16TH EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING THESSALONIKI 18 - 21 JUNE 2018

SITE RESPONSE EVALUATIONS THROUGH VERTICAL ARRAYS IN ISTANBUL

Ozge FERCAN[1], Aslı KURTULUS[2], Atilla ANSAL[3], Erdal SAFAK[4]

ABSTRACT

1D and 2D site response analyses are carried out for calculating surface accelerations at Rapid Response Network strong motion stations using the bedrock acceleration records from Zeytinburnu vertical seismic array (ZYT) located around Zeytinburnu district based on the soil profiles determined at these locations during the Istanbul Microzonation Project for the European Side. 1D and 2D soil profiles are based on the borings, laboratory and geophysical tests carried out in each cell of the grid system adopted for the Istanbul Microzonation Project. Soil stratification and shear wave velocity profile are determined down to engineering bedrock based on the data from borings and in situ tests. 1D equivalent linear site response analyzes are conducted using bedrock record obtained at 288 m depth from ZYT vertical array. It was observed that the acceleration records calculated on the ground surface were similar to the ones recorded by the surface arrays. In addition, an optimization study was carried out by Monte Carlo simulation to achieve a higher compatibility between calculated and recorded values on the surface. For the case of 2D site response analysis where the change in lateral continuity, geometry of layers and depth of bedrock were modeled, it was observed that calculated accelerations on the ground surface were lower than the recorded ones. Soil stratification varying in horizontal and vertical directions indicates the need for more comprehensive analysis of the observed complex structure.

Keywords: Vertical seismic array; 1D and 2D site response analysis; best-fitting Vs profile, Monte Carlo simulation

1. INTRODUCTION

In seismically active regions, site specific response analysis of ground motion amplification is required to quantify the seismic hazard. Installation of strong motion sensors at the top and bottom of the vertical (downhole) seismic arrays allows detection of site amplification, vertical wave propagation, and for validating the modelling parameters, and allows to determine the uncertainties in site response analysis. The advantage of the method is, to be able to compare the recorded and calculated ground motions and to be used for the validation and calibration of site effects. Large-Scale Seismic Test site in Lotung, Taiwan, Kiban-Kyoshin network (Kik-net) of vertical seismometer arrays in Japan and vertical seismic arrays in Istanbul are the few examples installed in seismically active regions. By the application of vertical seismic array methodology throughout the world, different approaches were suggested for the detection of site effects beside the classical ones which gave rise to significant discussions. The most standard method for the detection of site amplification was the spectral ratio technique which required a pair of instruments, one located at the site and the other one on a “reference rock site”. Another site dependent technique was introduced by Nakamura (1989) for the detection of site effects based on microtremors measurements. Both methods were used to characterize the site effects by validating the theoretical data with the observed and recorded by vertical strong

[1]Research Ass., Dept. of Civil Engineering, Ozyegin University, Istanbul, Turkey, ozge.fercan@ozyegin.edu.tr
[2]Assoc. Prof., Dept. of Civil Engineering, Ozyegin University, Istanbul, Turkey, aslı.kurtulus@ozyegin.edu.tr
[3]Professor, Dept. of Civil Engineering, Ozyegin University, Istanbul, Turkey, atilla.ansal@ozyegin.edu.tr
[4]Professor, Dept. of Earthquake Engineering, Bogazici University, Istanbul, Turkey, erdal.safak@boun.edu.tr

motion arrays (Theodulidis et al. 1996; Margheriti et al. 2000; Assimaki et al. 2008; Kokusho and Sato, 2008; Cadet et al. 2012; Kaklamanos et al. 2015). Vertical strong motion arrays provided a valuable data set of bedrock motions recorded simultaneously with the surface motion, for the locations where no outcrop was available on the surface. On the other hand, as it was stated by many researchers (Kramer, 1996; Safak, 1997; Baise and Glaser, 2000), the interference of down and up going waves recorded at the downhole rock stations, may be misinterpreted if the records were not properly processed. Since the vertical strong motion arrays are the best indicators for the characterization of dynamic soil properties, 1D and 2D equivalent linear and nonlinear site response models are generally adopted to validate various parameters governing the soil behavior (Ansal et al. 2010; Kaklamanos, 2013; Ansal et al. 2014).

