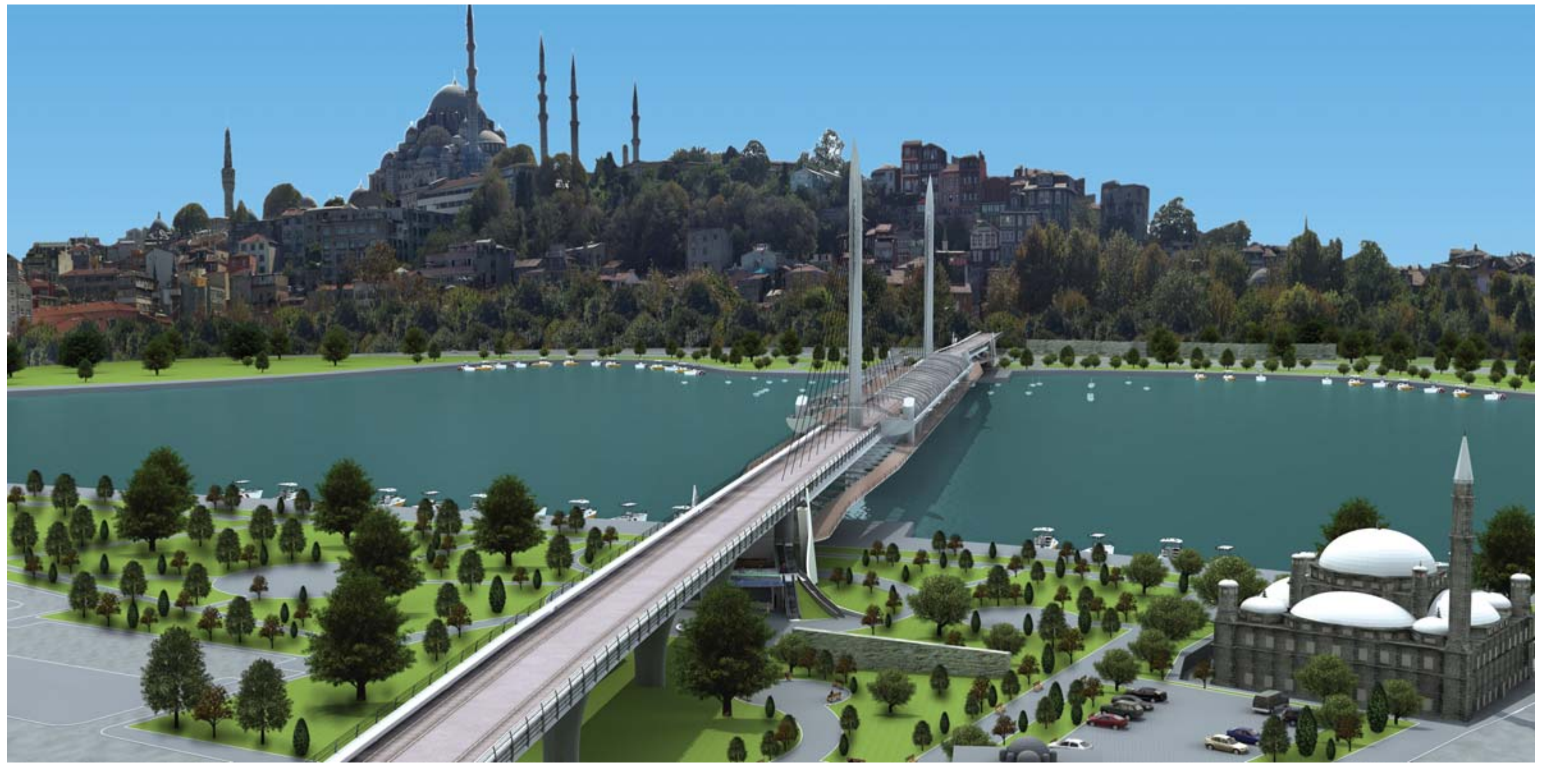


POINTS OF VIEW

Design of a new bridge in an historically-sensitive site in Istanbul has demanded an unusual solution and had to overcome difficult ground conditions, according to **Hakan Kiran** and **Boris Wiessler**

The new metro bridge over the Golden Horn will connect two of the most important historical sites of Istanbul; both Galata-Pera and the city's historic peninsula are designated World Heritage sites by UNESCO. The historic peninsula is the heart of Istanbul and the capital of three empires; Byzantine, Rome, Ottoman. The city has also been acknowledged as the centre of three major religions.

