ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
UDC/UDK 624.191.1.034.5:528.48(560)

MARMARAY BOSPHORUS CROSSING PROJECT: SURVEYING ACTIVITY AND GEODETIC MONITORING

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Original scientific paper
The ongoing Marmaray Project is one of the largest transportation infrastructure projects in the world. The total length of the over ground and underground Marmaray project is 76,7 km. The first part of project is the Bosphorus Crossing (BC1) with a length of 13,6 km. The BC1 project contains the construction of three bored tunnels and immersed tunnel under the Istanbul Strait. The construction studies in the tunnels and immersing tube were completed in the beginning of 2012. The planning and design of engineering projects are the main study focus of the engineering survey which is a basic requirement for many engineering projects. This paper explains the recent advances in engineering surveying operations, such as establishing the geodetic control network, deformation monitoring and as-built surveys, in the scope of BC1 project. The experiences gained during the measurement studies are presented as a guide for similar projects that will be realized in the future.

Keywords: *geodetic monitoring, Marmaray, surveying, tunnel*

Marmaray projekt prelaska Bosfora: geodetske djelatnosti i geodetsko praćenje

Izvorni znanstveni članak
Tekući Marmaray projekt jedan je od najvećih transportnih infrastrukturnih projekata u svijetu. Ukupna duljina na tlu i i ispod tla Marmaray projekta je 76,7 km. Prvi dio projekta je Prijelaz Bosfora (BC1) s duljinom od 13,6 km. BC1 projekt sadrži izgradnju tri bušena tunela i jedan uronjen tunel ispod Bosforskog tjesnaca. Građevinska ispitivanja u tunelima i uronjenoj cijevi bila su dovršena početkom 2012. Planiranje i oblikovanje inženjerskih projekata glavno su žarište istraživanja inženjerske topografije koja je osnovni uvjet za mnoge inženjerske projekte. Ovaj članak objašnjava najnovija dostignuća u inženjerskim geodetskim aktivnostima, kao što su uspostavljanje geodetskih kontrolnih mreža, praćenje deformacije i izvedenih mjerenja, u okviru projekta BC1. Iskustva stečena tijekom studija mjerenja prikazana su kao vodič za slične projekte koji će se realizirati u budućnosti.

Ključne riječi: *izmjere, geodetski nadzor, Marmaray, tunel*

1 Introduction

A railway tunnel under the Bosphorus was first proposed in 1860. However, at that time underwater tunnel construction was not to emerge as a viable technology for road or rail transport. In 1902, a similar design for a Bosphorus tunnel was considered, this time with the tunnel lying on the seabed, but it was never built.

With its population of more than 12 million, Istanbul is the largest city in the Republic of Turkey. The city is located on both the European and Asian sides of the Bosphorus. The Marmaray Project will provide mass transit for the city's population and the Project will help to solve many of the city's problems by providing a rail link beneath the Istanbul Strait. The construction work of the project was scheduled to be completed in April 2009, but this was later revised to October 2013.

After the project is completed, the number of passenger journeys by train in Istanbul is expected to increase from 3 % to 27 %. Crossing the Bosphorus Straits by train will take only 4 minutes, in comparison to the 20 minute ferry ride or the 30 minute to 60 minute car journey across a heavily congested bridge [1].

The Marmaray project was divided into the two main contracts. The Bosphorus Crossing (BC1) contract covers the 13,6 km of two-track, immersed, bored, and cut-and-cover tunnels. It includes the tracks and three new underground stations. The tunnel will be the deepest immersed structure (55 m below sea level) in the world. Of the total BC1 contract there is 9,8 km of bored tunnel; 2,4 km built using cut-and-cover methods and the remaining 1,4 km as an immersed tunnel. The immersed section is connected to the shore by tunnels bored using tunnel boring machines (TBM) to create separate bores for each train line.

The Commuter Rail (CR3) contract encompasses all the infrastructure and tracks on the 63 km long, 3-track surface alignment, including all railway and electrification systems, the 37 surface stations, operations control center. The project started in December 2012 and the completion aims to be in September 2014.