The first step in a site response analysis is the definition of the soil profile based on V_S-shear wave velocity (m/sec) for each soil layer. Various methods were proposed to determine shear wave velocity profiles, however the most reliable one was specified as the in-situ testing which includes in-hole and on the soil surface geophysical measurements. Another way to determine shear wave velocity profile may be based on empirical correlations (Iyisan, 1996) with respect to in-situ standard penetration blow counts and V_S values. However, V_S-profiles determined from standard penetration blow counts and REMI methodology may not always be representative of the real soil profile due to inaccuracies of the measurements and uncertainties in empirical relationships. Assimaki and Steidl (2007) used an optimization algorithm in the wavelet domain to estimate the shear wave velocity for horizontally layered media with predefined layer thicknesses by using measured and predicted processes at the surface stations of the Kik-Net array. Successively, best fit elastic profiles were subjected to recorded strong motion time histories to approximate the nonlinear site response. In Assimaki et al. (2008), optimization analyses were conducted in series for each profile, global optima of soil-property vectors were obtained and finally the velocity inverted structures were averaged across the multiple events to evaluate the best-fit profiles.

Recorded low amplitude surface motions from Istanbul Rapid Response Network (IRRN) stations and ZYT vertical array were compared with the results obtained from 1D and 2D site response analysis. 1D site response analysis was carried out by modelling the soil profiles based on the microzonation data and by using the ZYT vertical array bedrock motions recorded at the triggered IRRN stations for the earthquakes within the range of M_L=3.6-4.7. In addition, an optimization procedure was applied to obtain best-fitting soil profile with the intend of improving soil models. The method suggested by Kurtulus (2011) was adopted to obtain the best fitting soil profile in terms of shear wave velocities, by utilizing recorded bedrock and surface motions from Istanbul downhole strong motion arrays and IRRN stations. 1000 random soil profiles were generated by Monte Carlo simulation and the best-fitting soil profile was determined by calculating the least square differences between recorded surface motion and 1D modelled surface motion. 2D site model was also generated along a cross-section line passing through the rapid response stations in Zeytinburnu and ZYT vertical array based on the boring profiles in each grid. Finally, seismic response of on the ground surface were evaluated based on the comparison of the results from 1D and 2D site response analyzes.

2. STRONG MOTION ARRAYS

Istanbul Rapid Response Network (IRRN) that is operated by KOERI, has 100 free field strong motion stations distributed through the city of Istanbul, out of which 55 of these stations are located in European side (Figure 1). The network consists of strong motion instruments (Güralp CMG-5T) located at the base level in low rise buildings and real-time data is transmitted to KOERI by GSM and GPRS modems following an earthquake (Erdik et al., 2003). The detailed site investigation study involving 2912 geotechnical borings was carried out for the European side in the scope of Istanbul Microzonation Project (OYO, 2007). The geotechnical data from the in-situ tests were utilized to determine the local soil conditions. In addition, three downhole strong motion arrays were installed to study the site amplifications at different sites (Kurtulus, 2011, Kurtulus et al. 2011). Detailed site and laboratory investigations were carried out for the locations of the vertical strong motion arrays. The three downhole strong motion arrays composed of four or three borehole and one surface accelerometers were installed in Ataköy, Zeytinburnu and Fatih districts in Istanbul (Kurtulus, 2011).

