dry-dock, with the upper half cast afloat. Waterproofing measures include a 7mm thick steel membrane on the bottom and sides, and plastic membrane on top.

TBM tunnels will be driven through concrete sockets for final connection to each end of the immersed tube tunnel (Figure 6).

Seismic design of the immersed tube tunnel was one of the most critical elements because of the tunnel’s proximity to an active seismic zone with recent activity inflicting significant damage and loss of life. Seismic design was based on a single-level design basis earthquake (DBE) of Richter Magnitude 7.5.

Seismic performance requirements of the tunnel structures specify that when subjected to the DBE:
- Damage can be repaired easily and will not result in a loss of functionality or lives.
- The tunnel remains watertight and operational following the earthquake.
- Repair work can be performed with minimum disruption to operations.

Advance ground treatment of marine sediments below the immersed tube was significant, including dredging and replacement of liquefaction-prone soils, compaction grouting, and 2800 cement grout columns at 1.7m spacing in high risk areas.

Immersion of all 11 tunnel elements was successfully completed in 2009.

4.0 TBM Bored Tunnels

Bored tunnels are being excavated with four slurry type Tunnel Boring Machines (TBM) and one Earth Pressure Balance (EPB) machine. Cut diameters are 7.97m or 7.85m.

Finished inside diameter is 7.04m (Figure 7). Cross passages are constructed every 200m.

Tunnel Segmental Lining (Figure 8):

- Configuration: 6 piece ring + key
- Outer Diameter: 7.64m
- Inner Diameter: 7.04m
- Thickness: 300 – 320mm
- Width: 1500mm
- Weight: 4.4 tonnes
- Concrete: C50
- Reinforcement: 132 kg/m3
- Manufacturer: AFA (Turkey)

Fire protection is not provided in the lining concrete. However final design will utilize 50mm of spray-on cementitious material with fire inhibitors at critical areas.

The internal tunnel diameter of 7.04m accommodates intercity (high speed), commuter and freight trains. The tunnel is cleared for UIC506 structure gauge and accommodates a 1.4m wide escape walkway at 900mm above rail level and a 500-mm wide squeeze way at 760mm above rail level.

The main tunnelling challenges facing the contractor are:

- Many buildings are old and constructed on minimal foundations.
- Ground conditions are extremely variable, with loose fill, sands, stiff clay, and hard rock up to 200 MPa strength.
- Limited tunnel cover in some areas.
- High ground water level.
4.1 Lovat EPB TBM

- Cut Diameter: 7.994m
- Overall Length: 10.0m
- Maximum Thrust: 64,000 kN
- Max. Drive Power: 7 x 300 = 2100 kW
- Muck Disposal: Continuous screw to open trough conveyor @ 800 tonne / hr
- Backfill Grout: Accelerated OPC grout through trailing shield
- Spoil Additives: CONDAT CLBF4/M soil conditioning foam

TBM 1 completed an initial 100m excavation from the European side in Nov. 2007, but was delayed by property expropriation and archaeology. It resumed excavation in April 2010. TBM 1 is responsible for two 2.5km tunnels. Anticipated advance is 12m/day. Geology is stiff to hard clay with water-bearing sand layers.

4.2 Hitachi Zosen Slurry TBMs

- Cut Diameter: 7.900m
- Overall Length: 11.0 m
- Maximum Thrust: 75,000 kN
- Max Drive Power: 8 x 250 = 2000 kW
- Muck Disposal: Slurry pumping
- Backfill Grout: Accelerated OPC grout through segment ports
- Spoil Additive: Bentonite to improve pumpability in sands, and CMC organic thickening agent for slurry viscosity

The Hitachi TBMs are designed for a maximum water pressure of 8 bar.

Rock cutter discs were specified for hard rock consisting of interbedded mudstone and sandstone (20 - 100MPa compressive strength) intruded by intermittent diabase dykes (200MPa max). The rock cutter arrangement consists of 17 centre, 34 face, 4 gauge, 1 reamer (56 total). Soil cutter teeth consist of 96 cutter and 12 trimmers (108 total). Cutters are tungsten carbide in a steel matrix. The original 17 inch gauge cutter life was low at 200 - 300m, and has been subsequently modified to 19 inch cutters and are now returning 400 - 500m cutter life.

