

# Monitoring of the Marmaray Project construction activity and HSE performance

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ABSTRACT: Marmaray Project is a modern fast rail-track transportation scheme of 76.3 km connecting the European and Asian sides of the Istanbul City underneath the Bosphorus at a depth of 58 m. The objective of the Project is to establish a transportation capacity for about 150.000 passengers per hour in both directions of the route and to reduce the present total traveling time of 185 minutes by nearly halve.

13.56 km of the total length is a new underground route within the scope of the Contract BC1, Railways Bosphorus Tube Crossing, Tunnels and Stations, which is constructed at the undertaking of the Joint Venture of the Contractors TAISEI from Japan, GAMA and NUROL from Turkey. The BC1 Project consists of a twin route of 1385 m immersed tube tunnels, 9725 m TBM tunnels, 445 m NATM tunnels, 1085 m of cut-and-cover and 920 m at-grade sections through the route of 13560 m, along which totally 5 stations have been located in places such as 2 cut-and-cover, 1 tunnel and 2 surface stations.

The Contractor is committed, through its declared policy statement, to save the public, protect the environment and fulfill the specified quality requirements of the Project, which has been designed for a lifetime of more than 100 years without any derogation from the specified comfort level of service.

Any construction activity within the scope of the Project is planned and designed, implemented, monitored, corrected and improved as required. Monitoring therefore plays a very important role for follow-up of the performance of the overall work as well as the individual construction activities. The followings are the basic examples of monitoring applications in the Project and all related issues connected thereto shall be described and assessed in the present paper:

- i. Geotechnical monitoring,
- ii. Monitoring of concrete properties,
- iii. Monitoring for Health-Safety-Environment (HSE),
- iv. Marine works monitoring.

Furthermore, smart monitoring applications in the Marmaray Project-Contract BC1 shall also be introduced in the paper within the integrity of the subject matter.



# 1 MARMARAY PROJECT

The Marmaray Project is a modern fast rail-track transportation scheme with 40 stations along a route of 76.3 km connecting the European and Asian sides of the Istanbul City underneath the Bosphorus at a depth of 58 m.



### Figure 1. General layout of Marmaray Project

The objective of the Project is to establish a transportation capacity for about 150.000 passengers per hour in both directions of the route and to reduce the present total traveling time of 185 minutes by nearly halve.

The proposed modern rapid mass transit system renders significant social and economical benefits on the urban life such as reduction of the prevailing traffic congestion and air pollution and saving on the energy consumption. Furthermore, the Marmaray Project, together with the Euro Tunnel and Kars-Tbilisi-Baku Railway, provides an uninterrupted railway connection from London to Beijing.

The Marmaray Project is implemented under 3 separate contracts as the following:

Contract	Scope	Company
BC1	Bosphorus Crossing	Joint Venture of TAISEI – Japan GAMA and NUROL – Turkey
CR3	Upgrading of Commuter Lines and Electro-Mechanical Works	Joint Venture of OHL and DIMETRONICS – Spain
CR2	Supply of Commuter Trains	HYUNDAI ROTEM - South Korea

Table 1. Contract packages for implementation of Marmaray Project



# 2 MARMARAY PROJECT - CONTRACT BC1

13.56 km, out of the 76.3 km of the total route, is a new underground section, namely Railways Bosphorus Tube Crossing-Tunnels and Stations, within the scope of the Contract BC1, which is a lump-sum fixed price Engineering-Procurement-Construction (EPC) Contract under FIDIC Silver Book 1999 1<sup>st</sup> edition.



Figure 2. General layout of Marmaray Project - Contract BC1

The BC1 Project, designed for a lifetime of more than 100 years, consists of a twin route of 1385 m immersed tube tunnels, 9725 m TBM tunnels, 445 m NATM tunnels, 1085 m of cutand-cover and 920 m at-grade sections through the route of 13560 m, along which totally 5 stations have been located in places such as 2 cut-and-cover, 1 tunnel and 2 surface stations.