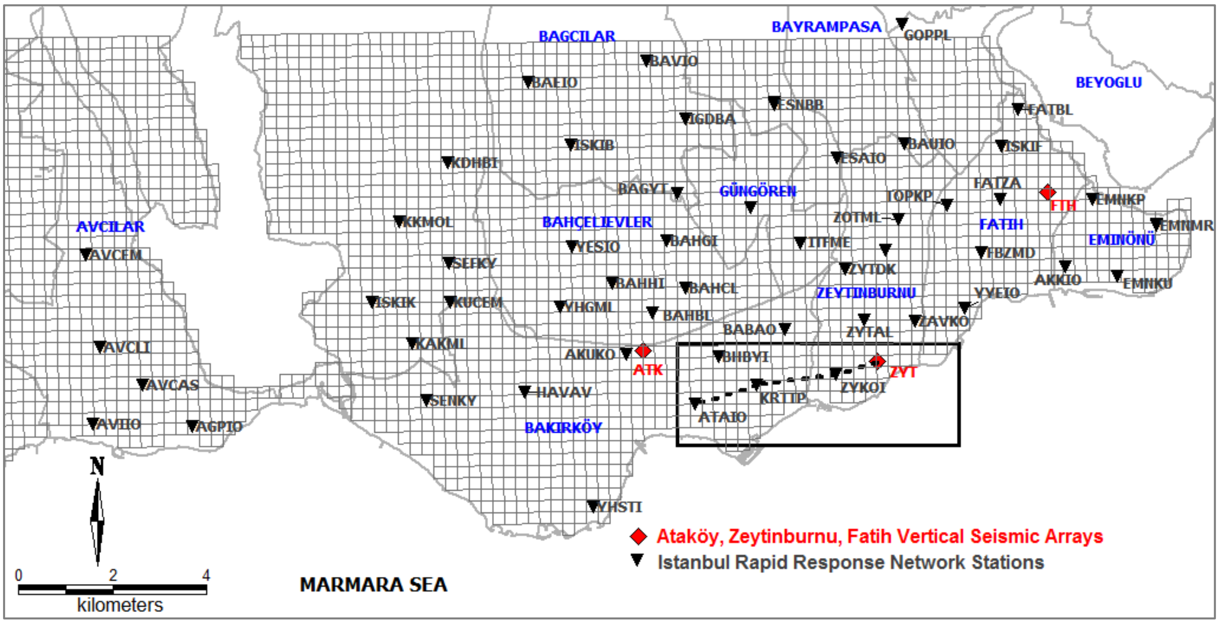

Figure 1. Seismic array in the European side of Istanbul and the grid system defined by 250mx250m cells. The region in the black frame presents the study area and the dashed line beginning from ATAIO station ending at ZYT vertical array represents the cross-section line for the configuration of 2D soil profile.

Geotechnical Downhole arrays and Rapid Response network stations were shown in Figure 1. In the scope of this study, it was prefered to use the acceleration records of Zeytinburnu array since it had the property of being the deepest among the others and it was on the linear cross-section line (Figure 1) and completely provided all of the bedrock acceleration records for the recorded events at ATAIO, KRTTP and ZYKOI rapid response stations. As it was presented in Figure 1, ZYT downhole array was located close to the coastline of Zeytinburnu district and composed of four triaxial accelerometers installed at the depths of 30, 57, 288 m (bedrock) and one on the ground surface. The other two vertical arrays reached to the bedrock at 140 m depth for ATK and 136 m for FTH arrays. However, when the location of the stations in the black frame in Figure 1 were taken into consideration, it was observed that all of them are arranged in a linear line parallel to the coastline comprising of similar soil units. Since the bedrock depth of ZYT array was the highest, it was assumed that site effects have less influence on the recorded bedrock motions.

2.1 Seismic Data

In Marmara Region, number of minor earthquakes, generally with local magnitudes M_L<5.5 are recorded by three vertical seismic arrays in Ataköy, Zeytinburnu and Fatih districts of Istanbul and by the Istanbul Rapid Response Network (IRRN). Among these recorded strong motion database, a total number of 7 earthquakes (Figure 2) with a magnitude range of M_L=3.6-4.7 recorded by ZYKOI, KRTTP, ATAIO rapid response stations near Zeytiburnu (ZYT) vertical array, were analyzed (Table 1) and marked by their dates. Epicentral distance of M_L4.2 Marmara Sea earthquake (16.11.2015) was estimated as 22.2 km to ZYKOI rapid response station, defined as the closest earthquake whereas 111 km for M_L4.5 Marmara Sea earthquake (28.10.2015) was the furthest distance. The range of PGAs observed in the studied earthquakes, is between 0.1-3.0 mg (Figure 3).

