The Marmaray Project is one of the world’s largest transportation infrastructure projects currently underway. It encompasses Turkey’s 76 km-long upgraded or new railway extending from Halkali to Gebze and includes the first rail crossing of the Bosphorus Straits. Marking a major step forward in transportation in Turkey – expected to be a future frontier of the EU – it is scheduled for completion in 2011, and estimated to cost US$3 billion.

Referred to as the Bosphorus Crossing, Bosphorus rail tunnel project and Istanbul commuter railway upgrade, the Marmaray project was named by combining Marmara, the name of the sea off Istanbul’s south coast, with ‘ray’, the Turkish word for rail.

The project is ambitious in scale, scope and schedule. Its major components include:

- A 1.4 km-long immersed tunnel under the Bosphorus;
- Bored tunnels totalling 9.8 km-long;
- Cut and cover tunnels 2.4 km-long;
- Three new huge underground stations;
- 250 linear km of new track;
- 37 new surface stations;
- An operations control centre;
- Rail yards, workshops and maintenance facilities;
- Electrical and mechanical systems, including tunnel ventilation, rolling stock control, system integration and signalling; and a 25 kV overhead electrification system.

The complexity of the project is further exacerbated by the requirement that all the tunnels and stations be designed to remain operational after an earthquake of 7.5 on the Richter scale. Further complicating matters are the larger than usual rail tunnels and trains, with 10-car high-speed transit trains capable of travelling from Berlin to Baghdad.

PB’s involvement began with its 1985 feasibility study in which it concluded that such a connection would be both feasible and cost-effective. However, a more recent involvement came about in February 2002, when Avrasyaconsult, a JV with which PB is an associate partner, won a long-term contract to provide design, tender preparation and construction supervision as employer’s representative.

The client (employer) is the general directorate of railways, harbours and airports construction (DLH), part of the ministry of transport and communication. Lead JV partner, as well as PB’s client, is Pacific Consultants International of Japan. The other three partners are Yuksel Proje (Turkey) and Japan Railway Technical Service (JARTS) as well as Oriental Consultants (Japan).

**CHALLENGES**

Our challenges have been diverse. For example, Istanbul’s unique history as capital of three great empires – Eastern Roman, Byzantine and Ottoman – necessitated extensive archaeological excavations before construction of the stations could begin. Other challenges included:

- Immersing a tunnel in one of the world’s busiest waterways with strong and unpredictable currents;
- Communicating among people with different work cultures and expectations;
- Designing and constructing all tunnels and stations in accordance with the highest international earthquake standards;
- Overlaying two signalling systems to cater for intercity and commuter trains; and
- Designing fire-life safety systems required for a 100 MW freight train design base fire.

**CONTRACT STRUCTURE**

The project was divided into three main contracts, all...
of them being prepared for a design build procurement in accordance with the International Federation of Consulting Engineers’ (FIDIC) silver book:

1. The BC1 (Bosphorus Crossing) contract covers the 14 km of two-track, immersed, bored and cut & cover tunnels under Istanbul and the Bosphorus Straits. It includes the tracks, three new underground-stations and all related E&M systems. The contract was awarded to the Japanese and Turkish JV of Taisei, Kumagai Guma and Nurol with a commencement date of August 2004.

2. The CR1 (commuter rail) contract encompasses all the infrastructure and tracks on the 62 km-long, 3-track surface alignment, including all railway and electrification systems, the 37 stations, operations control centre, and rail yards, workshops and maintenance facilities. The contract was awarded to the French, Japanese and Turkish JV of Alstom, Marubeni and Dogus with a start date of June 2007.

3. The CR2 contract covers rolling stock and is scheduled for award in 2008.

As of June this year, the following progress has been made:
- Detailed design under BC1 was 80% complete;
- Archaeological works were 80% complete;
- The first three tunnel-boring machines had commenced tunnelling;
- Dredging and compaction grouting of the Bosphorus Straits was complete;
- Station excavation and construction were underway;
- Works had commenced for the installation of new power substations and diesel generator compounds;
- Detailed design under the CR1 contract was underway.

