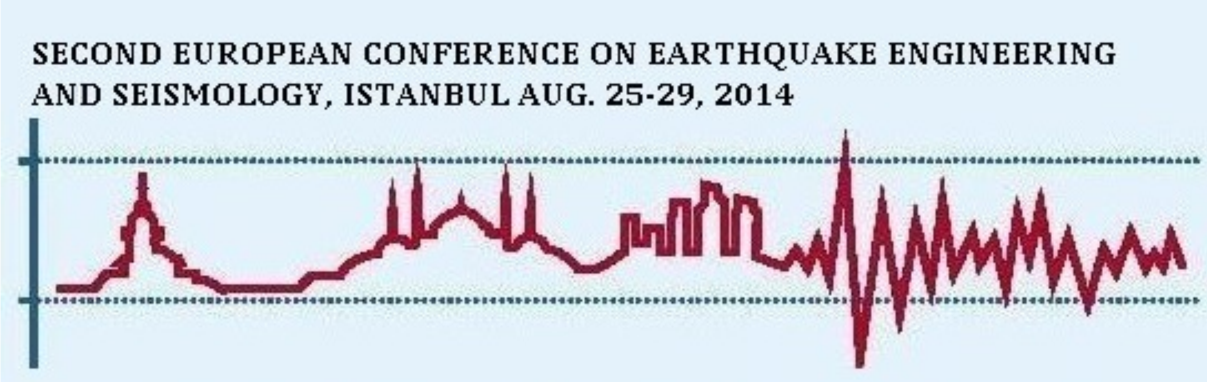

STRUCTURAL HEALTH MONITORING SYSTEMS IN ISTANBUL

Eser ÇAKTI[1] and Erdal ŞAFAK[2]

ABSTRACT

A number of Structural Health Monitoring (SHM) networks exist in Istanbul. They have been designed and implemented over a timespan extending more than twenty years by the Department of Earthquake Engineering of Kandilli Observatory and Earthquake Research Institute of Bogazici University (DEE-KOERI). They are installed in several high-rise buildings, historical structures, lifeline structures across the Bosporus, and industrial facilities. The monitoring systems installed in historical structures in Istanbul are unique, as they form the largest group of monumental structures in the world monitored in the same city. The structural monitoring networks record the dynamic motions of the structures continuously, and the data are transmitted in real time to the monitoring center at the DEE-KOERI. The majority of the systems use accelerometers for monitoring. Some structures are also instrumented with tilt meters and GPS sensors. An in-house real-time modal analysis software is used to process and analyze the data. The software includes data processing, spectral identification and animation modules. The results are displayed in real time, showing the time variations of modal properties and the structure's configuration. In addition to standard modal identification techniques, more advanced real-time techniques are explored by using the data from the structures. Installation of more monitoring systems in other structures are in progress.

INTRODUCTION

Numerous seismic hazard studies done following the destructive M=7.4 Kocaeli, Turkey earthquake of 17 August 1999 all conclude that Istanbul is likely to have a damaging earthquake in the near future (Parsons et al. 2000; Parsons, 2004). Fig. 1 shows the westward migration of earthquakes on the North Anatolian fault during the last century, where the last one occurred is the 1999 Kocaeli Earthquake. Istanbul is the industrial and commercial center of Turkey with 15 million inhabitants. The probability of having an earthquake of magnitude 7 or above in Istanbul is estimated around 40% within the next 30 years (Parsons, 2004). The earthquake will most likely take place on one or more segments of the North Anatolian fault in the Marmara Sea to the immediate south of Istanbul.

To assist in the reduction of losses in Istanbul from the expected earthquake, the Department of Earthquake Engineering of Kandilli Observatory and Earthquake Research Institute (DEE-KOERI) of Boğaziçi University in Istanbul, Turkey has installed and been operating for some time a large number of structural and ground motion monitoring networks in Istanbul.

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The strong ground motion monitoring networks are installed throughout the city, as well as at the bottom of Marmara Sea, for early warning and rapid response purposes. Currently there are more than 120 stations operating in real time and more stations are in planning. Additionally three down-hole arrays and one very densely instrumented short-aperture array are operational in Istanbul.

The structural monitoring systems are installed in critical structures to monitor their seismic response and evaluate their seismic safety. They are installed in a large number of historical structures, critical lifelines crossing the Bosporus, several high-rise buildings, and industrial facilities. A real-time data processing and modal identification software is developed to analyze and interpret the data from the instrumented structures.

More detail on each group of instrumented structures is presented below.