Figure 3. Longitudinal profile of Marmaray Project - Contract BC1



2.1 Immersed tunnel



Figure 4. Illustrative picture of immersed tunnel

The 1385 m long immersed tunnel of the Bosphorus Crossing is connected to the TBM tunnels at the Sirkeci and Üsküdar shores of the Bosphorus:



Figure 5. Cross section and profile of immersed tunnel

The Bosphorus Crossing of the Marmaray Project is unprecedented among about 150 various immersed tube projects as the deepest one with a depth of 58 m below msl. Furthermore, the immersion has been done against a current of 3 m/sec flowing in 2 opposite directions at the surface and depths.



# 2.2 TBM tunnels

Table 2. TBM	tunnels of Ma	armaray Project	- Contract BC1

Tunnel	Location	TBM Type	Function	Length
TBM1	Yedikule-Yenikapı	EPB	Main Route Rail-track	2X2430 m
TBM2 TBM3	Yenikapı-Sirkeci- Bosphorus	Slurry	Main Route Rail-track	2X3045 m
TBM4 TBM5	Ayrılıkçeşme- Üsküdar-Bosphorus	Slurry	Main Route Rail-track	2X4250 m
TBM6	Sirkeci North Ent.	EPB	Pedestrian entrance	120 m



Figure 6. A view through a TBM tunnel



Figure 7. Typical cross section of a TBM tunnel



# 2.3 NATM tunnels

Table 3	NATM	tunnels	of Marmara	v Project -	- Contract BC1
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No	Tunnel	Location	Function	Length	
1	Station	Sirkeci Station	Main Route Rail-track	2X400 m	central corridor, platform and station cross passages
2	Inclined	Sirkeci South Entrance	Pedestrian passage	50 m	
3	Inclined	Sirkeci North Entrance	Pedestrian passage	50 m	
4	N. Kemal	Yenikapı Station	Main Route Rail-track	2X18 m	
5	Turnback	Yenikapı Station	Manouevering Facility	230 m	
6	European cross over	Sirkeci	Cross over	232 m	
7	Asian cross over	Üsküdar	Cross over	125 m	
8	Cross passages	TBM tunnels	Emergency Escape	4-15 m/each	40 cross passage tunnels



Figure 8. A view from the Turnback Tunnel during construction





Figure 9. Cross section of the Turnback Tunnel

# 2.4 Stations, ventilation buildings, shafts and entrance structures

Table 4. Stations, ventilation buildings, shafts and entrance structures of Marmaray Project-Contract BC1

No	Structure	Туре	Size
1	Ayrılıkçeşme Station	Surface	L = 180 m
2	Ayrılıkçeşme Ventilation Building	Cut & Cover	L = 80 m, H = 20 m
3	Üsküdar Station	Cut & Cover	L = 275 m, H = 30 m
4	Sirkeci South Entrance	Cut & Cover	L = 28 m, H = 30 m
5	Sirkeci North Entrance	Cut & Cover	L = 53 m, H = 32 m
6	Sirkeci West Vent. Shaft	Shaft	D = 22 m, H = 60 m
7	Sirkeci East Vent. Shaft	Shaft	D = 22 m, H = 60 m
8	Yenikapı Station	Cut & Cover	L = 245 m, H = 24 m
9	Yenikapı Ventilation Building	Cut & Cover	L = 135 m, H = 25 m
10	Yedikule Ventilation Building	Cut & Cover	L = 90 m, H = 14 m
11	Kazlıçeşme Station	Surface	L = 75 m



# 2.4.1 Ayrılıkçeşme



Figure 10. View of Ayrılıkçeşme Station with road interchange arrangement

2.4.2 Üsküdar



Figure 11. Aerial view of Üsküdar Station during construction

The Üsküdar Station of the Marmaray Project is located at the Anatolian shoreline of the Bosphorus as a huge structure of 278 m by 32 m extending down to a depth of 30 m below msl.

The Üsküdar Station itself is an unprecedented structure as the biggest cut-and-cover station building ever constructed under a depth of 30 m below msl.





