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Considerations and strategies behind the design and construction requirements of the Istanbul Strait immersed tunnel

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Abstract

This being a design-build project, the challenge faced during preparations of the Employer's requirements for design and construction of the Istanbul Strait immersed tunnel was to give the contractor as much freedom as possible and yet specify enough so that the Employer obtained the required facility. When completed, this will be a world-class facility. This paper discusses on a strategic level many of the aspects to be presented by the author in two papers in later sessions of the day. Unusual features of this crossing include the deepest ever immersed tunnel crossing, extra waterproofing requirements, strong currents with bi-directional flow, close proximity of the North Anatolian Fault which is predicted to have a major seismic event during the life of the tunnel, and the method of connecting the adjacent bored tunnels to the immersed tunnel. Safety during tunnel construction and operation has been paramount, and resulted in changes to contract packaging and extra requirements. Other challenges discussed include fish migration, control of an international waterway, environmental issues and ensuring the stability of the soft soils during a seismic event.
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1. Introduction

This being a design-build project, the challenge faced during preparations of the Employer's requirements for design and construction of the Istanbul Strait immersed tunnel was to give the contractor as much freedom as possible and yet specify enough so that the Employer would obtain the required facility. Most of the requirements are performance-based, though some are specified in some detail. Some items such as seismic design and concrete are specified in some detail to ensure not only that all bids received are designed and constructed to equal standards, but that exactly the right product is obtained. When completed, this project will have been designed and constructed to international standards and will be a world-class facility.

Since the project is being constructed in Turkey, naturally all structures must comply with Turkish national and local authority standards and codes of practice. However, to ensure that the latest design and construction concepts are incorporated, the contractor is obligated to design all structures additionally to satisfy a set of international standards and codes that must be Japanese, British, Euro-Codes or US. In some cases, particular documents to be followed are specified. Since Britain does not experience severe seismic events, seismic design must follow Turkish plus either the US or the Japanese requirements.

2. Issues associated with depth

This tunnel will be the deepest immersed tunnel so far, 58 m deep, with the nearest contender, BART in San Francisco, being 40 m deep (see Fig. 1). This somewhat affected the concepts being presented in the Employer's requirements. It was not that the requirements or the project were particularly innovative, but rather that external pressure and long-term loading would be an order of magnitude greater than previously experienced. It was felt that extra

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Fig. 1. Artist's rendering of BART tunnel.

precautions were warranted to ensure the product would have the design life intended. Furthermore, since a serious seismic event is almost certain to occur in Istanbul during the design life, the tunnel must be able to not only survive that event, but to be usable following the event. Unlike most areas, Istanbul does not really experience a large number of smaller seismic events at all before the large event, making seismic design here more challenging.

The potential of water leakage was a serious concern and was addressed in a number of ways. Naturally, the avoidance of cracking during construction is paramount. Very close attention will be paid to construction sequencing, avoidance of early age cracking (especially through cracking), and curing. In fact, one requirement is that the concrete be constructed to be watertight on its own. A number of Dutch tunnels and the Øresund tunnel between Denmark and Sweden have been constructed without external waterproofing. Lessons learnt from these projects were adopted. However, to be on the safe side, since the tunnel is so deep as to make practical external repairs by diver near-enough impractical, an external waterproofing membrane is also mandatory. Ideally, a membrane that totally adheres to the concrete is best, since this would prevent leaks from migrating beneath the surface. However, when one considers methods of construction, single-shell steel tunnels (like BART) and sandwich-type steel tunnels both have an external structural steel plate that is integral to the structure and which normally would be considered the waterproofing membrane. It was therefore decided that a steel waterproofing membrane could not be ruled out for a concrete tunnel, such membranes being fairly common. To reduce extensive migration of water beneath such a steel membrane and to make the repair of leaks more likely to be successful, it was decided that a steel membrane should be divided into panels not exceeding 10 m^2, for example by ribs embedded in the concrete.

The contractor is intending to use a steel membrane for the sides and base, and an adhering waterproofing sheet on the roof covered with protective concrete. The top slab may be waterproofed using San-A Sheet, made of Ethylene Vinyl Acetate (EVA) that has napped (hairy) layers on both sides. This material has a 25-year history of use and complies with JIS A6008. The concrete is first primed and then a layer of polymer cement paste is applied as adhesive for the EVA sheet. The protection concrete will also adhere to the napped upper surface. The edges are sealed to the steelwork using epoxy adhesives. In lieu of anchoring ribs for the steel waterproofing, strips of the same material will be used to divide the surface of the steel waterproofing membrane into the required 10 m^2 panels.