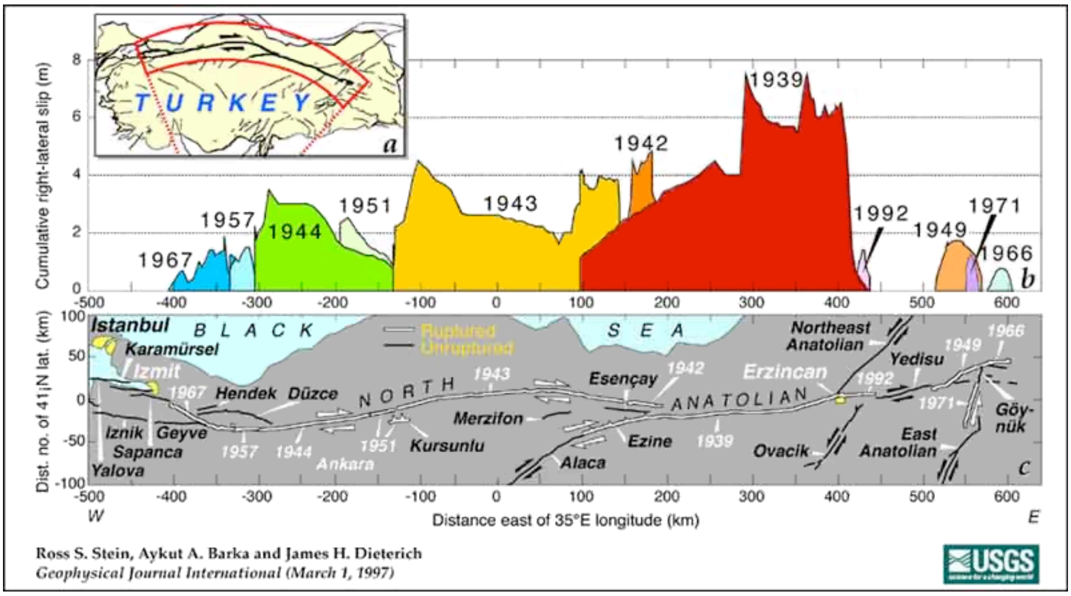

Figure 1. Westward migration of earthquakes on North Anatolian Fault in the 20th century (from Stein et al., 1997)

STRUCTURAL MONITORING NETWORKS IN HISTORICAL STRUCTURES

The first installations of structural monitoring systems in Istanbul have started with historical structures. They include the 35-channel Hagia Sophia Museum; 47-channel Fatih Mosque; 27-channel Süleymaniye Mosque; 30-channel Sultanahmet Mosque and the 35-channel Mihrimah Sultan Mosque systems. Each system consists of 3-component accelerometers placed in structurally critical locations. They record continuously the vibrations of the structures and transmit the data in real-time to the data center at DEE-KOERI. Three of them (Hagia Sophia Museum, Fatih Mosque and Mihrimah Sultan Mosque) also include four two-channel tiltmeters. Among the monitored historical structures, the 6th Century Hagia Sophia Museum is the oldest, and the 17th Century Sultanahmet Mosque (i.e., the Blue Mosque) is the youngest. The Hagia Sophia Museum and the sensor layout are shown in Fig. 2. The system in the Mihrimah Sultan Mosque is presented in Fig. 3. More information on them can be found in Cakti (2014).

We also monitor two minarets in Istanbul. Because of their slenderness, minarets are very vulnerable, not only to earthquake-induced vibrations, but also, although to lesser extent to the wind-induced vibrations due to vortex shedding. The first minaret instrumented is one of the four masonry minarets of the Hagia Sophia Museum. The second minaret is one of the four reinforced concrete minarets of the Maltepe Mosque, which is currently the tallest modern minaret in Istanbul. The Maltepe mosque with its minarets is shown in Fig. 4.

