Structural Health Monitoring and Strong Motion Networks in Istanbul

Eser Çaktı[1], Erdal Şafak[2]

[1] Boğaziçi University, Kandilli Observatory and Earthquake Research Institute, Istanbul, Turkey
[2] Boğaziçi University, Kandilli Observatory and Earthquake Research Institute, Istanbul, Turkey

ABSTRACT: Department of Earthquake Engineering of Kandilli Observatory and Earthquake Research Institute of Boğaziçi University has installed and been operating for some time a large number of structural and ground seismic monitoring networks in Istanbul.

The structural health monitoring networks monitor continuously the vibrations of the structure, and try to detect and locate damage after an extreme event, such as a large earthquake. The structures with structural health monitoring systems include historical structures in the historical peninsula of Istanbul, suspension bridges on the Bosporus, several tall buildings, and industrial facilities. A real-time data processing and modal identification software is developed to analyze the real-time data from the instrumented structures. 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.

The ground motion systems include the 220-station Istanbul Earthquake Rapid Response Network, 10-station Early Warning Network, and three 3- or 4-level down-hole arrays. The aim of the Rapid Response Network is to provide the agencies and institutions in Istanbul with maps of estimated damages right after an earthquake to assist in the logistic planning of rescue operations. The objective of the Early Warning network to provide an early warning signal for Istanbul before the earthquake waves hit Istanbul. The system is more research oriented at the moment. Down-hole arrays are located in the areas of Istanbul, where site amplification is expected to be critical. More stations and dedicated systems are added to the networks every year.

1 INTRODUCTION

Numerous seismic hazard studies done following the destructive M=7.3 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; Erdik et al., 2004). The probability of having a magnitude 7 or above earthquake in Istanbul is estimated at about 65% within the next 30 years.

To assist in the reduction of losses in Istanbul from such an 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 seismic monitoring networks in Istanbul.

The structural health monitoring systems are installed in a large number of historical structures, the two suspension bridges on 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.

The seismic networks include the 220-station Istanbul Rapid Response Network, 15-station Early Warning Network, and three 3- or 4-level down-hole arrays. 120 stations belong to DEE-KOERI. 100 of the stations in the Rapid Response Network belong to IGDAS, the company that operates the Istanbul's natural gas distribution network. These 100 stations are placed at IGDAS's District Regulators (i.e., pressure reduction stations). In addition to the networks in Istanbul, DEE-KOERI operates the 12-station Antakya Basin Strong Motion Network.

The rapid response network provides the critical values of ground shaking (PGA, PGV, and spectral accelerations at 0.2 and 1.0 second) automatically within minutes of an earthquake, which are than transmitted to those agencies dealing with emergency response. The IGDAS stations have an additional objective that when the shaking exceeds a specified threshold level at the station the gas flow is automatically cut off for locations downstream. The objective of the early warning network is to provide 5 to 7 seconds early warning of an earthquake, which can be used for automatic shutdown of some of the critical systems in Istanbul. Down-hole arrays, located in the areas of Istanbul, where site amplification is expected to be critical, aim to study the site response on the European side of Istanbul.

Brief descriptions of the networks are presented below.

2 STRUCTURAL MONITORING NETWORKS

DEE-KOERI has designed and been operating a significant number of structural monitoring networks in Istanbul. The majority of them are in historical and critical structures. The structural networks include the 35-channel Hagia Sophia Museum; 47-channel Fatih Mosque; 27-channel Süleymaniye Mosque; 30-channel Sultanahmet Mosque; 44-channel Fatih Sultan Mehmet Bridge (the 2nd Bosporus bridge);, 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. In the Hagia Sophia Museum and Fatih Mosque networks, in addition to accelerometric stations, four two-channel tiltmeters are installed. Figure 1 shows the structural monitoring network in Hagia Sophia. The systems in Fatih, Süleymaniye and Sultanahmet Mosques have similar instrument layouts. The monitoring systems installed in historical structures in Istanbul, along with three planned additions, are unique, as they form the largest group of monumental structures in the world monitored in the same city and under the same earthquake hazard conditions. In Figure 2, the instrumentation on the Fatih Sultan Mehmet Bridge is displayed. Figure 3 shows the instrumentation at the 62-story Saphire Building, which currently is the tallest building in the city and in Turkey.