Figure 12. Excavation and support system of Üsküdar Station

2.4.3 Sirkeci Station – South Entrance



Figure 13. View of Sirkeci Station - South Entrance





Figure 14. Excavation and support system of Sirkeci Station - South Entrance

2.4.4 Sirkeci Station – North Entrance



Figure 15. View of Sirkeci Station - North Entrance





Figure 16. Excavation and support system of Sirkeci Station - North Entrance

2.4.5 Yenikapı Station



Figure 17. View of Yenikapı Station



2.4.6 Kazlıçeşme Station



Figure 18. View of Kazlıçeşme Station

# 3 MONITORING REQUIREMENT OF THE PROJECT

The Technical Requirements of the Employer (ERQ) [DLH (2004)] prescribes that an instrumentation monitoring programme shall be defined, implemented and maintained in order to enable detection and record of all significant changes on the ground, groundwater and existing structures resulting from the construction work. The information collected therefrom shall be used for:

- Documentation of the effects of construction operations,
- Timely implementation of needed remedial actions,
- Verification of the related design assumptions and
- Modification and improvement of construction procedures.

The type and quantity of instrumentation and the frequency of use shall be such as to achieve the intended purpose of the instrumentation programme. Appropriate types and quantities of instrumentation shall be used to monitor the developing deformation behaviour of the excavation support system and the structure under construction as well as the changes on the groundwater level, ground and built environment within the potential influence zone of the construction work.

Furthermore, construction induced vibrations and noise shall also be monitored and recorded.

# 4 MONITORING STRATEGY OF THE PROJECT

The Project is administrated through the following Management Systems:



# Table 5 Management Systems used in Marmaray Project-Contract BC1

1	Quality	ISO 9001
2	Occupational Health and Safety	OHSAS 18000
3	Environment	ISO 14000
4	Project and HSE Risks	IRMP

The so-called "Deming Cycle", as illustrated herein below, is applied as a systematical approach for planning and execution of the construction operations in compliance with the requirements of the Project as well as the above Management Systems:



# Figure 19. Deming Cycle

According to that, any construction activity within the scope of the Project shall be;

- planned and designed with respect to the requirements,
- implemented,
- monitored,
- corrected and improved as required.

Accordingly, monitoring plays a very important role for follow-up of the performance of the construction work. The followings are examples of the basic monitoring applications in the Marmaray Project:

- i. Geotechnical monitoring,
- ii. Monitoring of concrete properties,
- iii. Monitoring for HSE and
- iv. Marine works monitoring,



Although it is not of a systematical usage, there have been however some important smart monitoring applications in the Marmaray Project-Contract BC1, which shall be described and assessed in the present paper within the integrity of the subject matter.

# 5 GEOTECHNICAL MONITORING

It is clear that any construction activity, on the sub-surface and underground, may trigger off deformations on the surrounding ground and changes on the groundwater table, which in turn affect the structure under construction and the adjacent built environment (existing structures and utilities).

Within the scope of the Marmaray Project-Contract BC1, TBM and NATM tunnels have been driven and open excavations have been made for cut-and-cover structures and shafts. Excavation and tunnelling induced deformations may jeopardize stability of such structures and the built environment existing within the zone of influence unless adequate support is provided in places to withstand such deformations at all stages of the construction.

In this respect, the deformations which may be induced from the construction activity are predicted on the basis of the mechanical properties of the ground and the method of excavation in order to determine appropriate excavation support systems, with which stability of the excavated ground is secured. However, because of the rather complex behaviour of the disturbed soil media, the deformation scheme predicted through theoretical calculations may exhibit deviations from the actually developing deformation pattern, even to an extent of threatening stability of the construction and existing built environment.

In this context, a "geotechnical instrumentation monitoring programme" is defined, implemented and maintained for each structure of the Project with the purpose of detection of all significant changes in the subsurface conditions during the execution of the works in order to provide an early warning information against imminent stability problems so that the needed remedial actions can be implemented in time.

The "geotechnical instrumentation monitoring programme" is performed in accordance with a documented plan, in which the type and quantity of instrumentation and the frequency of use are specified. Appropriate types and quantities of instrumentation are used so as to achieve the intended purpose of the instrumentation programme.

# 5.1 Cut-and-Cover and Shaft Structures

Open excavations for cut-and-cover and shaft structures are subjected to lateral forces resulting from unbalanced pressures of the adjacent mass of earth and groundwater. Besides, surcharge loads and hydro-dynamic pressures, which may be transmitted through the earth and pore water, must also be taken into account. The lateral forces developing with the progress of excavation of the box shall be resisted by the ''earth support system'' until the proposed structure is built up.