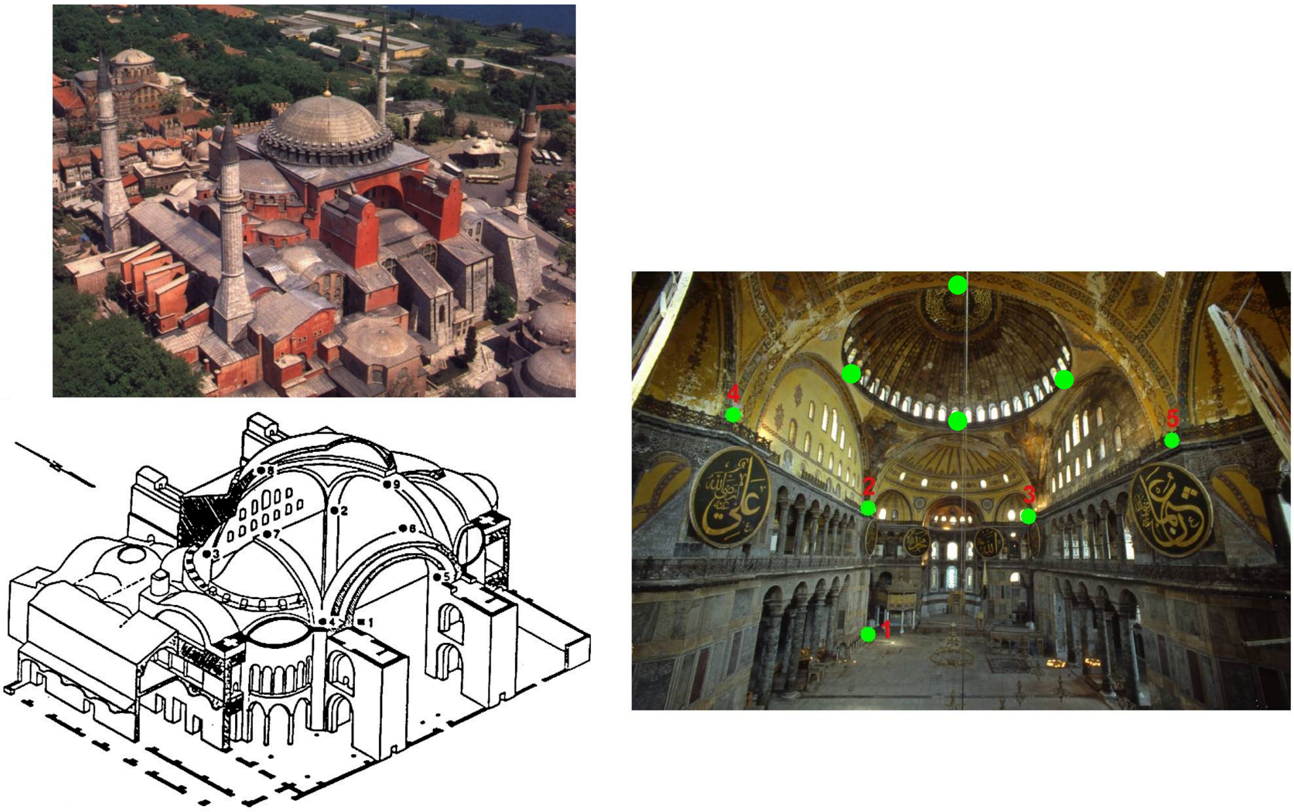

Figure 2. Hagia Sophia Museum SHM network adopted from Durukal et al. (2003)