Galata-Pera was the first settlement of Genoese citizens from Italy; Pera, which means 'other side', is the centre of cultural diversity and activities in the city. The Golden Horn Metro Bridge will link these two sites; the location of the station on the bridge in the middle of the Golden Horn will have a panoramic view of the area and will be the perfect spot from which to begin a tour of historic Istanbul.

In fact the Metro Crossing Project consists of a total of four bridges and two station entrance structures, with one entrance structure being located on each bank of the Golden Horn. The total length of the four bridges is just under 950m. The south west bank of the river is known as the Unkapani side and the north east bank is known as the Beyoglu side.

In addition to the main cable-stayed bridge, the crossing features a swing bridge and two approach bridges. On the cable-stayed and swing bridges, the total deck width is 13.7m, narrowing to 12.6m for the approach bridges. The decks carry two railway lines – on the approach bridges they are 4.6m apart but this widens to 6.4m on the cable-stayed and swing bridges to accommodate the bridge towers in the centre of the deck. Emergency walkways run along the entire bridge.

The modest cable-stayed bridge has a total length of 387m over four steel piers, consisting of a main span of 180m, flanked by two spans each 90m long, and a 27m-long side span. The cable-stayed bridge has two towers which rise 64.5m above the deck and each have a single plane of stay. The deck is formed of a three-cell steel box girder with orthotropic deck that is approximately 17m above the Golden Horn water level.

But the most unusual feature of the cable-stayed bridge is that its main span houses the station platform and carries a roof canopy.

Two footbridges on both sides of the deck give access to the station platforms and connect back along the main bridge to the two station entrance structures on the banks of the Golden Horn. The footbridges are linked to the platform by a series of stairs and elevators.

The swing bridge is situated between the cable-stayed bridge and the Unkapani approach bridge. It has a total length of 120m – two spans of 50m and 70m – which is supported on a central steel pier that contains the main pivot shaft. The swing bridge is designed to swing 90º in plan to allow the ships and ferries using the Golden Horn to pass through, and the swing mechanism is designed in such a way as to have minimum impact on the operation of the Istanbul Metro system. The deck is also a three-cell steel box girder with orthotropic deck that is approximately 15m above the Golden Horn water level.

The approach viaducts on the Unkapani and Beyoglu banks consist of reinforced concrete decks 13.7m wide, on reinforced concrete piers. The Unkapani approach bridge has six spans ranging from 17m to 42m long, and a total length of almost 169m. The Beyoglu approach bridge has eight spans ranging from 23.5m to 45m long and giving a total length of 268m. Both approach bridges connect to tunnel portals where the metro line enters the underground sections of the line.

The approach bridge foundations required careful design and alternative solutions were necessary so as not to disturb or damage underground historical ruins.

Entrance structures for the bridge station are located on both banks of the Golden Horn, underneath the Unkapani and Beyoglu approach bridges at the exact location where the approach bridges connect to the swing bridge at the Unkapani bank and the cable-stayed bridge at the Beyoglu bank. The entrances are concrete structures with three floors above ground and a basement.

The design of the foundations for the Golden Horn Metro bridge was the biggest challenge of the entire bridge. The cable-stayed section is founded on four deep piled foundations with pile lengths up to 100m; the foundations for each of the two main towers consist of five piles each with piles of 87m and 97m deep.

The metro station is situated on the main span of the cable-stayed bridge

The Golden Horn waterway has an approximate depth of 30m in which the piles are free-standing, followed by a very soft layer of clay which has the potential to liquify; ultimately the piles are socketed into a fragmented poor rock to a depth of 10-30m depending on the pile location. The upper third of the piles consists of 2.5m-diameter steel casing piles with wall thicknesses ranging from 45mm to 85mm. In order to limit the thickness of the steel plate and hence the total weight of the piles, engineers decided to fill the lower portions of the pile with reinforced concrete and take into account the composite action of the piles. To ensure that the piles act compositely, shear rings have been added to the inner surface of the pile casings. The steel casing of the pile will be installed to a level just below the rock surface and the heavily reinforced concrete pile socket will then be extended to the required length of approximately 30m.