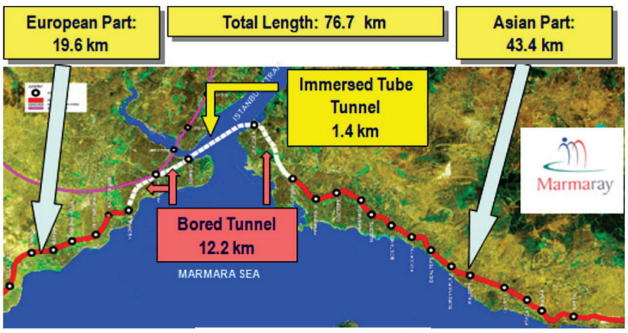

Figure 1 Marmaray project

The primary tectonic feature affecting the Project area is the Marmara Fault System on the south side of the Project area (Fig. 2). This is an extension of the North Anatolian Fault Zone, splaying westward toward the Marmara Sea region into a complex system.

The main Marmara Fault, exhibits features typically associated with a strike-slip fault. The velocity vectors shown in Fig. 2 determined as the result of Global Positioning System (GPS) measurements and the long-term seismicity indicate that this strand is more active than the southern strand; therefore, it governs the seismic design of the tunnel structures.

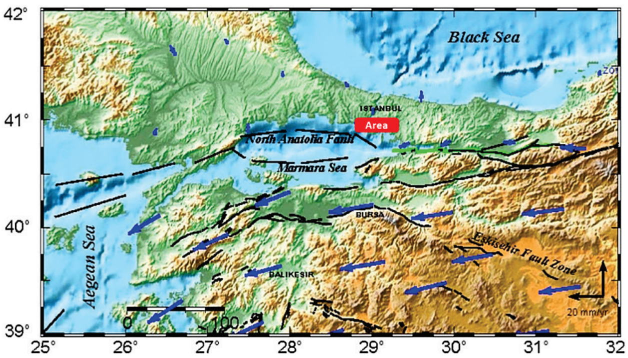

Figure 2 Project alignment relative to the main North Anatolian fault

For this project, the minimum seismic design requirements are based on a single-level earthquake defined as the design basis earthquake. Both probabilistic and deterministic approaches were used to assess the seismic hazards. The project design basis earthquake corresponds to a $MW = 7{,}5$ (moment magnitude) earthquake [2].

There have been several studies on the Marmaray project, for example; [3] presented information related to Seismicity, Environmental Concerns and Historical Heritage. Also, [4] have given information about the organization and management of the BC1 project.

The high cost of tunneling and recent advances in the technology require a survey engineer to design the survey control for the alignment of the tunnel axis with the highest possible accuracy so that the opposing headings meet at the breakthrough points without any need for an adjustment of the excavations. Many other tasks are required of the survey engineer during the tunnel construction, such as setting-out the specified grade and line of the tunnel, checking the profiles of the cross section of the excavations, guiding the boring machine or determining the location of the drill holes for blasting operations and finally, measuring deformations of the tunnel cross section [5].

2 Geodetic Surface Network

The surface geodetic network which gives an outer geometric frame provides information for the construction work and this is most important for the successful realization of tunneling projects. The establishment of the surface geodetic network is often separated into horizontal and vertical parts.

In the BC1 project the tunnels must be positioned, in the horizontal and vertical dimensions, to within ±100 mm (total tolerance) of their designed locations [6]. The measurement tolerance (T_M) within total tolerance (T_T) is calculated by the equation given below [7]:

$$T_M = T_T \cdot \sqrt{\left(1-(1-p)^2\right)}. \tag{1}$$

By assuming p as 10 %, the share of measurement tolerance within total tolerance is obtained as

$$T_M = T_T \cdot \sqrt{1-0{,}9^2} = 0{,}44 \cdot T_T \tag{2}$$

In the BC1 project, 44 mm of total tolerance is reserved for surveying error with the remaining portion of the tolerance 66 mm budgeted for TBM guidance variations. The error budget of 44 mm for surveying was interpreted as the maximum relative error between two points located anywhere in the tunnel $\varepsilon_{max} = 44\sqrt{2} = 62\ \text{mm}$. Since many systematic errors, such as lateral atmospheric refraction in the tunnel and instrument calibration errors, are difficult to predict, half of the 62 mm for the relative positioning error budget was reserved for systematic errors, with the remaining half being apportioned to random errors [8].