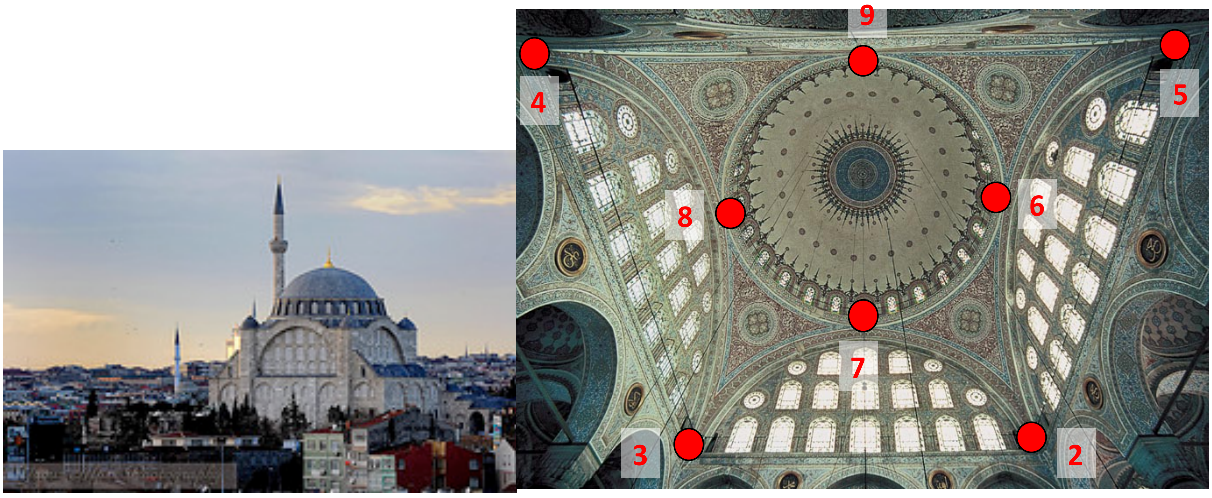

Figure 3. Mihrimah Sultan Mosque SHM network

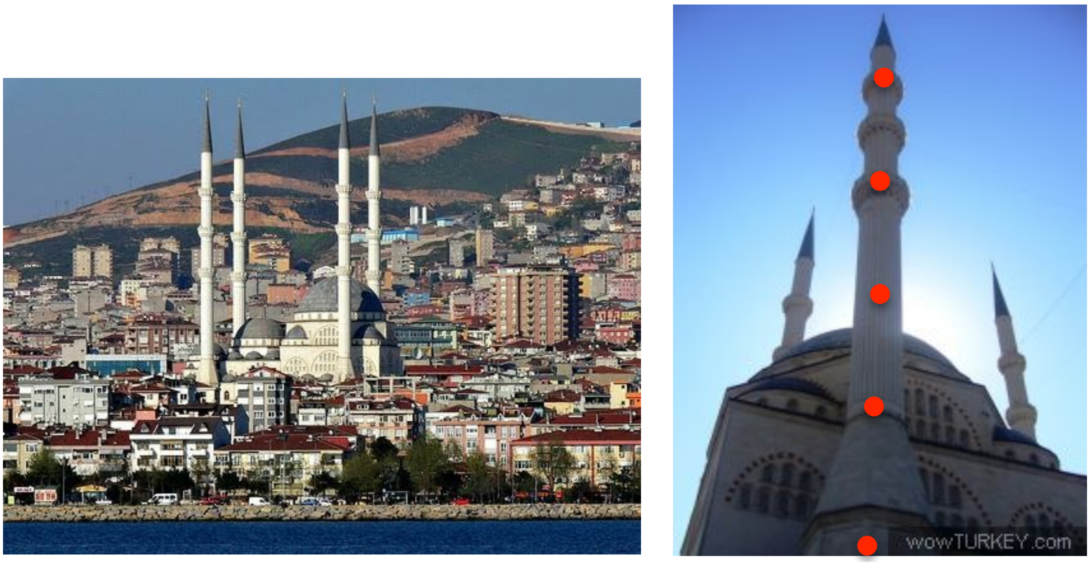

Figure 4. Maltepe Mosque, its minarets (the tallest in Istanbul) and sensor layout

STRUCTURAL MONITORING NETWORKS IN LIFELINES

The three critical lifeline structures that are installed with SHM systems in Istanbul are the two suspension bridges on the Bosporus and the recently completed rail tube tunnel under the Bosporus.

The SHM system at Fatih Sultan Mehmet Bridge (i.e., the Second Bosporus Bridge) was installed by DEE-KOERI in 2008 as part of a research project funded by EU. It is composed of 44 channels of accelerometers placed inside the deck, on the towers, and the center of suspension cables. The bridge and the instrument layout are shown in Fig. 5.

The third suspension bridge across the Bosporus is currently under construction. We work on the design of a comprehensive SHM system for this bridge.

The SHM system at Ataturk Bridge (i.e., the First Bosporus Bridge), operated by the General Directorate of Highways, was installed in 2007 during a major maintenance work done on the bridge. It is composed of 258 channels of real-time data from 168 sensors, which includes accelerometers, GPS sensors, tilt meters, laser-based displacement meters, load sensors, thermo couples, and strain gauges. The bridge dimensions and the locations of the sensors are presented in Fig. 6.

The Marmaray rail tube tunnel runs at the bottom of the Bosporus at a depth of 60 meters. It is composed of two adjoining tunnels. The tube is composed of reinforced concrete segments. Each segment is monitored for accelerations and relative displacements in real time Fig.7 shows the schematic view of the tube and the sensor layout (Erdik, 2013)..

STRUCTURAL MONITORING NETWORKS IN BUILDINGS AND INDUSTRIAL PLANTS

The SHM systems in buildings and industrial plants include the 36-channel Saphire Tower, and 15-channel each Kanyon Building, Isbank Tower, and Enron Power Plant. Each system consists of 3-component accelerometers placed in structurally critical locations. Fig. 8 shows the 62-story Sapphire Building, which is currently the tallest building in Turkey, and the sensor layout. It houses the most comprehensive structural monitoring system to date in Turkey. Monitoring systems in other structures have fewer stations. They are installed mainly for operational needs of their owners.