Two main types of immersed tunnel construction have emerged, known as steel and concrete. Steel tunnels use structural steel, usually in the form of stiffened plate, working compositely with the interior concrete, whereas concrete tunnels do not do so, relying instead on steel reinforcing bars or prestressing cables. The number of concrete tunnels is almost twice that of steel tunnels. Steel tunnels can have an initial empty draft of as little as about 2.5 m before the concrete is placed afloat, whereas concrete tunnels have a draft of almost the full depth since they are usually complete when floated out. Tunnel cross-sections may have flat sides or curved sides.

Although the next deepest tunnel, BART, is constructed as a steel tunnel where the immersion joints were made rigid after installation on the seabed, and there was strong support for only permitting that type of construction (and as had been envisaged during concept design studies in the mid 1980s), it was felt that some contractors would only bid a concrete tunnel. There did not seem to be a logical reason to exclude a concrete tunnel, since it could almost certainly comply with criteria, and so a concrete tunnel was permitted. A review was also made of steel tunnel practice. Three types are common, double shell (US only), single shell, and sandwich (Japan only). Of these, only the double shell has substantial quantities of tremie concrete – i.e., non-structural concrete. With the much greater depth, it was considered advantageous to insist on as much concrete as possible being structural, and therefore only the single shell and sandwich types of steel tunnel were permitted.

3. Continuous strong currents

The currents through the Bosphorus (Istanbul Strait) are mainly driven by a difference in water level between the Black Sea to the north and the Sea of Marmara to the south, and by a difference in salinity. The difference in level is nominally 0.3 m, but this can change due to atmospheric pressure and winds. Tides are barely noticeable. There is a constant 3–6 knot surface current southbound and a constant 1–2 knot deep current northbound with a turbulent layer between them. Placing tunnels will be much simpler when the current is low, and forecasting this is a priority to reduce risk. Current forecasting was used very successfully for the Øresund tunnel and a similar requirement was made for this project. Data is being recorded by the contractor and a forecasting model is being developed and calibrated using data retrieved.

Model testing is required to demonstrate that the proposed installation methods will work in strong currents, although simulating a model test with bidirectional flow remains a challenge yet to be overcome.

Temporary access into the immersed tunnel by a shaft and survey towers indicating position are usually installed prior to immersion, but on this project, currents make this unlikely. Access will need to be installed later if stability of the tunnel element on the seabed is to be ensured, and later adjustment of position may be needed after survey checks from within the placed element.

4. Seismic issues

The North Anatolian Fault (NAF) is an active plate boundary. Displacements along the fault seem to migrate westwards and the last section that moved was 100 km east of Istanbul near Izmit in 1999, an event with $M_w = 7.4$. Two of the three faults near Istanbul are late in their earthquake cycles, so that it is probable that an $M_w = 7.5$ event will occur within 35 years. This is well within the 100-year life of the tunnel, which must therefore resist such an event and continue to be useable thereafter.

The minimum seismic design requirements for this project are based on a single-level design earthquake, defined as the Design Basis Earthquake (DBE). On account of the importance of the project structures, the DBE is an $M_w = 7.5$ (moment magnitude) earthquake occurring within the Sea of Marmara at locations that affect the Site. Forecast bedrock ground-motion time histories for three nearest-fault distances were prepared together with required detailed analysis methodology before documents were issued for tender so that all bidders would bid on the same basis.

A preliminary review of previous borehole data, now nearly 20 years old, made it clear that new data using new techniques was required. Some additional boreholes were drilled during the tender period and the data given to bidders. A requirement for additional borings was also written into the contract requirements to ensure that the work considered necessary for final design would be carried out. A potential for liquefaction of some of the subsurface soils was evident and requirements for analyses and mitigation were drafted for inclusion in the requirements. Now that these site response and liquefaction analyses have been carried out, an easterly portion of the underwater alignment appears susceptible to liquefaction. To remove the liquefaction risk to the tunnel of these foundation soils, ground improvement using the contractor's selected method of compaction grouting has started at the eastern end of the immersed tunnel from the location where rock drops below the tunnel. Four boring rigs are mounted off the end of an anchored barge; a combination of movements of these rigs and of the barge enable a defined pattern of grouting through guide casings to be made and CPT tests to ascertain whether the first round of improvement is sufficient. Occasional second improvements between the earlier improvements may need to be made in some areas if analysis indicates excessive tunnel movements during and after the seismic event (see Figs. 2 and 3).

A further consequence of the seismic event is that all granular soils, whether they liquefy or not, will suffer some post-seismic settlement. Investigation of this is also part of the requirements. Sufficient space in the tunnel has to be provided so that a track alignment can still be provided within specification after the seismic event.

Investigations were made (before the recent disastrous Indonesian tsunami) into whether a tsunami could be expected in the Sea of Marmara as a result of a major seismic event. Fault movements are expected to be primarily slip and are therefore not likely to produce much in the way of a tsunami; however, there is a real risk that the underwater slopes close to the nearby Prince's Islands are liable to have major slides, and if that is triggered by the seismic event, a tsunami could affect Istanbul 3–6 m above existing level within a few minutes of the slide happening. Historical records of Istanbul indicate that this has happened before.