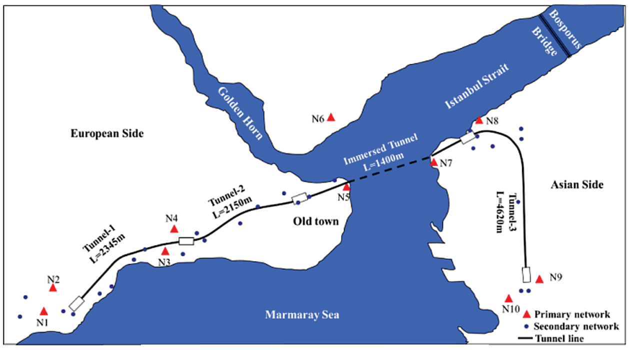

Figure 3 The horizontal control network

For the BC1project a high accuracy horizontal control network was formed in 2004 to be used in constructing structures and providing the above mentioned tolerance for deformation measurements. The horizontal control network has two levels; primary and secondary (Fig. 3).

The primary horizontal control network consists of 10 pillars and the secondary horizontal control network consists of 17 pillars. GPS receivers were used for the horizontal control network measurements with the differential techniques to guarantee an accuracy of ± 4 mm for the relative positions of the pillars. The GPS observations were realized by recording L1-L2 frequency and selecting 15 seconds record interval and a 15° satellite elevation mask with geodetic Trimble receivers/antennas in static mode. The measurement periods vary from 5 to 12 hours in the primary control network and 2 hours for the secondary network. The primary network is evaluated with academic software based on the ISTA, TUBI, TRAB, NICO, SOFI and BUCU International GNSS Service (IGS) stations in the region [9, 10]. The accuracy information of the horizontal network after evaluation is given in Tab. 1.

Table 1 Accuracy information of horizontal control network (in m)

Standard deviation	Maximum value	Minimum value	Mean value
Latitude, φ	0,005	0,002	0,004
Longitude, λ	0,005	0,002	0,004
Ellipsoid height, h	0,010	0,004	0,008

In 2012, a new GPS observation campaign of the surface network was executed in order to verify the local movement of the horizontal control network. Tab. 2 shows the difference between the latitude and longitude coordinates obtained in the first and second campaign with the results being in the range of 20 mm.

Table 2 Differences between the first and second campaign

Position	Mean value / m
Latitude, φ	0,016
Longitude, λ	0,022
Ellipsoid height, h	0,040

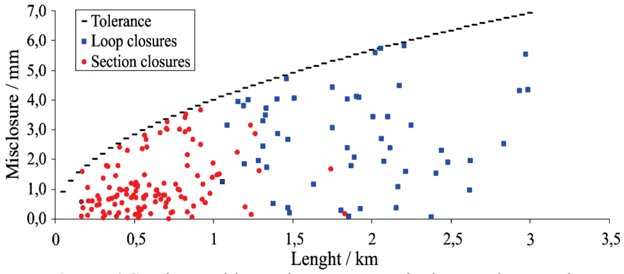

Figure 4 Section and loop closures at vertical control network

The design of the vertical surface control network consists of 66 benchmarks distributed throughout the project area. The precise leveling measurements were realized by using a Wild N3 precise leveling instrument and invar rod. Each section closure that was not within the allowable tolerance ($T=4\sqrt{L_{(km)}}$) was measured again. The actual and allowable section closures are shown against distance of the section together with the tolerance (Fig. 4). The loop closures were determined on regular basis to guard against gross errors and temporary benchmark instability between reoccupations. There were no loop closures outside the allowable tolerance.

The vertical control network is adjusted through the Least Square Adjustment Technique in order to determine the initial accuracy of network. The accuracy of the vertical network was estimated as 3 mm at the 95 % confidence level.

3 Immersed tunnel

During the 20th century, more than one hundred immersed tunnels were built world-wide. These immersed tunnels are constructed as float-in structures and then lowered into a pre-dredged trench and covered. These tunnels have enough effective weight to prevent them floating.

Immersed tunnels are usually constructed as a number of tunnel elements essentially prefabricated in manageable lengths, each often 100 m long, that are eventually joined up below the water to form the final tunnel. They have temporary bulkheads across the ends of each element to allow them to float keeping the insides dry. Fabrication is either completed in a dry dock, or the elements are launched like a ship and then completed afloat close to their final location. In most cases, the completed tunnel elements are barely capable of staying afloat unaided. The immersed tunnel under the Istanbul Strait is 1,4 km long, including the connections between the immersed and adjacent tunnels. Both rail tracks run in the same binocular tunnel elements, separated by a central dividing wall, [11].