The expected deformation behaviour of the temporary support system is an overall displacement of the piles and diaphragm walls (DW) towards the open cut as well as a bulging of the vertical support elements at the mid-span of the restrained sections as shown herein below:





Figure 20. Expected deformation behaviour of temporary support system

For the cut-and-cover and shaft structures, a typical instrumentation plan in accordance with the expected deformation behaviour is illustrated in the following figures:



Figure 21. Typical geotechnical instrumentation for cut-and-cover stations and shaft structures

A geotechnical instrumentation monitoring programme is prepared and implemented with the type and location of the instruments selected. A particular study in this instance is a risk assessment and mitigation plan (RAMP) prepared in relation with the construction of a DW at the Uskudar station. In this context, a task specific geotechnical monitoring plan [Gollub (2006)] has been prepared and implemented on the basis of the envisaged impacts.

# 5.2 Tunnels

The expected deformation behaviour of two adjacent tunnels is illustrated herein below:





Figure 22. Expected deformation behavior of tunnels

For the tunnels, a typical instrumentation plan in accordance with the expected deformation behaviour is illustrated in the following figure:



Figure 23. Typical geotechnical instrumentation for tunnels

Similar to the cut-and-cover and shaft structures, a geotechnical instrumentation monitoring programme is applied for the tunnels.

# 5.3 Existing Structures

The open excavations and tunnelling works result in movements on the ground, settlement/heave and/or lateral displacements, basically because of the inevitable phenomenon of volume loss during excavation, which practically cannot totally be avoided. As a consequence thereof, the existing structures remaining within the zone of potential influence of tunnels and open excavations undergo deformations as illustrated herein below:



3D: Electro optical 3 dimensional measurements Cr: Crack meter Sb: Settlement bolt



Figure 24. Expected deformation behaviour of existing structures and instrumentation

The selected instruments for monitoring of the expected deformation of such existing structures are indicated also in the above figure.

The deformations on the ground surface appear in the form of a bell shape settlement trough (Gaussian error function) as the following:



Figure 25. Settlement trough

A detailed comprehensive procedure has been prepared and implemented in the Project for protection of the existing structures from construction induced deformations. The basic steps of the procedure are as follows:

- Condition survey reports,
- Settlement analysis,
- Structural studies and analyses,
- Damage assessment,
- Precautionary and preventive measures,
- Intensified geotechnical monitoring.



A technical paper [Demir (2011)] has been presented to the 37<sup>th</sup> WTC-2011 of ITA for protection of the existing structures.

# 5.4 Groundwater Table

During execution of the Project works, a significant drawdown of the groundwater level at the Uskudar site occurred for the reason explained as the following: The TBM-4 and TBM-5 tunnels were driven from the Ayrılıkçeşme portal down to the Uskudar station, where the DW would be cut to allow entry of the equipment inside the station box so that the TBM could proceed towards the immersed tube connection. However, once the DW was drilled through to make an openning for the passage of the TBM, the groundwater started flowing into the station box and the operation was stopped. Settlements up to about 10 cm were recorded at the Uskudar square as a consequence therefrom. This critical situation was overcome then by freezing the groundwater through application of a special technique with liquid nitrogen.



Figure 26. A picture for freezing of groundwater with liquid nitrogen

As experienced at the Uskudar and Sirkeci sites of the Project, drawdowns on the groundwater table occurring as a consequence of excavations cause consolidation settlements on the ground and existing structures. Piezometers are extensively used at all sites in order to monitor groundwater level and/or pore water pressure in fully or partially saturated soils as illustrated herein above.

# 5.5 Monitoring of Geotechnical Response to Incidents

During execution of the works, 2 important incidents occurred resulting with a sudden increase of the strut loads and the corresponding geotechnical response were monitored by increased measuring frequency within the essence of the implemented programme:

# 5.5.1 Sudden Increase of Strut Loads at Uskudar Stations

Daily measurements demonstrated a sudden increase of the strut loads at the Uskudar station most likely because of the dynamic impacts resulting from pile driving at the nearby Uskudar coastal road. Further measurements performed with a frequency of 4 times a day revealed a gradual diminishing trend of the strut load increase.