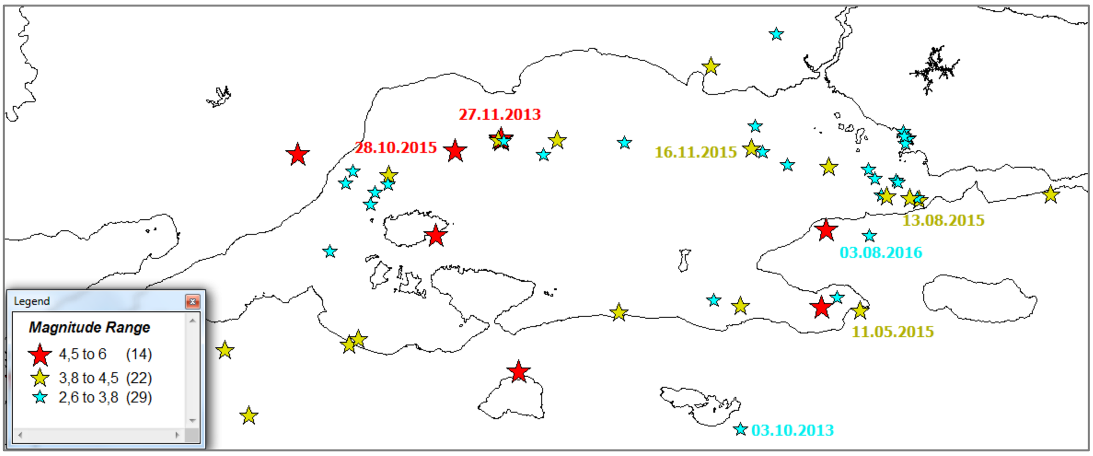

Figure 2. Location and magnitude range of the events in Marmara Region recorded by Istanbul vertical seismic array and IRRN. The studied 7 earthquakes were marked by their dates on the figure (Number of the recorded earthquakes falling in each magnitude range was given in the legend).

Table 1. List of M ≥3.6 local events recorded by ZYKOI, KRTTP, ATAIO rapid response stations and Zeytiburnu vertical array.

Date	Location	M_L	Lat.°	Long.°	Depth (km)
27/11/2013	Tekirdag	4.7	40.85	27.92	9.6
28/10/2015	Marmara Sea	4.5	40.82	27.77	12.7
16/11/2015	Marmara Sea	4.2	40.82	28.76	7.7
11/05/2015	Gemlik/Bursa	3.9	40.41	29.12	7.5
13/08/2015	Yalova	3.8	40.70	29.30	10.6
03/08/2014	Termal/Yalova	3.6	40.60	29.16	6
03/10/2013	Yalova	3.7	40.11	28.72	2.3

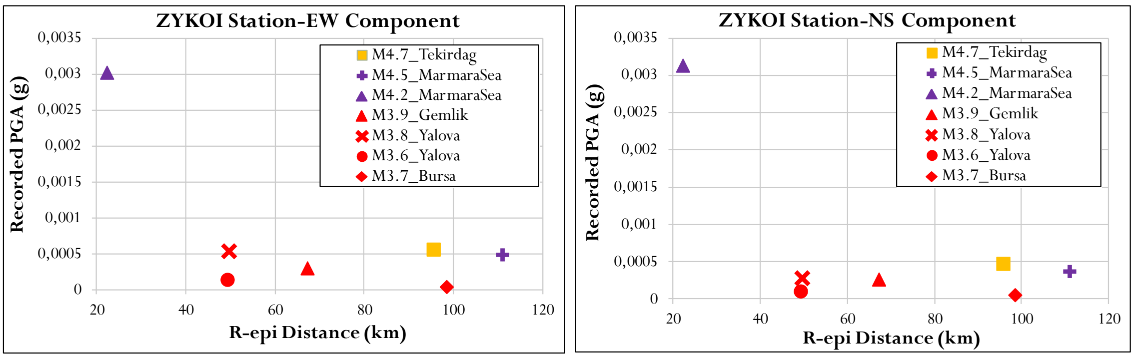

Figure 3. Recorded PGAs with respect to epicentral distance at ZYKOI station near ZYT vertical seismic array

3. SITE RESPONSE MODELS

For ZYKOI, KRTTP and ATAIO rapid response stations, and ZYT vertical array, soil profiles were determined by combining the data obtained from boring logs, REMI measurements and SPT tests carried out during Istanbul Microzonation Project (OYO, 2007) as shown in Figure 4. Borehole logs have shown that dominant soil type was clay and limestone forming Bakırköy and Güngören formations. Ceylan and Trakya formations were identified as the bedrock.

1D site response analyzes were conducted to model the recorded accelerations at ATAIO, KRTTP, ZYKOI and ZYT seismic stations on the ground surface. In the first stage, 1D site response analysis were carried out on the soil profiles obtained from the geotechnical investigations from the microzonation project (Figure 4). At the second stage, site response analyzes were carried out for the soil profiles determined by a best fitting procedure among the Monte Carlo simulated 1000 soil profiles.