The immersed tunnel is being built in eleven elements, each approximately 135 m long, 15,3 m wide and 8,6 m high and weighing about 18 000 tones, (Fig. 5). Structurally, the cross section of the tunnel is a rectangular concrete box with a separate tube for each track direction and designed for 100 years of service life. More information about the immersion tube and the difficulties in concrete work during the construction of these tubes can be obtained in [12].

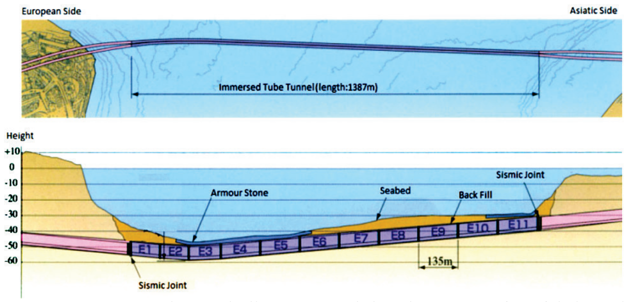

Figure 5 Immersed tunnel alignment and the placement of prefabricated tubes [9, 13].

3.1 Real time kinematic GPS measurement technique and using on immersed tunnel

Real Time Kinematic (RTK) GPS technique was effectively used in bathymetric map production, filling works in the sea bottom, leveling, digging and immersion of the tube.

The RTK satellite navigation is a technique based on the use of carrier phase measurements of the GPS where a single reference station provides the real-time corrections, providing up to centimeter-level accuracy. In practice, RTK systems use a single base station receiver and a number of rover units. The base station broadcasts the phase of the carrier that is measured, and the rover units compare their own phase measurements with those received from the base station. There are several ways to transmit a correction signal from the base station to the rover station. The most popular method is low-cost signal transmission using a radio modem, typically in the UHF band. This allows the units to calculate their relative position in millimeters, although their absolute position is only as accurate as the accuracy of the position of the base station. The typical nominal accuracy for these dual-frequency systems is 2 ÷ 3 cm horizontally and 3 ÷ 5 cm vertically [14, 15].

The ability to determine positions with high accuracy in real time within the project area is very important therefore a carrier phase-based RTK GPS positioning system was established. The immersion of the tunnel elements are carried out by accurately determining the position of the immersion operation vessel using RTK GPS installed on the operation vessel, and proceeding with the immersion while monitoring the element position and shape of the sea bottom using a multi-beam sonar system (Fig. 6). To make the final connection between an element already in position, as the next element is lowered to the bottom the distance between the two elements, the axial deviation, and the orientation deviation are measured using ultrasonic distance measurements sensors installed on the opposing end surfaces of the two elements [16].

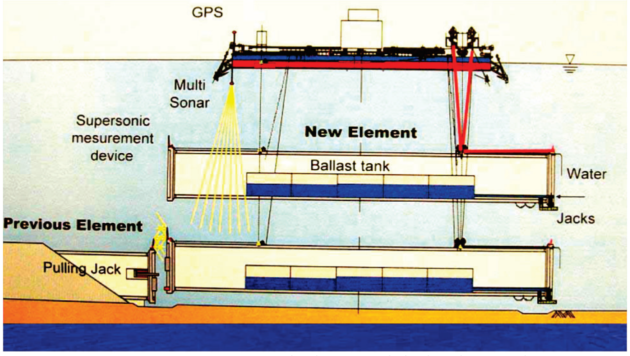

Figure 6 Measurement devices used during immersion

In order to determine the performance of the RTK technique for the immersion tube operation a test study for the BC1 project was made between points N5 and N7 (as shown in Fig. 3) which are accurately known [17]. The base GPS was installed at point N5 and the position of point N7 was determined by the rover GPS, (Fig. 7). [17] took into consideration the geoid ondulation (N) value which was calculated as 36,41 m for the immersion region and stated that there was a horizontal difference of 2 cm and a vertical difference of 5 cm between the measured position and accurately known position of N7. These values comply with the forecasted tolerance in the project.