Data from the structural monitoring networks are transmitted in real time to the monitoring center at DEE-KOERI. An in-house real-time modal analysis software, KOERI_MIS, 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. Figure 4 gives a screen-plot of KOERI_MIS for a tower structure with a heavy mass near the top.

In addition to modal identification, other alternative methods for data analysis and system identification are currently being explored. They include detection and identification of changes on geometry based on GPS data, changes in the velocity of seismic waves within the structure, and methods based on the concept of *Seismic Interferometry* (Safak, 1999; Safak and Hudnut, 2006; Snider and Safak, 2006; Safak and Cakti, 2009).

3 GROUND MOTION NETWORKS

3.1 *Istanbul Earthquake Early Warning Network*

The current Istanbul Early Warning network is composed of 15 broadband seismic stations operating in real time. 10 of these stations are operated by DEE-KOERI. Five of the stations, operated by UDIM, are Ocean Bottom Seismometers (OBS) placed on the fault line at the bottom of Marmara Sea. The locations of the stations are shown in Figure 5. The data from these stations are transmitted continuously to the data center at DEE-KOERI. Considering the complexity of fault rupture and the short fault distances involved, a simple and robust early warning algorithm, based on the exceedance of a specified threshold amplitude level is implemented. Currently, two ground motion parameters are used for early warning, the PGA (peak ground acceleration) and the CAV (the cumulative integral of absolute accelerations).

The early warning information consisting of three alarm levels can be communicated to the appropriate servo shut-down systems of the recipient facilities, which should automatically decide proper action based on the alarm level.

3.2 *Istanbul Rapid Response Network*

The Istanbul Rapid Response Network is composed of 220 strong-motion stations, all operating in real time. The 100 of the 220 stations in the Rapid Response Network belong to IGDAS, Istanbul Natural Gas Distribution Company. These 100 stations are placed at IGDAS's District Regulators (i.e., pressure reduction stations) with the objective that, when the shaking exceeds a specified threshold level at the station, the gas flow is automatically cut off for locations downstream. The station locations of the Rapid Response Network along with the IGDAS and Early Warning stations are shown in Figure 5.

The records from the network are analyzed continuously and various parameters of the shaking (such as, PGA-Peak Ground Acceleration, PGV-Peak Ground Velocity, and PSA- Pseudo-Spectral Accelerations at specified periods) are calculated in real time. Warnings are issued if any of the the shaking parameters exceeds a predefined threshold value. Once the warning is issued, seismic hazard and risk maps are automatically generated within minutes of the earthquake based on a 400m x 600m (0.01° x 0.01°) cell-based representation of the region. Seismic hazard values at the center of each cell are displayed in terms of PGA (Peak Ground Accelerations), PGV (Peak Ground Velocities), and PSA (Pseudo-Spectral Accelerations) at specified periods. The seismic demand at the center of each geo-cell is computed from spectral displacements. Each cell is also pre-assigned a structural type based on the 24 structural categories determined from the structural inventory studies done for Istanbul. Using the spectral displacements, and the spectral-displacement based fragility curves (i.e., the Capacity Spectrum Procedure) for the 24 building categories, the building damage in each cell is computed and damage distribution maps are generated. This Rapid Response Information (i.e., the shake and damage distribution maps) that is generated automatically are then transmitted immediately to the Emergency Response centers at the Istanbul Governorate and the Istanbul Municipality. The health of the rapid response system is tested automatically every day at 10:00 am by setting off a false trigger (Erdik et al, 2003).

3.3 Down-hole Arrays

We operate three geo-technical down-hole arrays on the European side of Istanbul. They are located in Fatih, Zeytinburnu and Ataköy (Figure 6). In each array there is one surface station and three (Zeytinburnu and Fatih arrays) or four (Ataköy array) borehole 3-component accelerometers installed at depths chosen to match the soil profile characteristics. The deepest instrument is always at the engineering bedrock level (Kurtuluş, 2011). The primary purpose of these arrays is the assessment of site amplification effects on the European side of Istanbul that is more prone to such effects with its weaker site conditions when compared to the Asian side.