TBMs 2 and 3 were delayed by station archaeology on the European side and eventually got underway in Dec. 2009. TBMs 2 and 3 are 40% complete and are expected to dock with the IMT in Jan. 2011. TBM 4 has completed tunneling on the Asian Side and successfully docked with the IMT in Feb. 2010. TBM 5 is 85% complete and is expected to dock with the IMT in Sept. 2011. TBM 4 & 5 experienced some abrasion and pumping-related delays, and modifications to on-board crushers were made for TBM 2 & 3. The anticipated advance rate was 12m / 24 hour day. Actual advance for TBM 4 & 5 was 6 – 14m/day, with best advances of 70m/week and 18m/day. The modified TBM 2 & 3 are averaging 10 – 18m/day, with best advances of 100m/week and 18m/day.
5.0 Underground Stations

5.1 Uskudar Station (Asian Side)

- Station Box: 275m length, 35m width, 30m depth
- Soil Improvement (Soft Sand): 10m deep X 3m diameter jet grout columns
- Excavation Support: 1.5m thick diaphragm wall (C40 concrete), 3m x 1m reinforced concrete struts
- Design Capacity: 41,500 passengers / hr
- Contractor: Gama-Nurol (Turkey)
- D-wall Contractor: Bauer (Germany)

Several historical buildings are adjacent to the station, which required extensive protection measures including compensation grouting under an ancient mosque.

Completed diaphragm walls at Uskudar Station are shown in Figures 11, 12, 13. These provide primary ground support and groundwater control for the station excavation in variable fill conditions.

Pumping wells below the excavation floor have successfully maintained dry working conditions in the station box, despite the close proximity to the Bosphorus Strait. A pumping well pipe is shown in the foreground of Figure 12.

Figure 12 illustrates top-down excavation of loose fill between 1.5m thick reinforced diaphragm walls. Reinforced concrete struts 1m thick by 3m wide were formed at each main level to provide structural support.

Figure 13 shows installation of the 7mm waterproof membrane used to provide permanent inflow control to the station box. This membrane was installed on all floors and walls prior to forming the internal reinforced concrete station structure.
5.2 Yenikapi Cut & Cover Station (European Side)

- Station Box: 250 m length, 32m width, 20m depth
- Excavation Support: 0.8m & 1.0m diameter X 25m deep secant pile wall (C30 hard / C5 soft concrete) with 35 tonne tie-back anchors
- Design Capacity: 75,000 passengers / hr
- Contractor: Gama-Nurol (Turkey)

Excavation progress at Yenikapi Station was significantly affected by extensive archaeological work to prepare and remove discoveries for permanent preservation. Primary excavation support is provided by secant pile walls and tieback anchors.

Figure 14 shows the cut & cover ventilation building supported by secant piles and tubular steel struts.

5.3 Sirkeci Deep Station (European Side)

- Station Box: 235m length, 60m depth, NATM-style mined station with 2 access shafts
- Excavation Support: HEB 150mm steel arch, 300mm sprayed concrete, 4 – 6m long rockbolts
- Station Design Capacity: 34,000 passengers / hour
- Contractor (Entrances): Gama-Nurol (Turkey)
- Contractor (Tunnels): Taisei Corp. (Japan)

6.0 Contract BC1 Progress and Schedule

- Uskudar Cut & Cover Station - excavation completed early 2008, civil works in progress
- Yenikapi Cut & Cover Station - archeology works completed September 2009, civil works in progress
- Sirkeci Deep Station - 1 access shaft completed September 2008. Platform tunnels, walkways excavation in progress by NATM (65% complete)
- Immersed tube tunnel completed September 2008, awaiting connections to TBM tunnels
- TBM 1 tunnels complete by December 2011 (Europe side)
- TBM 2 and 3 tunnels complete in January 2011 (Europe side)
- TBM 4 and 5 tunnels complete by September 2010 (Asian side)
- All tunnel civil works complete in 2011, all track work complete in 2012

7.0 References