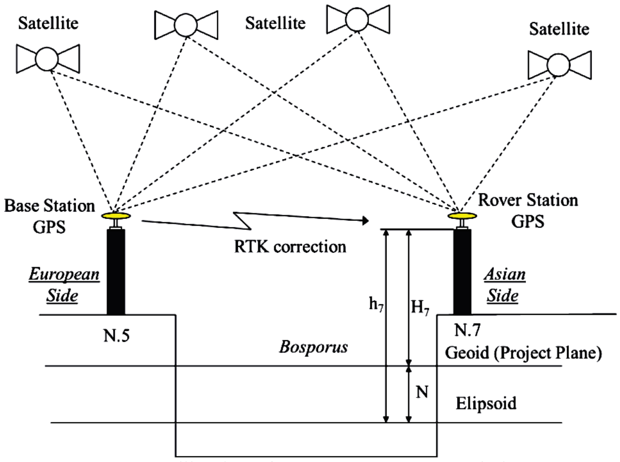

Figure 7 Calibration of RTK Measurement Technique (modified after [17])

4 Tunnels and Geodetic Underground Network

In urban areas, the TBM is most commonly used for tunnel construction. TBM tunnel construction consists of several typical phases including preparatory tasks, working shaft construction, initial setup, tunnel construction, and removal shaft construction.

The length of the tunnels in BC1 project is totally 9800 m. On the European continent Tunnel 1 is 2345 m and Tunnel 2 is 2150 m; on the Asian continent Tunnel 3 is 4620 m and the inlet and outlet of immersion tube is 685 m (Fig. 3). The internal diameter of the finished tunnels is 7,04 m [18] explained how the final minimum, specific and functional requirements of the bored tunneling works to be carried out using the FIDIC EPC/Turnkey Project conditions have been achieved. In this section, the studies undertaken concerning Tunnel 1 are examined in detail. The TBM is guided with the Tacs guidance system based on the tunnel control network. The Tacs guidance system continuously defines the TBM position and compares it with the design tunnel axis. The Tacs system receives input measurements from a laser theodolite, which is placed on a bracket attached to the left upper wall of the tunnel (Fig. 8). The guidance station bracket is incrementally moved forward as the TBM advances.

In order to perform redirection using the laser theodolite within the forecast tolerance, the geodetic network within the tunnel should be very accurately positioned. The effect of lateral refraction is well known but remains an intractable problem especially in a tunnel environment. As [5] has pointed out, even a very small lateral temperature gradient can produce a severe error if it prevails over the length of a line-of-sight. Therefore, comprehensive mathematical pre-analyses were undertaken to determine a suitable tunnel survey network configuration and observation scheme. The geodetic underground network formed for Tunnel 1 consists of a total of 109 benchmarks, 49 in Tube 1 and 60 in Tube 2. The benchmarks in the tunnel were located at intervals of approximately 50 m.

Leica DNA03 levels and Leica TC1201 total stations were used for the leveling and angle-distance measurements. The accuracy of the measurements is typically ±0,3 mm/km for precise leveling and 1" for angles and 1 mm + 2 ppm for distances with total stations. Meteorological and scale projection corrections were applied to the distance measurements. Angle measurements were conducted with four series. The network adjustment was also achieved using HANNA software developed by the Institute of Geodesy, University of Hannover. In the adjustment process of the measurements the Gauss-Markov model was used consisting of functional and stochastic parts as given by the expression

$$l = A\,\hat{x} - v, \quad \Sigma_{ll} = \sigma_0^2\,\boldsymbol{Q}_{ll}, \tag{3}$$

where A is the design matrix, v is the residual for the observations, σ_0 is the variance for the observations and $\boldsymbol{Q}_{ll}$ is the covariance matrix of the observations. The solution given by minimizing the weighted squares sum of residuals

$$\hat{x} = N^{-1}n = (A^{\mathrm{T}}\boldsymbol{P}A)^{-1}A^{\mathrm{T}}\boldsymbol{P}\,l, \quad \Sigma_{xx} = \sigma_0^2\,\boldsymbol{Q}_{xx}, \tag{4}$$

where $\boldsymbol{P}$ is the weighting matrix of the observation and $\boldsymbol{Q}_{xx}$ is the covariance matrix. The results of the network adjustment are the coordinates of the benchmark and their standard deviations. The underground network is fixed with an absolute accuracy of ± 5 mm in relation to the surface network, (Tab. 3).