# 5.5.2 Sudden Increase of Strut Loads at Sirkeci South Entrance

At the Sirkesi South Entrance Structure, an accidental fall of a 16 tons machine occurred from a height of 25 m. The measurements performed thereafter, with a frequency of 3 times a day, demonstrated a sudden increase of the strut loads up to about 70 tons, which corresponds 19% of the maximum load bearing capacity of the struts:



Figure 27. Sudden increase of the strut loads at Sirkeci South Entrance

The phenomenon is illustrated in the following figure. According to that, the falling mass (m) with a certain velocity (v) incurs an impulse of p=mv, which in turn is exerted on the ground as a dynamic load of  $F=p/\Delta t$ , where  $\Delta t$  is the time elapsing from the first touch to the ground with the velocity of v to the position of rest (v=0). This vertical force of F is somehow transmitted on the ground mass behind the piles as f, which in turn causes an increase of the effective stress and thus the strut loads.



Figure 28. Illustrative description of the phenomenon



#### 5.6 Geotechnical Instrumentation Monitoring Programme

Geotechnical instrumentation monitoring programme has been prepared and implemented with the type and location of the instruments selected:

- Cut-and-cover and shaft structures [Olgunöz (2007)] and
- Tunnels [Olgunöz&Bağdadi (2007)].

The measurement methods and instruments used in the monitoring programme are described in these documents. A schedule of the geotechnical instruments used in the Project is shown in the following table:

No	Instrument	Location	Monitoring Item	Measuring frequency	No
1	Ground settlement bolt	Onto the ground next to excavation and in top of tunnel excavation	Ground settlement	D-W-M	585
2	Building settlement bolt	Over buildings next to excavation and on top of tunnel excavation	Ground settlement	H-D-W-M	1956
3	3D bolt	Over buildings next to excavation, on top of tunnel excavation and in tunnel portal	Displacement	D-W	293
4	Inclinometer	Onto the ground next to excavation	Displacement	D-W	83
5	Extansometer (horizontal, vertical, inclined)	Onto the ground next to excavation	Displacement	D-W	32
6	Piezometer	Onto the ground next to excavation	Water level	D	79
7	Piezometer	Onto the ground next to excavation	Water pressure	D	18
8	Strain gauge	Structural members	Stress	D	333
9	Load cell	Struts or pre-stressed anchors	Axial load	D	160
10	Convergence bolt	NATM tunnels	Convergence	D	473
11	Crack meter	Structural R/C members	Crack width	D-W	94
		·		H: Hourly D: Daily	

Table 6 Schedule of geotechnical instruments used in the Project

W: Weekly

M: Monthly

Geotechnical monitoring results are compiled in monthly reports together with a technical assessment of the measured behaviour.

#### GEOTECHNICAL MONITORING-SMART APPLICATIONS 6

#### 6.1 *Monitoring of settlements under the Imaret Building*

The so-called Imaret Building, a historical heritage structure from the Ottoman time, has undergone settlements during excavation of the Uskudar station, being only a few meters distant therefrom. In order to control the settlements underneath the Imararet Building, a special compensation grouting was performed in the course of excavation. The construction induced settlements at one hand and the compensating effect of the special grouting on the other hand had to be balanced in such a way that the resultant movement of the building could be minimized as much as possible, which certainly required a sensitive monitoring of the movements underneath the building.

A special monitoring programme, as documented in [Olgunöz (2007)], has been applied in accordance with the following layout:





Figure 29. Layout of the monitoring points at the Imaret Building

Accordingly, 12 of lasy2-receivers are fixed on the Building in such a way that the beams of 2 rotating lasers cover all receivers. The ray is generated by a rotating laser and the sledge is moved by a motor which is controlled by a micro processor integrated into the receiver. All lasy2-receivers are connected to an electricity supply by a system, which serves at the same time as interface to a PC. The lasy2 –software on the PC extracts from each receiver the movements and shows them in a time-distance chart and records the data.

The monitoring setup as such is **smart**, because it automatically provides instantaneous settlement data so that the compensation grouting can be executed accordingly with adjustment of the injection pressure and duration.