In dealing with the potential of a major seismic event, the predicted event has been estimated. Should the event

Fig. 2. Drilling offshore boreholes.

Fig. 3. Compaction grouting (at left end of barge).

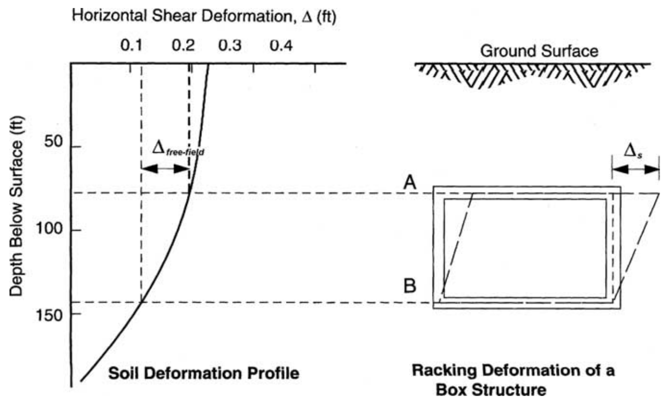

Fig. 4. Ductility in the overload range particularly applies to racking deformations.

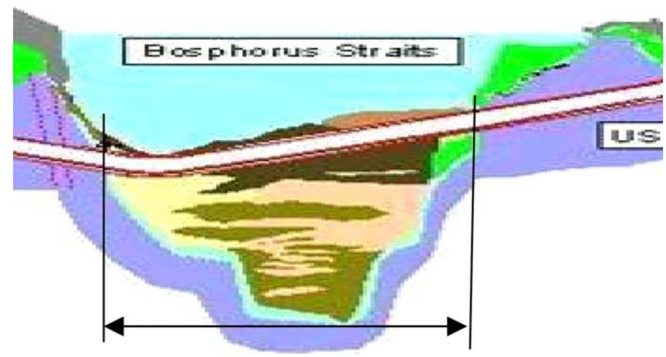

Fig. 5. Immersed tunnel terminates at rock faces.

that actually occurs be worse than forecast, requirements were included to provide floodgates each side of the Bosphorus so that should for some reason flooding occur in the underwater section, it could be isolated so that the remaining below-ground land sections would still be able to be used and the system integrity preserved. Furthermore, ductility in the overload range would ensure that even though the tunnel may get damaged under this scenario, it would not collapse and therefore passengers would still be able to escape safely (see Fig. 4).

There is also a requirement for the contractor to investigate whether there is a need for seismic joints. According to the contractor's basic design analysis, flexible joints in the bored tunnel are required close to the immersed tunnel terminal joints to ensure bored tunnel integrity.

5. Geotechnical challenges

Clay, silt and sand exist in the central portion of the waterway where the immersed tunnel is specified. The tunnels adjacent to the immersed tunnel are in rock. The concept design from the 1980s envisaged an excavation over 50 m deep into Sarayburnu Park on the western shore with immersed tunnels laid from this location, presumably with the temporary access shaft at the same sheltered location. Looking at the capabilities of today's TBM machines and at the complexities involved in bringing the end of the immersed tunnel ashore at that location, the original concept of three separate contracts (one for each land portion and one for the immersed tunnel) was abandoned in favor of allowing the contractor to decide where to put the interface and how to make it.

Bored tunnels have previously been driven into an immersed tunnel in the late 1970s for the transit system in Hong Kong. The tunnel drawings were modified to show an interface where rock tunnels reached soft-ground offshore, without specifying exactly where, and modifying the Employer's Requirements to cover this situation (see Fig. 5). All three bidders opted for a bored tunnel solution into the immersed tunnel without the more usual interface structure, though all three had slightly different interface locations.

Rock tunnels will be bored using four 7.84 m diameter slurry TBMs from Hitachi-Zozen. The bores on the western side will be the world's longest slurry shield bores. The rock is essentially heavily fractured sandstone with some inactive faults and a high risk of high groundwater pressures. An EPB Lovett soft-ground machine is also to be used at the western end of the project. The first four machines will be manufactured by the end of the year and start operating in the spring of 2006.

Lest the bidding contractors should gloss over aspects of the soil behavior associated with immersed tunnels, the requirements outlined the steps that have to be considered. The immersed tunnel is laid in a trench excavated in the seabed. During excavation, some soils will rebound (heave). After placing the tunnel and also after backfilling, some of the rebound is recompressed, but not all because the immersed tunnel effective specific gravity is less than the soil it displaces. After considering all long-term and post-seismic settlements, the challenge is to estimate the correct installation level for the tunnel elements so that they finish up at the required elevations. Internal clearances must ensure that alignments meet the required design parameters for expected ranges of movement.