Table 3 Accuracy information of underground network (in m)

	Standard deviation	Maximum value	Minimum value	Mean value
Tube 1	s_y	0,005	0,002	0,004
	s_x	0,007	0,001	0,005
Tube 2	s_y	0,004	0,001	0,004
	s_x	0,007	0,002	0,006

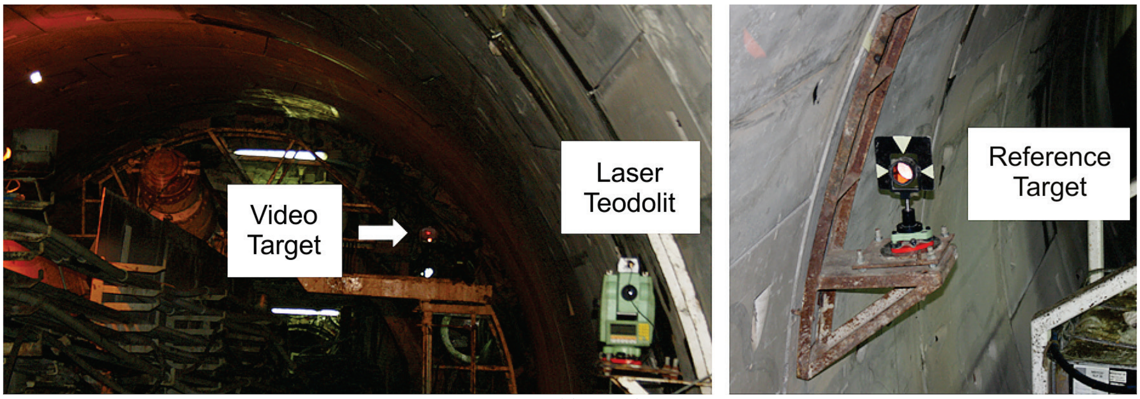

Figure 8 Guidance of TBM

5 Deformations and Transversal Profiles Surveys

The construction and operation of tunnel projects can result in a restriction of services, and damage to surface or subsurface structures. In a metropolitan city such as Istanbul where housing is very intensive and quantity of historical structures are high it is very important to determine the deformations on the surface and in the structures due to the bored tunnels. Deformations in tunnel borings occur in two ways; first, the deformations on the surface due to volume loss and second deformation due to the pressure on the tunnel perimeter applied by the mass over the tunnel.

The surface settlement trough assumes a bell-shaped curve centered on the tunnel axis, which since the work of [19] has been widely described in the form of a Gaussian curve (as shown in Fig. 9) and given as

$$s(x) = s_{\max} \exp\left(-\frac{x^2}{2i^2}\right), \tag{5}$$

where x is the horizontal distance to the tunnel axial plane, $s_{\max}$ the maximum settlement on the axis and i a parameter characteristic of the trough expanse. The distribution parameter i, is mainly dependent on the depth to tunnel axis z_0 and nature of ground conditions. A recent review of existing correlations by [20] concluded that this parameter could be reasonably estimated, using the following expression

$$i = K \cdot z_0, \tag{6}$$

with the coefficient, K is being a function of the ground type. The settlement trough tends to be of a broader extent in clays than in sands, with the K values typically in the range 0,4 ÷ 0,6 for tunnels in clays and 0,25 ÷ 0,45 in sands.

In the BC1 project, the depth to tunnel axis z_0 value varies from 8,5 m to 28 m depending on the topography. The K constant varies from 0,38 to 0,6 according to the data obtained from ground sounding. Accordingly, the distribution parameter i varies between 5 m and 10 m.

The monitoring system used for surface settlements was composed of a set of marks affixed to buildings and fastened into the ground located within a bandwidth of approximately 30 m on both sides of the Tunnel 1 alignment. This system provides the basic elements for tracking surface settlements. The digital level Leica DNA03, having an accuracy of 0,3 mm/km was used for the measurements in combination with a bar-coded staff. The use of digital levels has augmented the speed of measurements, thus, the time needed for the observations can be considered as instant. All the vertical deformation measurements were performed daily depending on the vertical surface control network as explained in Section 2. Although the vertical network benchmarks are out of the sphere of influence of the tunnel, the stabilization of the vertical network was controlled periodically. The settlement marks heights calculated from the leveling measurements (H_t) were statistically compared with the reference height (H_0). Therefore, it was determined whether the calculated deformations are originated from real surface settlements or measurement errors.