**BENEFITS**

When complete, the project will increase from 3 to 27% the number of passenger journeys by train in Istanbul. Crossing the Bosphorus Straits by train will take only four minutes, in comparison to the ten- to 18-minute ferry ride or the 30-minute to 60-minute car ride across the heavily congested bridge. The current 185-minute rail-ferry-rail trip from Halkali to Gebze is expected to take only 104 minutes. Sustainable development features include using prefabricated elements and establishing a confirmed disposal facility for contaminated dredged materials. In addition, the Bosphorus’s rich aquatic habitat will not be affected, nor will its water currents or salinity, and the spectacular views over the Bosphorus and Istanbul’s historic skyline will be preserved.

Daniel Horgan is PB’s project manager on the Marmaray Project. This article is an extract from his introduction to the publication Linking Two Continents: The Marmaray Project – Overview and History, published in PB Network Technical Journal #55, pages 6-8, 2007. For further articles on the many technical aspects of this project, see issue #65 on PB’s website at www.pbworld.com/news_events/publications/network/past_issues.asp

**Secrets behind immersed tunnel construction**

**S**

O WHY is the Bosphorus rail tunnel so special? Walter Grantz, PB’s immersed tube specialist, outlines the project and the preparatory work required to design and build this engineering marvel.

The Bosphorus rail tunnel has long been regarded as the most difficult immersed tunnel project in the world. Over the years, many detractors have questioned its feasibility and for good reason:
- The tunnel crosses at a great depth that reaches 61 m. The immersed portion that starts and ends in such deep water must be reached with four boring machines, two from the Asian shore and two from the European.
- The Bosphorus is characterised by constantly changing and difficult to predict currents of up to six knots that are driven by the variation in the hydraulic gradient between the Black Sea and the Sea of Marmara.
- The project area is seismically active and portions of the tunnel lie in ground that must be stabilised against liquefaction.

- The Bosphorus Straits are relatively narrow but must accommodate some 52,000 ships per year (around six per hour on average).

**TUNNEL**

The immersed tunnel is being built in 11 sections or ‘elements’, each around 135 m-long, 15.3 m-wide and 8.6 m-high, and weighing 18,000 tonnes. In cross section, the tunnel is a rectangular, structural concrete box section with a separate tube for each track direction.

Externally, a 7 mm-thick steel waterproof membrane is provided on the bottom and sides. Lapping on to this, a special plastic membrane (trade name SAN A) will provide waterproofing at the top of the tunnel. A special steel end shell’ structure at each end of every element will enclose the end bulkheads and support the immersion joint GINA gasket and its contact plate. These end shell structures and steel membranes are being fabricated in Izmir, some 700 km from Istanbul by road, and trucked to dry dock in Tuzla where they are constructed into tunnel elements.

**TUNNEL BED**

The immersed tunnel will be constructed in a trench, dredged so that the structure will have a minimum cover of 2 m after backfilling. The connecting tunnels at both the European and Asian ends will be bored through rock by TBMs until they emerge into a transition zone of low strength sand-cement cover placed by tremie method out to circular steel sleeves provided at the ends of the immersed tunnel. The TBMs will then bore their way into the sleeves where they will be sealed to the immersed tunnel and eventually dismantled and removed.

Counting from the European end at Element 4, there is a 3 m-thick area of ground that must be overdredged and replaced because it is seismically unstable. And midway from Element 8 through to Element 11, the ground contains layers that could liquefy during an earthquake. The subordinate of this section of tunnel has now been treated by compaction grouting to a depth of up to 8 m. The latter operation took 18 months and involved

Continued on page 14
FOCUS ON GREECE & TURKEY

Continued from page 13

injecting 2,778 grout columns into the ground on a 1.7 m grid.

The compaction grouting work was not an easy operation, considering it involved drilling holes in an accurate pattern at the bottom of the Bosphorus, starting at a depth of more than 30 m, with currents ranging up to 9.3 km/h, and then injecting cement grout in bulbs every 0.3 m up to the subgrade elevation of the tunnel foundation. Each drill string of the drilling barge was protected from the strong surface currents by a pipe sleeve that extended to a depth of 20 m. The effectiveness of this procedure was verified by cone penetrometer tests.