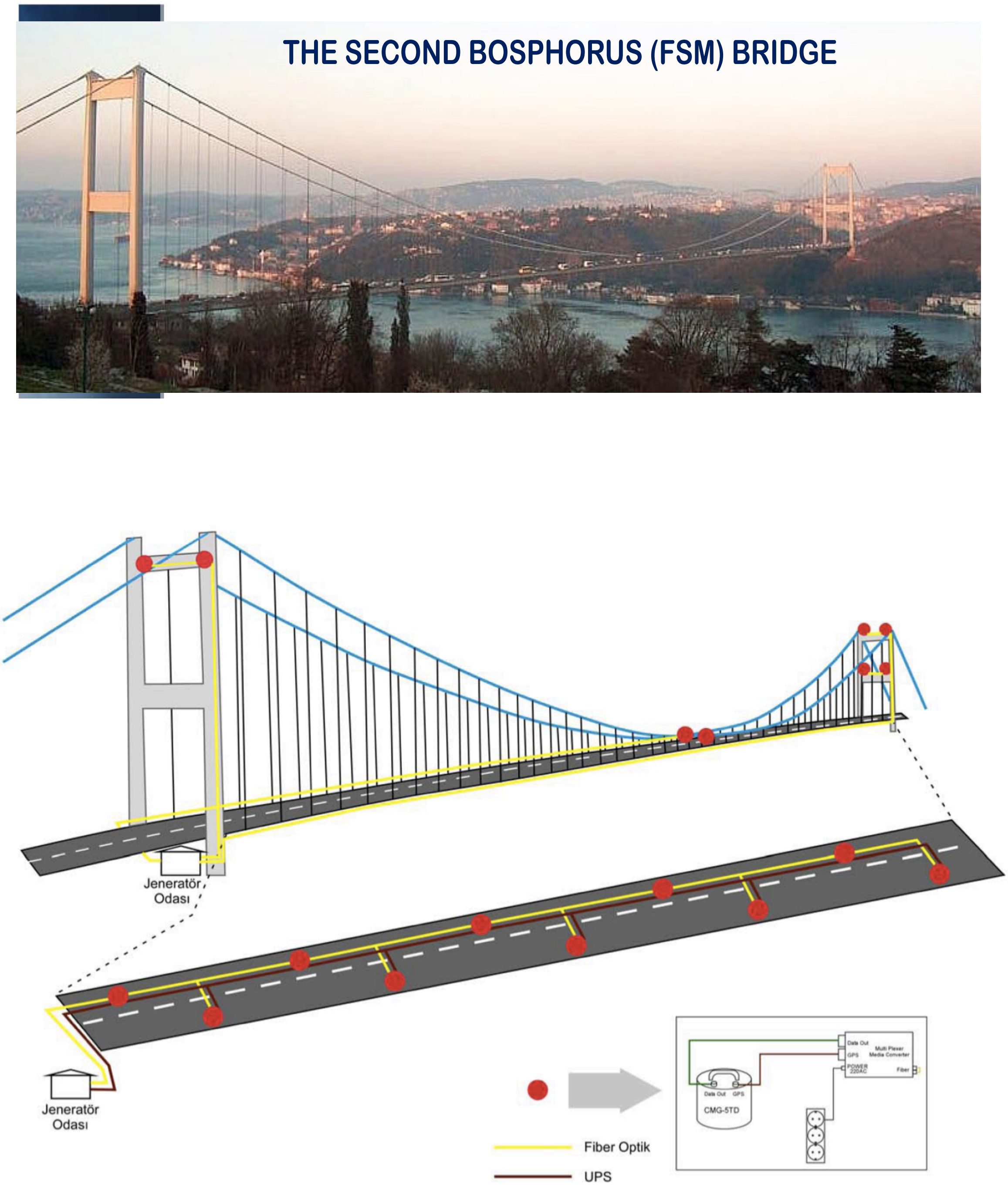

Figure 5. Fatih Sultan Mehmet (2nd Bosporus) Bridge and the sensor layout

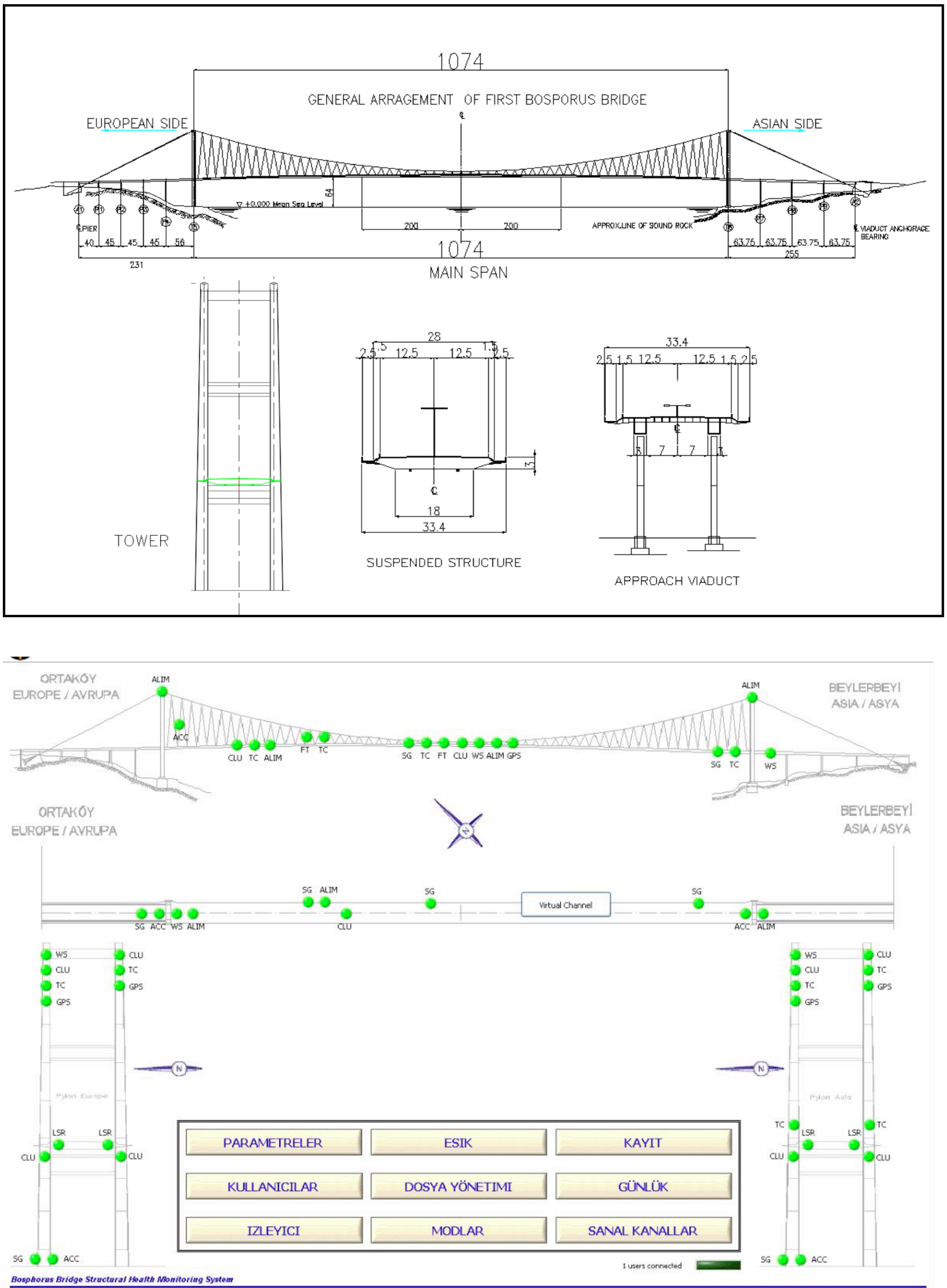

Figure 6. The schematic view of the Ataturk (1st