Vertical deformation of i settlement marks at t time domain

$$d_{t,i} = H_{t,i} - H_{0,i} \tag{7}$$

and the standard deviation of the vertical deformations

$$\sigma_{d_{t,i}} = \sqrt{\sigma^2_{H_{t,i}} + \sigma^2_{H_{0,i}}}. \tag{8}$$

The statistical significance of the determined vertical deformation was tested for confidence level 95 %, by applying the following one-sided statistical test:

$$\left|\frac{d_{t,i}}{\sigma_{d_{t,i}}}\right| \le z_{0,95} = 1{,}96, \tag{9}$$

where $z_{0,95}$ the corresponding value of normal distribution for a 95 % confidence level.

The measurement noise can be estimated at ± 1mm on average. So all vertical displacements greater than magnitude 3 mm were statistically significant.

Fig. 10 shows an example of a transversal settlement trough (Profile 8). The points represent final settlement measured after the passage of the tunnel face. The curve indicates the settlement computed using the expression (5) and (6).

As-built surveys are prepared after the completion of a construction project. This survey shows the as-built locations of improvements and utilities as opposed to the designed location.

The profiles monitoring system is comprised of an optical technique using a high specification robotic total station (Leica TCA1201), without using the prism having the declared measuring uncertainty for distance 3 mm + 2 ppm and for angels 1". The transversal profile survey was executed every 7,5 m of the tunnel. There were 15 ÷ 20 points measured at each profile. The Leica TMS (Tunnel Measurement System) is used for data processing, (Fig. 11).

In the project, the reference profile area was calculated as 38,046 m^2. According to this information the overprofile and underprofile areas were determined for each transversal profile.

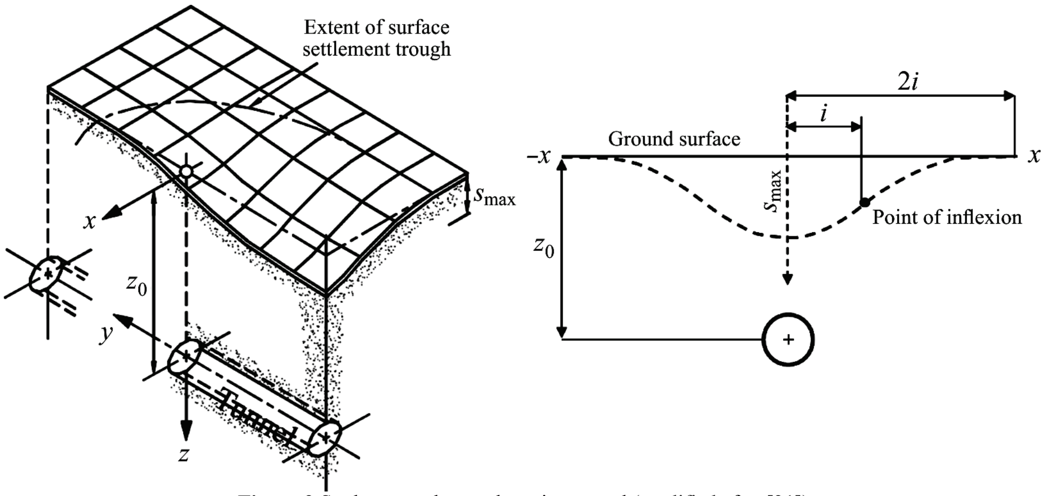

Figure 9 Settlements above advancing tunnel (modified after [21])