3.4 Antakya Basin Strong Motion Monitoring Network

DEE-KOERI operates a 12-station strong motion in the Antakya basin since 2009. The network has a T-shape. 9 accelerometric stations span between the two mountain ranges and cover the basin along its short-axis passing through the town of Antakya. 3 stations are installed parallel to the long axis of the Antakya basin. They extend between Antakya and Amik basin. The objectives of the project are monitoring the earthquake response of the Antakya Basin; improving our understanding of basin response; and contributing to earthquake risk assessment of Antakya which is a town marked with high earthquake hazard, and historical and cultural significance. It is the first permanent installement in Turkey dedicated primarily to basin effect studies (Çaktı et al, 2011).

4 PLANNED SYSTEMS

Installation of more real-time structural monitoring networks is in progress or at planning stages such as those for the Mihrimah Sultan Mosque in Edirnekapı, the two minarets of Hagia Sophia Museum and Maltepe Mosque, and the Marmaray Immersed Tube Tunnel under the Bosporus.

Another system planned for 2013 is the short-aperture array that will be installed in the Air Force Academy in Yeşilyurt that is located in the closest possible location to the segments of the North Anatolian Fault System in the Sea of Marmara. The station separation distances in the 66-channel Air Force Academy array will vary between 2.5m and 100m. Finally the number of stations in the IGDAS network is planned to reach 200 in the first stage, and 700 eventually.

5 CONCLUSIONS

DEE-KOERI currently operates 234 ground and 84 structural stations. The data from these networks can be used for a variety of scientific and practical purposes, as they provide the necessary information to conduct research in a wide range of topics varying from the characterization of earthquake sources to studying the response of different structural systems. Due to a high likelihood of a large earthquake expected in the near future, the analysis and interpretation of this information are particularly important to reduce seismic risk for Istanbul.

ACKNOWLEDMENTS

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. Particularly we would like to acknowledge following academic and technic personnel: Mustafa Erdik, Aslı Kurtuluş, Yavuz Kaya, Hakan Alçık, Aydın Mert, Nafiz Kafadar, Ahmet Korkmaz, Oktay Çırağ, Emre Özdemir, Bahar Tahtasızoğlu, Alev Berberoğlu and Ayten Korkmaz. We also acknowledge Murat Bikçe, Mehmet Cemal Geneş and Selçuk Kaçın of Mustafa Kemal University for their contributions to the Antakya network.

REFERENCES

Çaktı, E., M. Bikçe, O. Özel, M.C. Geneş, S Kaçın, Y. Kaya. 2011. Antakya Basin Strong Ground Motion Network. EGU2011-10705.

Durukal E, Cimilli S, Erdik M. 2003. Dynamic response of two historical monuments in Istanbul deduced from the recordings of Kocaeli and Duzce earthquakes, Bulletin of Seismological Society of America, 93 (2): 694-712 April 2003.

Erdik M, Fahjan Y, Özel O, Alçık H, Mert A, Gül M. 2003. Istanbul earthquake rapid response and the early warning system. Bull Earthquake Eng 2003;1:157–163.

Erdik M, Demircioğlu M, Şeşetyan K, Durukal E, Siyahi B. 2004. Earthquake hazard in Marmara region, Turkey. Soil Dyn Earthquake Eng; 24:605–631.

Kurtulus, A. 2011. Istanbul Geotechnical Downhole Arrays. Bulletin of Earthquake Engineering; 9: 5, 1443-1461.

Parsons, T., S.Toda, S.Stein, A.Barka and J.H.Dietrich. 2000. Heightened Odds of a Large Earthquake Near Istanbul: an Interaction Based Probability Calculation, Science, 288.

Safak, E. 1999. Wave propagation formulation of seismic response of multi-story buildings, *Journal of Structural Engineering*, ASCE, Vol. 125, No. 4, pp.426-437.