The critical load case for the piles is the tension that results from a 2,475-year earthquake. The piles are transitioned into a pyramid-like frame structure which in turn will be fully integrated with the deck. All joints between piles and piers as well as the pier to deck interface will be fully welded, posing a substantial challenge to the contractor as it will require adherence to strict tolerances during pile installation.

The superstructure itself is designed as a fully-welded orthotropic steel box supporting a metro station on its central span as well as a cantilevered pedestrian footway along the entire bridge. The deck is supported by means of a central fan-shaped cable stay arrangement. The two singles towers of the cable-stayed bridge are located in the middle of the deck and will be rigidly connected to the deck. The towers will be formed of fully-welded steel structures.

As a result of the centrally-located metro station the loading applied to the centre of the bridge is substantially higher that of the side span. This asymmetric dead load resulted in permanent uplift forces in the side span piers not only for the dead load but also for the live load and especially for the seismic loads. In order to ensure that these uplift forces can be transferred to the piers and foundations, a set of pendulums was designed to effectively transfer these forces and at the same time allow the large movements that result ▶

INFLUENTIAL SETTING

The alignment and aesthetics of the new bridge crossing have been strongly influenced by its historically-significant and culturally-important setting as well as having had to tie-in with existing metro lines on each side of the water. The Yenikapi-Taksim metro route was first planned in the 1980s, when a decision was taken to build connections on each side of the Golden Horn as well as a bridge over the Golden Horn. Approvals were obtained and tunnel construction began.

The majority of tunnel and station construction was completed by 2005; all except stations at Sehzadebasi, Sishane and Yenikapi. On each side of the Golden Horn, tunnel portals were built from which the lines were intended to emerge on to the new bridge crossing. The plan was to build a station on the banks of the Golden Horn, but this idea was eventually abandoned due to concerns that the station structure would have too great a visual impact on its historic surroundings. There were also concerns that technical difficulties would be encountered in trying to build an opening bridge for the metro lines – given the fixed vertical alignment which it had to meet.

In 2005 an analysis of the situation was carried out to try and determine appropriate design criteria for a new bridge – a proposal to re-route the line elsewhere was dismissed due to the fact it would have meant abandoning 1.6km of tunnels that had already been built.

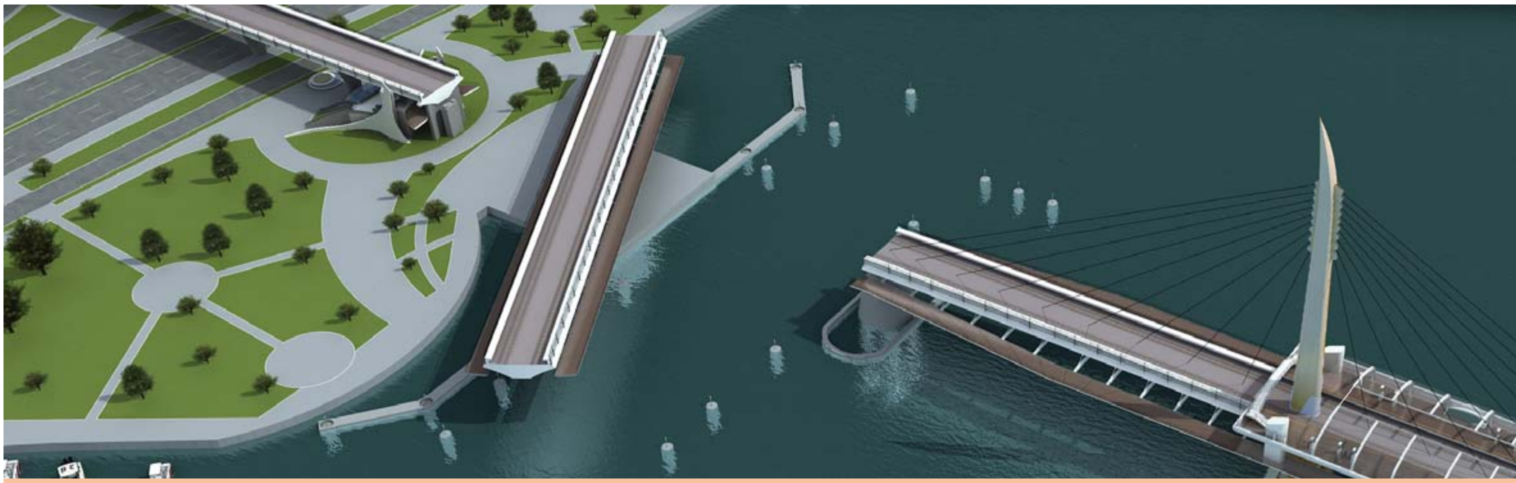
The main criteria were to develop a design befitting the historical peninsula, which would not affect the historical structures or city walls or block the circulation of sea water into the Golden Horn. What's more the bridge should be designed as a landmark structure which could transform the area and attract more visitors.