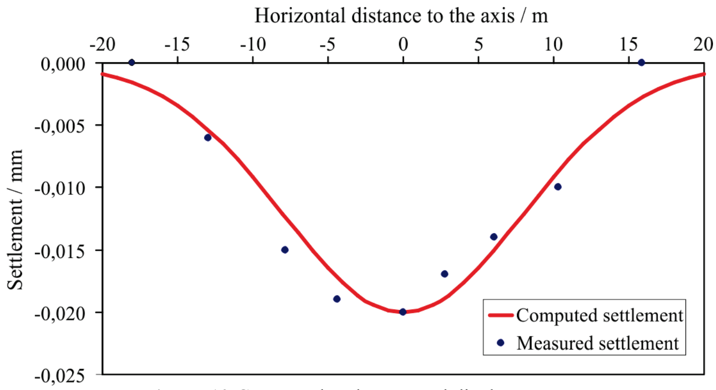

Figure 10 Computed and measured displacements

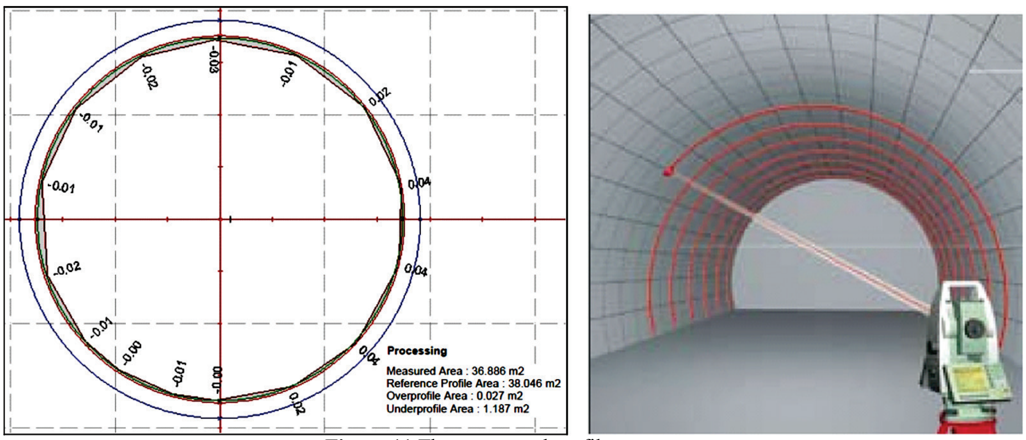

Figure 11 The transversal profiles survey

6 Conclusions

Transportation is one of the most important problems of metropolitan cities and the construction of underground railways is a preferred solution to this problem. However, there are difficulties in tunnel construction in cities such as Istanbul where there is dense housing and a large number of historical structures. The two most important problems to be faced are the possibility of damaging historical heritage and other aboveground structures due to tunnel boring. Therefore, positioning and measurement studies are very important in tunnel studies and for the BC1, they have been performed successfully. The BC1 project with a length of 13,6 km under Bosphorus Straits will create a railway connection between the continents of Asia and Europe with a planned completion in October 2013.

The role of geodetic surveying studies is very important in the successful completion of the BC1 project. Obtaining accurate and reliable results from geodetic surveying during the project initially depends on the horizontal and vertical control network created at the beginning of the project.

The horizontal control network should be measured using GPS in at least 6 hour sessions with 2 repetitions. In the ground measurements, equipment with measuring uncertainty at least 1mm+2 ppm and for angles 1" should be used. In the formation of the vertical network, levels with accuracy of at least 0,3 mm/km should be selected. In the evaluation of the measurements, an accuracy of 3 ÷ 5 mm for the horizontal control network and 1 ÷ 2 mm for the vertical control network should be obtained. The stabilization of the vertical and horizontal network formed to determine the deformations due to outer effects such as earth crust movement and ground water change, should be periodically (once a year) checked.

The connection of underground network with surface network is the most important subject in tunnel redirecting. At least 2 transverse points must be installed at the tunnel portal for the connection of underground network with surface network. The underground network should be designed as a chain network with double zigzag method due to refraction errors. The laser points used in redirecting should be checked every 40 rings for the alignment and even more frequently for the curves. Before the laser redirecting, redirecting the previous laser point should be checked. On completion of the measurement program, the redirecting should be checked again. The values obtained as a result of the evaluation of the deformation measurement should be statistically analyzed. Thus, it can be determined if the obtained values originate from measuring uncertainty or are deformation magnitudes.

The control and calibration processes of equipment used in all the measurement studies should be monitored since correct results are calculated from correct measurements. Therefore, paying attention to the in service training of the staff performing the measurements in the field is very important.

Technological measurement methods should be used in parallel to the technology developed in recent years. Particularly for the inter-tunnel profile measurements, 3D laser scanner method and for surface building settlement measurements the Interferometric Synthetic Aperture Radar (InSAR) method can be used.

Acknowledgements

I am very grateful to the Gama-Nurol Taisei Corporation and also to Avrasyaconsult and DLH for their contributions to the realization of this study.

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