Safak, E. and K. Hudnut. 2006. Real-time structural monitoring and damage detection by acceleration and GPS sensors, *Proceedings* of the 8th U.S. National Conference on Earthquake Engineering, San Francisco, California, 18-22 April 2006.

Snieder, R. and E. Safak. 2006. Extracting the building response using interferometric imaging; theory and application to the Millikan Library in Pasadena, California, *Bulletin of the Seismological Society of America*, Vol. 96, pp.586-598.

Şafak, E. and E. Çaktı, E. 2009. Applications of seismic interferometry for system identification in Earthquake Engineering, Proceedings of COMPDYN2009-Computational Methods in Structural Dynamics and Earthquake Engineering – Rhodes, Greece, 22-24 June 2009.

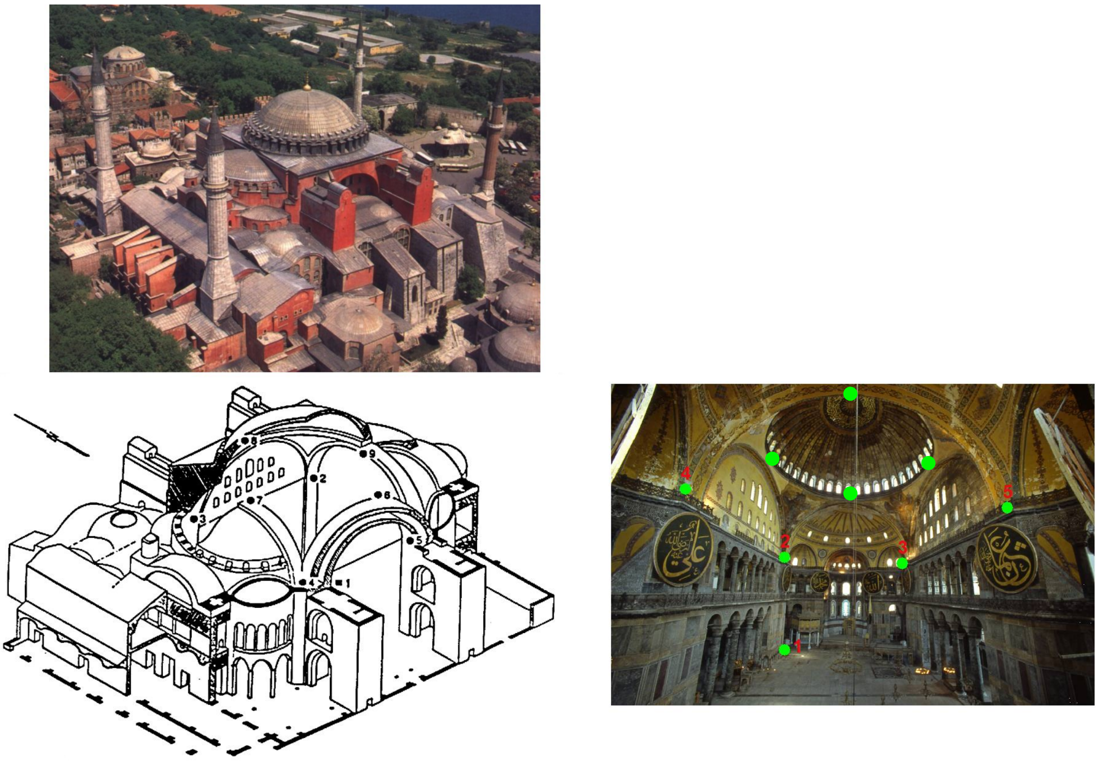

Figure 1. Hagia Sophia Structural Monitoring Network (adopted from Durukal et al, 2003)