# 6.2 Utilization of Smart Software for Inclinometer Readings

Inclinometers are used to monitor deflections from the vertical and rate of horizontal ground movements resulting from construction area through soft material and alongside open cut excavations and to monitor the deflection of piles and retaining walls. The inclinometer data is obtained by means of a special readout unit. The digital data is then processed in the PC through a **smart** software, INCLI2, for evaluation, calculation and graphical presentation.





Figure 30. Transfer of inclinometer data into PC by a smart software

# 6.3 Smart Software for Transfer of Opto-Trigonometric Readings

Urban tunnelling and deep excavations require close monitoring of the surrounding built environment. In this respect, many buildings and important utilities within the zone of potential influence are monitored through building settlement bolts and optical measuring prisms. Owing to thousands of measuring points, a highly efficient system has been provided for reading and data processing. In this respect, one of the most advance type of levelling instruments, designated as DNA 03, as shown in the following picture, has been used. The instrument makes very fast readings and stores the data in a memory card. The stored data is transferred into a PC directly from the instrument, shown herein below, and evaluation is done by means of a special **smart** software.



Figure 31. Levelling measurement and transferring data to PC



# 7 MONITORING OF CONCRETE PROPERTIES

### 7.1 Monitoring of Early-Age Temperature Development of Concrete

A special C 40 structural concrete is used for the Project with the following properties:

- A design life of minimum 100 years,
- No early-age cracking,
- Watertight,
- Frost resistant,
- Resistance to external exposure conditions,
- Low alkali-agregate reaction.

The structural concrete of the Project has been developed through a documented pre-testing process performed in the Marmaray Laboratory of the Istanbul Technical University (ITU), which is suitable to the requirements of ISO EN 17025. Further to that, the ITU Marmaray Laboratory has undertaken the production testing of the Project concrete, including the petrographic analysis. The studies performed for preparation, testing and QA/QC aspects of this special structural concrete of the Project have been presented in a technical paper [Akkaya (2010)].

Within the context of the requirements thereof, the temperature development of the early-age concrete is controlled through a **''smart** monitoring'' setup as illustrated in the following figure:



Figure 32. Smart monitoring setup for early-age temperature development of concrete



According to that;

- Thermocouples are installed inside the formwork in accordance with a pattern conforming to the requirements,
- The thermocouples are connected to a special data-logger through cables,
- The collected temperature development data is transferred to a remote computer network by means of a modem system,
- The digital data received from the network is processed in the PC through a special software to obtain the temperature development of concrete with respect to time,
- The special software is also capable of warning while the limit tempetature is reached.

The system is **smart**, because it automatically provides the processed data from many different remote casting places and may give warning for the limit.

### 7.2 Monitoring of Corrosion Development on Reinforcement

The structural concrete is supposed to be free from early-age cracks and has quite a high resistance to chloride diffusion. However, chloride ions would nevertheless find a way to penetrate deep into concrete to develop corrosion of reinforcement. In this connection, a setup, with reference electrodes and chloride sensors, has been built inside concrete to monitor the chloride concentration so that a preventive cathodic protection of the reinforcement can be initiated at any time if required. The monitoring setup is illustrated in the following figure:



Figure 33. Monitoring setup for long-term corrosion development on the reinforcement

### 8 MONITORING FOR HSE

### 8.1 Noise Monitoring

The Community Environment Plan adopted in the Project requires that the construction induced noise and vibration shall be monitored and controlled through appropriate mitigation measures



at all work sites of the Project. In this context, "Site Specific Plans for Noise Control" are prepared for each site [Yaman (2007)]. The noise level is continuously monitored at the sites of the Project with a frequency of a month and further measurements are made at every occasion of the change of the construction operation.



Figure 34. A noise barrier

# 8.2 Monitoring of Gas Emissions in Tunnels

According to the BS 6164:2001 "Code of Practice for Safety in Tunnelling in the Construction Industry", the air in the tunnel should be continuously monitored where the presence of methane at any concentration is foreseeable. The aspects related to gas detection and alarm in the tunnels of the Project are indicated together with all other related issues in the "TBM-1 Tunnels Task Specific HSE Plan" [Önen (2009)].

In connection with this requirement, the TBM has been equipped with a fixed monitoring equipment for a continuous detection of gases CH4, CO2, CO and O2. Furthermore, a portable gas detection equipment has been provided as a supplementary set.