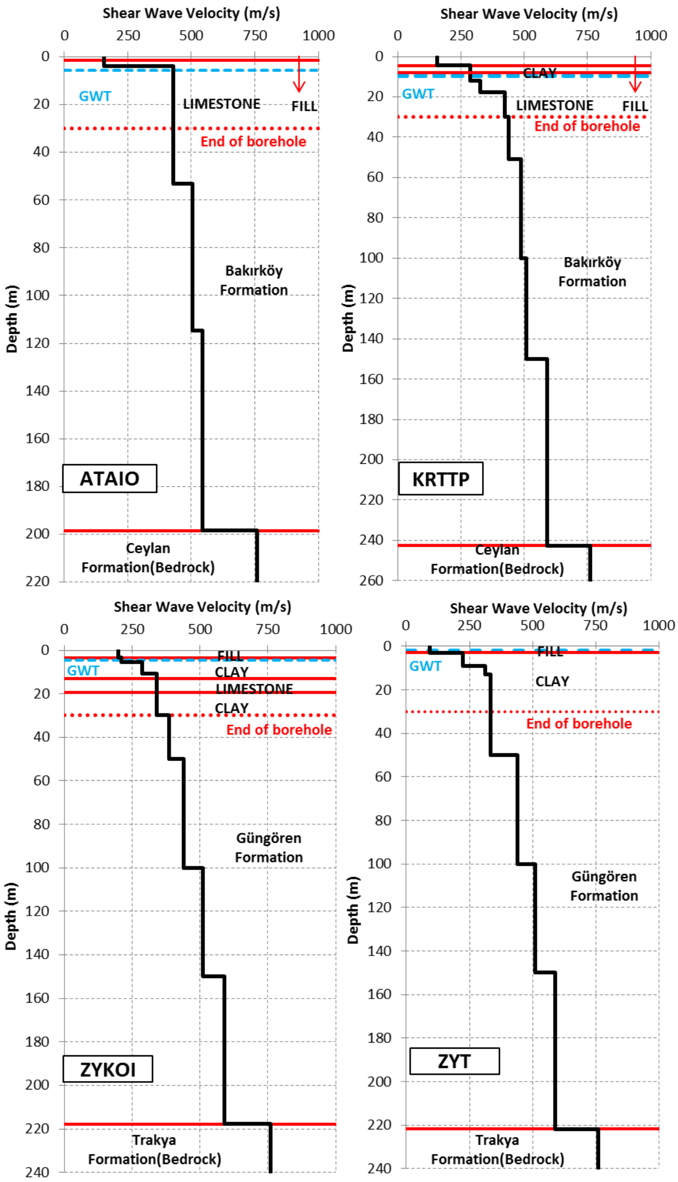

Figure 4. Shear wave velocity profiles and soil formations identified for the ATAIO, KRTTP, ZYKOI and ZYT stations down to the bedrock

In order to present a better understanding for the results of 1D site response analyzes, the corresponding shear wave velocity profiles obtained from the microzonation data was named as the 'Real Soil Profile' while the best fitting one was named as the 'Best-fitting Soil Profile'. In addition, 2D site response analyzes were carried out based on the soil profiles obtained from the microzonation data and explained in detail in the following section.

3.1 1D Site Response Analysis

The results from 1D Site response analysis are summarized in following two sections as given below; for Real soil profiles and Best-fitting soil profiles.

3.1.1 Real Soil Profile

The soil conditions for ATAIO, KRTTP, ZYKOI rapid response stations and ZYT vertical array are based on the boring logs and REMI test results. The bedrock record of ZYT vertical array was used as the bedrock input motion for the site response analyses for these three strong motion stations. 1D site response analyzes were carried out by DEEPSOIL software (Hashash et al., 2016) which was defined as a nonlinear, equivalent linear seismic site response analysis for one-dimensional soil columns.