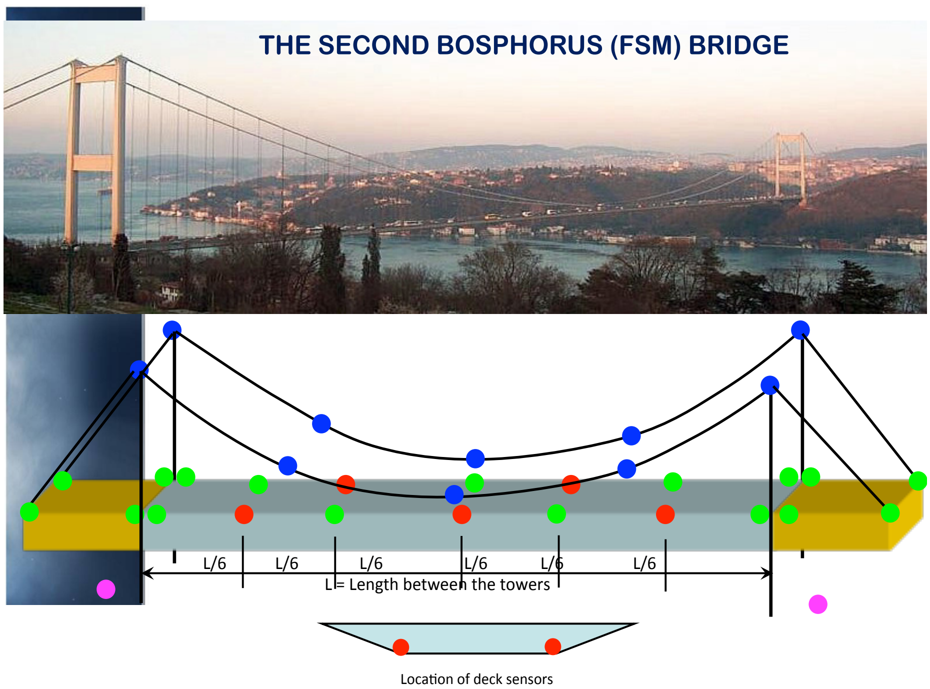

Figure 2. Instrumentation on the Fatih Sultan Mehmet Bridge on the Bosphorus

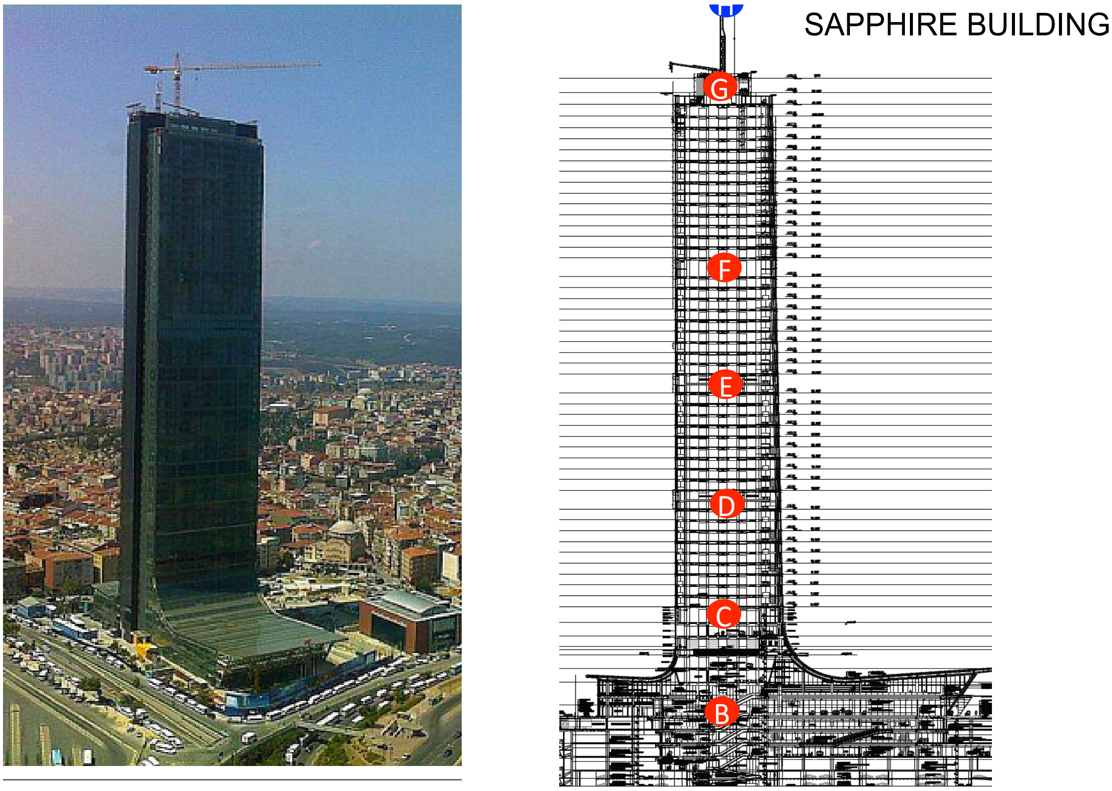