6. Tunnel structure

The next deepest tunnel is BART, designed by PB, so it was natural for PB in 1985 to select that tried cross-section for the proposed metro system, the purpose for which the tunnel was being provided. Internal diameter then was 5.2 m. When the project started in 2002, the system requirements had changed to commuter rail with occasional transits by intercity and freight trains, and clearances to meet UIC506 and local requirements. Consequently a larger internal clearance was needed, being about 7 m diameter. A basically circular section was selected as an illustrative design, chosen to eliminate the need for shear reinforcement and to keep moments within acceptable levels for the 58 m water depth to underside. The contractor was not obliged to follow this suggestion and selected a rectangular section.

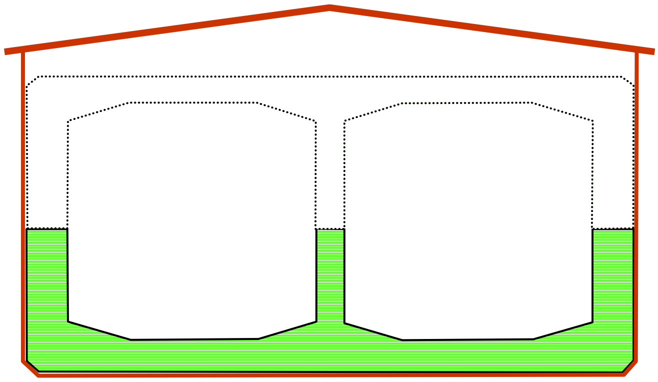

Fig. 6. Immersed tunnel construction in dry dock.

The availability of construction sites to the selected contractor and the proposed method of use dictated an immersed tunnel constructed using two dry docks at Tuzla, 41 km away from the immersion site by the proposed towing route. Each dock can take two tunnel elements. A steel plate surrounds the bottom and sides, and the sides are to be stiffened steel plate, including temporary bracings over the top of the tunnel. These and the end bulkheads form the basis of the immersed tunnel element. Two each are assembled in each dry dock. The base is then cast in a single operation, followed by half the wall height (see Fig. 6). This partially completed tunnel element is then floated out into the Employer's adjacent harbor, made available to the contractor. Using floating pontoons as working platforms, the elements are completed afloat, with the roof slab also being cast in a single operation. This procedure enables new tunnel elements to be started when the tunnel elements are only half finished, shortening the overall construction time.

Options available for the immersion joints in the immersed tunnel were to leave them elastic or to make them rigid (as the BART joints were). Benefits of both were considered and the option left open to the contractor.

For the terminal joints, now likely to be constructed in deep water as mentioned earlier, a procedure similar to that previously done in Hong Kong was expected, i.e., after placing the terminal elements, the ground surrounding the future bored tunnel plus an additional 2 m all around would be filled with a relatively impermeable soil mix to reduce waterproofing issues as the bored tunnel comes through to enter circular ends of the bored tunnel. Potential issues associated with this were incorporated into the documents, though without more detail than necessary. The contractor proposes to backfill the area around the end of the tunnel with mix-soil, a cementitious mixture with a strength of about 1 MPa which will form a more or less watertight transition from the adjacent rock to the immersed tunnel.

A number of serious tunnel fires in recent years prompted a look at ways to protect the tunnel from fire, at least long enough to get people to safety and to have a chance at putting out the fire. The best option available at the time of document preparation appeared to be the application of fireproofing in conjunction with limiting concrete and steel temperatures, at least for 2–4 h, depending upon the severity of the fire. Hence, where the partial loss of the tunnel structure can compromise the safety of passengers within it, such as beneath the Bosphorus, fire insulation is to be provided over ceiling and walls with no spalling of concrete beneath the insulation.

While these measures may not protect against a long-duration fire, they should provide ample time for escape and some fire-fighting. If for some reason there is a breach of the underwater sections of the tunnels, the flood gates can be closed.

7. Other challenges

Unlike many other tunnels, the seabed is not being left to fill up naturally, but must be backfilled to existing bed levels to ensure continuation of the existing environmental regime and the fish migration that occurs in the spring and autumn each year. Disturbances that could affect the migration will not be permitted, and this may severely limit excavation and backfilling during crucial months. Neither of these operations is particularly easy at the required great depths and with the contra-flowing currents that exist. Identification and control of the actual location of operations requires state-of-the-art technology.

Some of the materials to be excavated on the western side are contaminated and have to be removed to a confined disposal facility currently under construction. The location and quantities of these were specified in the bidding documents.

Since working areas extend into the international waterway through the Bosphorus, some control of the largest vessels transiting the tunnel alignment is unavoidable, and may at times result in one-way working.

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