The fixed monitoring equipment on the TBM is **smart**, because it continuously detects and records the measured gas content and gives warning to the operator, supervisor and the tunnel crew when the specified limit is exceeded.

# 9 MARINE WORKS MONITORING

The marine works consist of the operations for construction of the immersed tunnel. Two important survey programmes have been performed within the scope of marine works:

- Bathymetric survey and
- Hydrological survey and current forecasting.



# 9.1 Bathymetric survey

Bathymetry consists of a thorough topographical survey of the defined sea bottom area during Bosphorus trench dredging as illustrated herein below:



# Figure 35. Bathymetric survey setup

Functions of the survey instruments are summarized below:

- Multi beam echo sounder system: Capable of measuring the 2 dimensional shape of the sea floor with a width twice the water depth
- RTK-GPS: Measurement of the survey boat position
- Motion sensor: Measurement of the survey boat motion (heaving, pitching, rolling)
- Gyrocompass: Measurement of the survey boat direction

The sea bottom profile is identified through the bathymetric survey plan.

# 9.2 Hydrological survey and current forecasting

The ultimate purpose of the hydrological survey programme is establishment of a current forecast model, on the basis of which a decision of GO/NO GO shall be made for the immersion operation of the tunnel element.

The programme includes the following basic steps:

- Hydrological survey before construction,
- Online monitoring during construction and
- Forecast modelling

# 9.2.1 Hydrological survey before construction

The purpose of hydrological survey before construction is to obtain hydrological and meteorological conditions, such as current, water level, stratification due to salinity and temperature, wind and atmospheric pressure.





Figure 36. Schematic view of a survey of the cross sectional current

# 9.2.2 Online monitoring during construction

The purpose is an online survey of the hydrological conditions at the place of the immersion. The information obtained by the online survey is used as input data for the forecast model.

Instruments measuring the requested data shall transmit the real time data to Computer Center (CC) via modem communication, which is a **smart** monitoring application. Monitoring items consist of meteorological stations (wind velocity, atmospheric pressure), CTD (conductivity, temperature, depth (water level) sensor) and RDCP (recording doppler current profiler – vertical current profile). [Ito (2006)]

# 9.2.3 Forecast Modelling

The hydrological survey before construction provides the input data for forecast modelling. The model prepared on that basis is run and calibrated afterwards with the real-time survey results. The established forecast model develops current velocities for the incoming immersion time.

# 10 ASSESSMENT AND CONCLUSION

The geotechnical monitoring of the construction activity of the Project has been implemented in accordance with site specific "geotechnical instrumentation monitoring programmes" since the very beginning and the data collected therewith has been interpreted and reported on regular basis. The measured actual overall and local behaviour is assessed in comparison with the expected behavior and the related design assumptions in order to verify suitability of the adopted construction operations and decide on the safety of the construction sites and effected built environment.

The extraordinarily large and diverse geotechnical monitoring data collected over a period of 7 years and the related interpretations resulting therefrom have revealed some discrepancies with the adopted instrumentation programme, which are outlined herein below together with a broad view for correction and improvement:

- i. 3-D settlement bolts can be of automatic type (smart) and should be utilized more efficiently in combination with building settlement bolts.
- ii. Strain gauges used on the reinforced concrete struts can hardly measure actual strut loads as they are very sensitive to temperature changes and may not be compatible with the



mechanical properties of the strut material, i.e. modulus of elasticity. Furthermore, the results cannot be correctly interpreted because of the creep and shrinkage effects of the concrete.

- iii. Instead of strain gauges, load cells can reliably be used for measuring the strut forces provided that a special detail is developed for the installation.
- iv. Automatic (smart) systems should be adopted, instead of electro-optical readings, for measurement of the deformations of the excavation support system. Smart systems for inclinometers, strain gauges and load cells shall be very useful and practical because the changes on the conditions of the construction site can thus be identified instantaneously.
- v. For reliable interpretation of the actual geotechnical behaviour, instrumentation couples should be adopted such as
  - loadcells / strain gauges with inclinometers and
  - loadcells / strain gauges with 3D.
- vi. Adequate number of spare instruments must always be envisaged in order to secure completeness of the data collection even in case of damaged and disordered instruments.

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