Figure 3. Structural Health Monitoring Network at the Sapphire Tower in Istanbul.

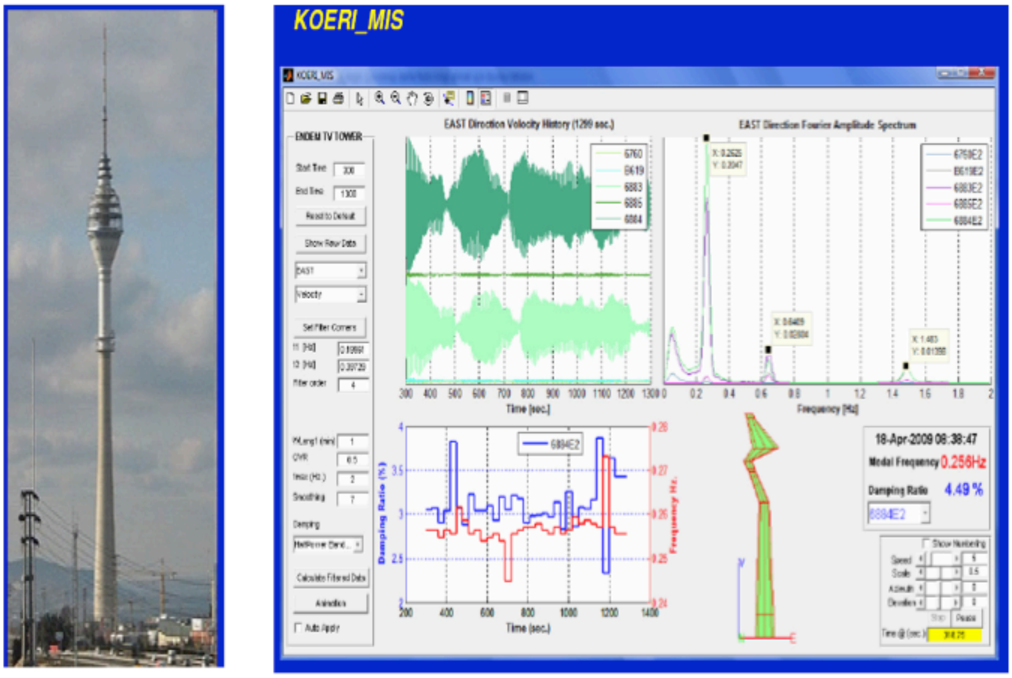

Figure 4. Screen-print of the KOERI_MIS data processing and analysis software.