CHALLENGES

One of the most difficult challenges posed by the Bosphorus is to determine when to initiate the placing operation of each tunnel element. To achieve this, the contractor devised a system that would identify when currents would be less than the 5.5 km/h maximum for a sufficiently long period, as allowed by his equipment. During this time, the elements need to be towed by barge into the Bosphorus, a complex anchor system must be set in place and the element lowered into the trench. Lowering sections is achieved in 5 m ‘drops’, with the weight of water ballast adjusted to achieve the correct descent rate. During this time, the exact position of the unit is relayed to monitors on the barge’s bridge.

The single access shaft will be the only means to get personnel and equipment into the tunnel until the TBM’s reach the immersed tunnel a couple of years later. This tall shaft must resist both the strong currents and the great hydrostatic pressures at the bottom, so it is very heavy. Its lower part is connected to Element 11 by a heavy steel tower. All this has required that 11.5 m of the Asian end of the tunnel be of steel/concrete sandwich construction.

Element 11 was the first section to be installed. It sits on jacking frames at each end. Subsequent elements will be positioned in guides on the previously placed element and a jacking frame at the outboard end. The jacking frame permits very accurate vertical and horizontal adjustment of each element once survey has determined where the outboard end comes to rest following the activation of the immersion joint.

Before placing the elements, a special, porous, gravel foundation blanket has been placed by tremmie pipe in the bottom of the trench. The jacking frames will be supported on this blanket which is designed to prevent liquefaction directly under the tunnel. Once in acceptable position, a special grout mixture will be pumped under the tunnel through ports placed every 8 m along the bottom. This material will not penetrate into the gravel foundation but will harden to support the element so that the jacks can be removed and the element backfilled.

When E11 was finally sunk into position on March 24, 2007, the accuracy achieved was impressive – only 16mm low at the Asian end and 8mm low at the European end. And although it was 100 mm ‘up station’, the deviations were within the corrective ability of the jacking system.

Currently, E11 and E10 are in place in the trench. Furthermore, E9, E8, E7 and E6 are now floating, with E5 and E4 being constructed in dry dock. Construction of E3 and E2 has just started.

Rough dredging is now complete but as the elements are readied for placing, the dredger will return to fine dredge the last meter or so. All the constantly shifting locations of the dredging and compaction grouting activities have involved careful coordination with the navigational authorities. During immersion activities, there will be periods of several hours when shipping lanes will be closed.

DRIY DOCKS

The dry dock facility is located at Tuzla, some 40 km east of the tunnel site, and it is here that the contractor fabricates and fits-out the tunnel elements. To do this, he built two dry docks, each able to hold two 135 m-long elements.

The dry docks have been designed to permit only the casting of the concrete base slab and partial walls of the tunnel sections, after which each element must be floated out to a jetty where the last concrete stage can be poured. After this, the element will be at ‘full draft’ – just floating, with the top of the element only 1.5 m above water – and must be towed to an anchorage where it can be fitted for the placing operation. This method reduced considerably the amount of excavation required for the dry dock, compared to what would have been necessary if all concrete work had been done before float out.

ELEMENT 11

Element 11 is special for two reasons:

- It is provided with sleeves to receive the TBM’s on the Asian side.
- It must carry an access shaft that will extend more than 34 m above it.

Walter Grantz, a senior consultant at PB, is a recognised authority on immersed tube tunnel design. This article is an updated version of his article on “Immersed Tunnel Construction” from the publication ‘Linking Two Continents: The Marmaray Project – Overview and History”, published in PB Network journal #65, pages 20-22, 2007. This can be viewed, along with further details of this project, in issue #65 on PB’s website at: www.pbworld.com/news_events/publications/network/past_issues.asp. TTC is grateful to Daniel Horgan, Walter Grantz and Elizabeth Morgan for their kind assistance in the publication of these articles.