Bosporus) bridge and the sensor locations. The system is operated by General Directorate of Highways.

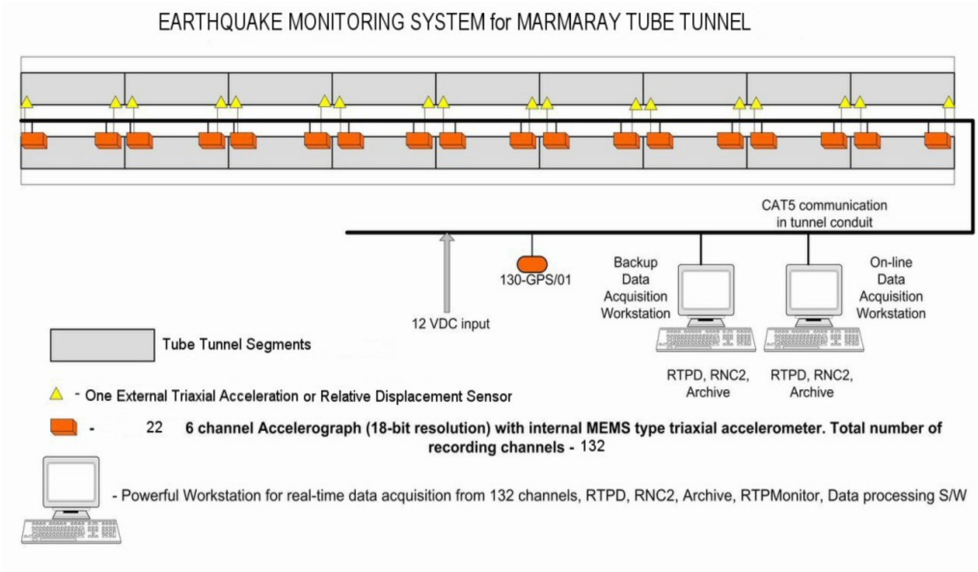

Figure 7. SHM system for the Marmaray rail tube tunnel (Erdik, 2013)