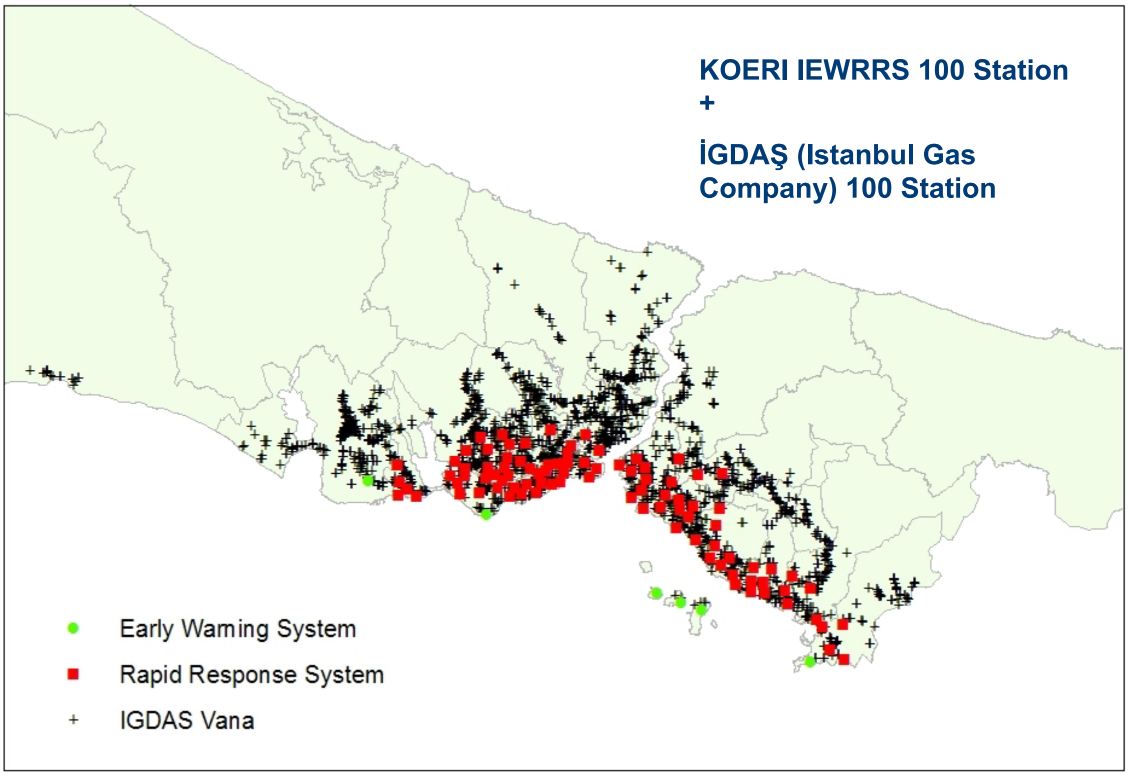

Figure 5. Istanbul Earthquake Rapid Response and Early Warning System . Also shown are the locations of IGDAS district regulators which are future station locations within the ğlanned expansion of the system.

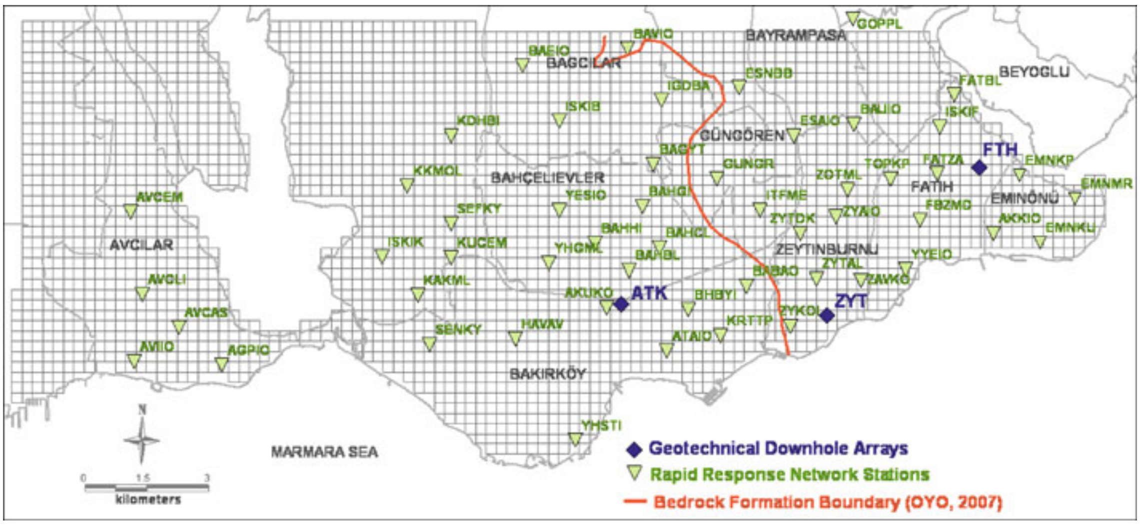

Figure 6. Locations of four down-hole arrays shown in blue, along with the rapid response stations shown in green (after Kurtuluş, 2011).