As noted in the main article, the poor ground conditions of the area were one of the biggest technical obstacles to be overcome. To try and reduce the influence of ground conditions on the design, the decision was taken to place as few footings as possible into the Golden Horn.

The height of the portals of the existing tunnels is 13m above sea level, which governed the height of the bridge deck above sea level. If a conventional girder structure were chosen for such a crossing, it would be massive and bulky. Therefore, post-tensioning technology has been used in viaducts and the thickness of profile has been minimised, and curved lines were used to reduce visual impact of the structure.

The choice of a cable-stayed bridge for the main bridge meant that the number of piers in the water could be minimised, and there will be no anchorages or massive abutments to accommodate on land.

Archaeological excavations were carried out at the locations where the bridge will touch down on the land. Efforts were made to minimise the number of timber buildings that would need to be expropriated at the tunnel portals. The tunnel which was intended to exit through Genoese city wall has been realigned so that there will no impact on the wall itself.



The swing bridge can rotate through 90º to allow passage for shipping traffic.

during an extreme seismic event. Due to the importance of these structures it was decided that a high degree of redundancy would be built into the design, in effect allowing two of the four pendulums to fail without resulting in a failure or collapse of the structure. This redundancy will also allow the replacement of the pendulums if necessary during the design life of the structure.

The heart of Istanbul is classified as a severe seismic zone, hence a substantial effort was made to accurately model the behaviour of the bridge under seismic loading. Analysis was carried out using three approaches; conventional response spectrum analysis, non-linear static or pushover analysis, and time-history analysis. The design of this bridge called for the consideration of an earthquake return period of 2,475 years (for the safety evaluation earthquake) which essentially governed the design of almost all components of this bridge. A fine balance had to be struck between the rigidity of the foundations which essentially determined the response of the structure to the seismic excitation, and the resulting superstructure displacements. The functional evaluation earthquake level was set at an earthquake with a 72 year return period.

The movable bridge makes use of an unusual concept to achieve the 90º horizontal rotation that is required for the opening of this bridge. In the closed or operating condition the bridge is supported at three positions. In order to open the bridge the entire span of 800t will be raised 120mm by means of a hydraulic cylinder located at the base of the tubular central shaft which also acts as the central support of the bridge in the open position. Once the entire deck has been raise the bridge is then rotated by 90º in five minutes, as called for in the performance specifications. The shaft has to be designed to withstand all forces including seismic, while the deck is in the open position.

One of the most important design features of the bridge is the station solution; in previous plans it was intended to be built on land, but would have destroyed the skyline of this historical peninsula. To solve the problem, the station is located in the middle of the Golden Horn, right on the bridge. The station has been designed as an open structure surrounded by a transparent ETFE membrane which is intended to protect passengers from rain and wind while not having any structural impact. ■

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Structural consultant: Michel Virlogeux
Detailed structural design: Wiecon Consulting Civil & Structural Engineers
Preliminary design: Systra
M&E design for swing bridge:
Detailed design: Wiecon Consulting Civil & Structural Engineers
Preliminary design: Hardesty & Hanover
Independent design checker: FCP Fritsch Chiari & Partners
Bridge contractor: Astaldi-Gulermak joint venture