REAL-TIME ANALYSIS OF SHM DATA

Data from the structural monitoring networks are transmitted in real time to the monitoring center at DEE-KOERI. An in-house real-time modal identification software is used to process and analyze the data. The software includes data processing, spectral identification, and animation modules. The results are displayed in real time, showing the time variations of modal properties and the structure's configuration. Fig. 9 gives a typical screen-plot of the graphical user interface of the software. There are four main windows. The window in upper right shows the selected (recorded or processed) waveforms. The window in upper left shows the spectral content of the selected waveforms. The window in lower left shows the time variations of the identified structural parameters from the data, such as modal frequencies and damping ratios. The window in lower right shows the real-time animations of the total or modal responses (Safak et al., 2010).

CONCLUSIONS

The paper presents a general summary of structural monitoring networks in Istanbul. The structures include a large number of historical structures (i.e., mosques, minarets, museums), the two suspension bridges on the Bosporus, the Marmaray rail tube tunnel, several high-rise buildings, and industrial facilities. The monitoring systems installed in historical structures in Istanbul are unique, as they form the largest group of monumental structures in the world monitored in the same city. Data processing, analysis and storage is carried out in real-time by dedicated modal identification software.

Including the free-field stations of the Istanbul Earthquake Early Warning and Rapid Response System, the stations of the three down-hole arrays in Ataköy, Zeytinburnu and Fatih; and the stations of the Air Force Academy Short Aperture Array, DEE-KOERI currently operates close to 230 ground and more than 100 structural stations. The data that are obtained from them can be used for a variety of scientific and application oriented purposes. Characterization of earthquake response of a series of systems, extending over a wide range of research topics from the earthquake source until the structural response of different structural types, is possible with the gathered information. Analysis and interpretation of this information are particularly important due to a high likelihood of a large earthquake expected to hit Istanbul in the near future.

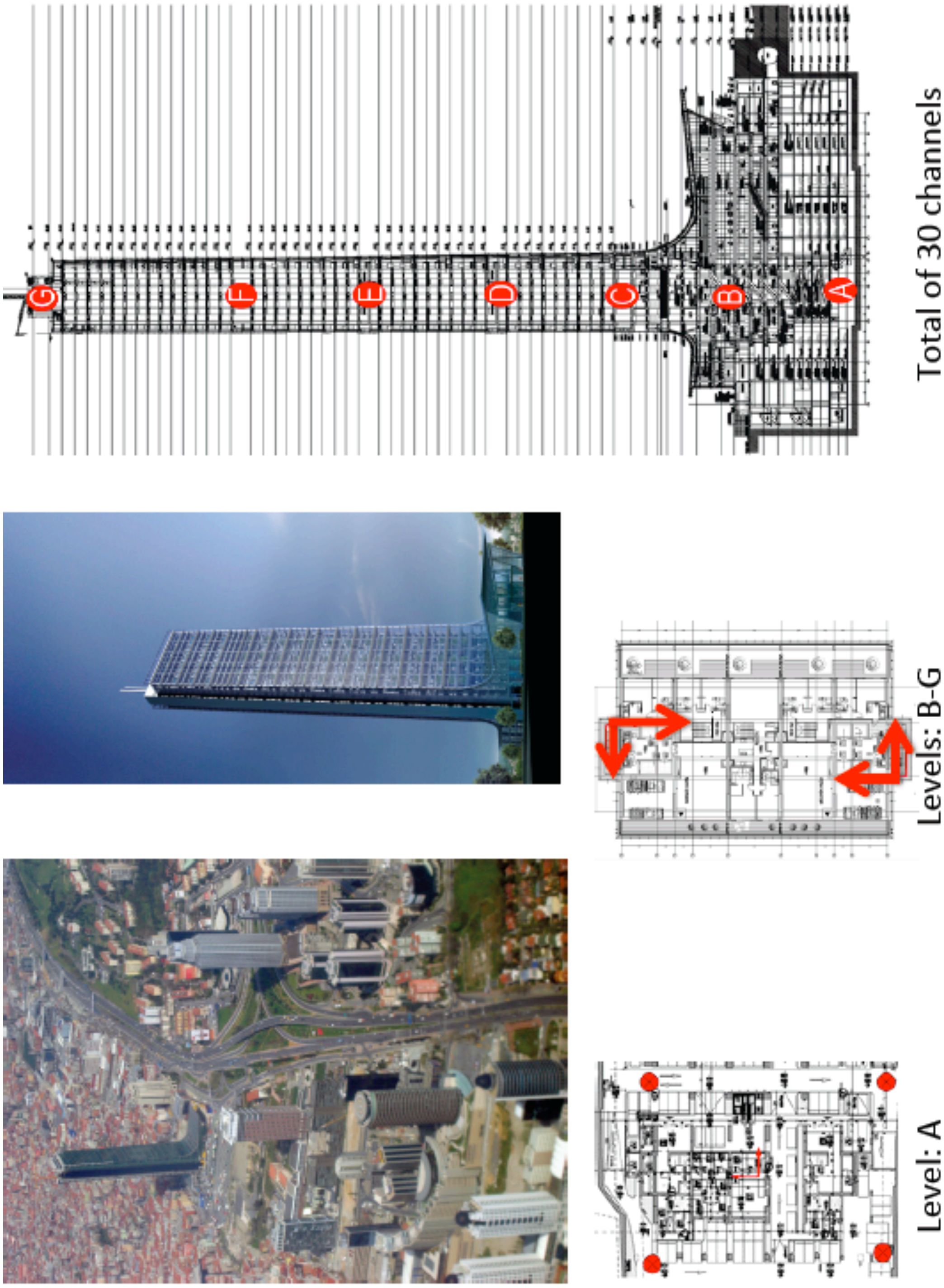

Figure 8. 62-story Sapphire tower and the sensor layout

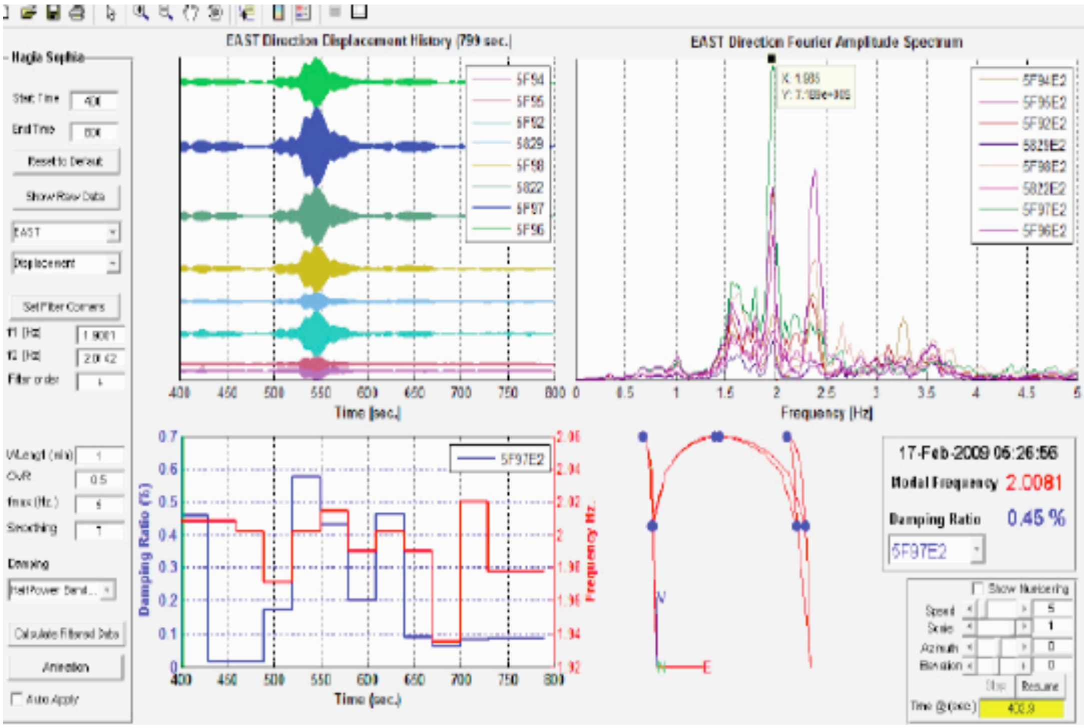

Figure 9. Typical screen shot of the real-time modal identification software.

Acknowledgments

Running and maintaining seismic networks, whether structural or ground, are due to the dedication and endless efforts of many individuals from the DEE-KOERI of Boğaziçi University. In this respect we would like to acknowledge following academic and technic personnel: Mustafa Erdik, Yavuz Kaya, Ahmet Korkmaz, Nafiz Kafadar and Emre Özdemir.

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