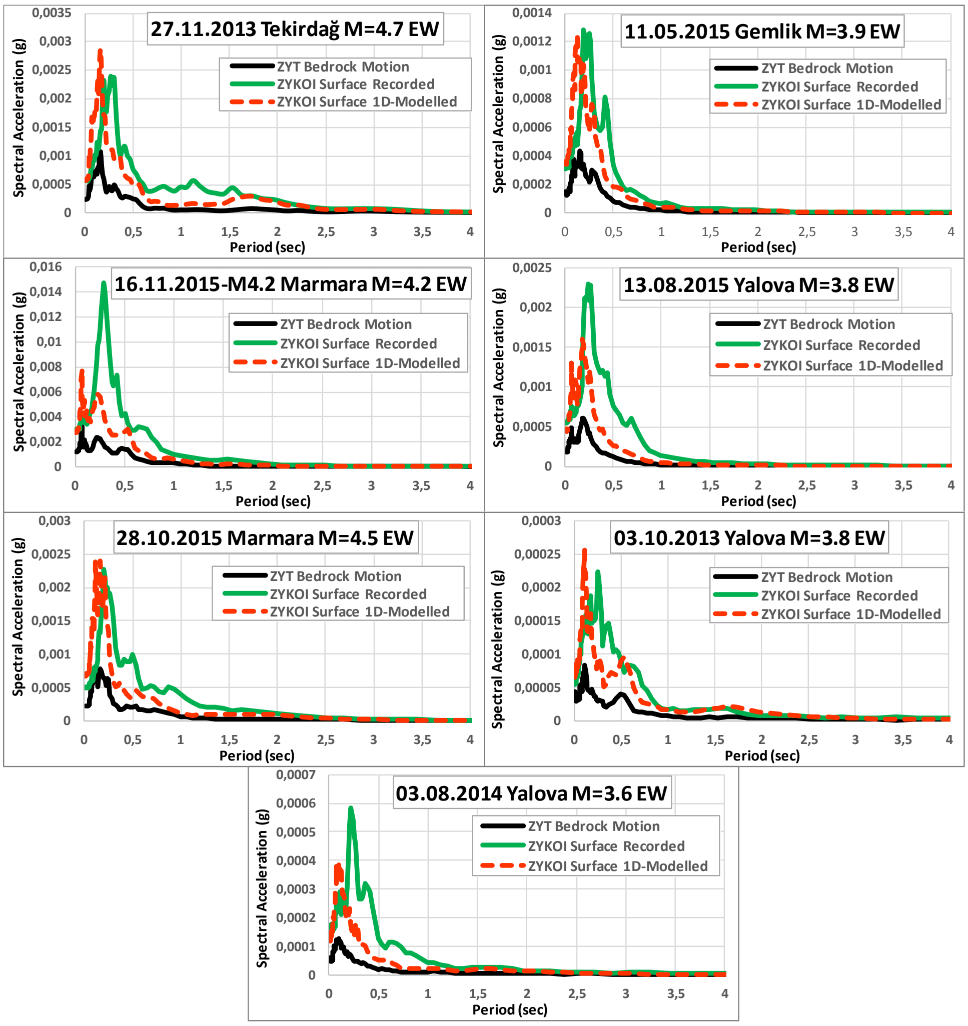

Figure 5. Acceleration response spectra on the bedrock and on the ground surface with 1D site response records for ZYKOI (IRRN) station.

For the earthquakes given in Table 1, spectral accelerations calculated on the ground surface are shown in Figure 5 for the ZYKOI stations. Since the optimization procedure by Monte Carlo simulation was carried out only for the ZYKOI station, in this section only site response analysis results for ZYKOI station were given. In each graph, the 1D-modelled surface motions were compared with recorded bedrock motions from ZYT vertical array in terms of spectral accelerations. Site response results are amplified versions of the bedrock motion with the same peaks in the response spectrum. Though the amplitude of spectral accelerations were relatively low, they showed quite meaningful agreement especially for the 28.10.2015, 27.11.2013 and 11.05.2015 earthquakes.

3.1.2 Best-fitting Soil Profile

With the intent of improving site models, downhole array recordings obtained during low-amplitude earthquakes, were used to optimize shear wave velocity profiles. An optimization study was performed using Monte-Carlo simulations to find a profile that would give a better agreement between calculated and recorded response spectra for the ZYKOI rapid response station. For the site response analysis Shake2000 (vertically propagating 1D SH waves methodology), (Ordonez, 2012) software was used. The median values of shear wave velocity and thickness of layers were assumed to be equal to the soil profile from the microzonation data. Total number of 1000 simulations were carried out for both by changing the values of shear wave velocity and layer thickness. Calculated and recorded response spectra for the three events among the earthquakes given in Table 1, were compared to find the best-fitting profile. Soil profile modeled by the tests in the microzonation project (real soil profile) and the optimized profile produced by Monte Carlo simulation were presented in Figure 6. In real soil profile, while the shear wave velocity was increasing layer by layer, for the best-fitting shear wave velocities in the intermedia layers showed higher values than the layers below. After 70 m depth, the optimized profile showed a stiffer soil characteristic than the real soil profile.

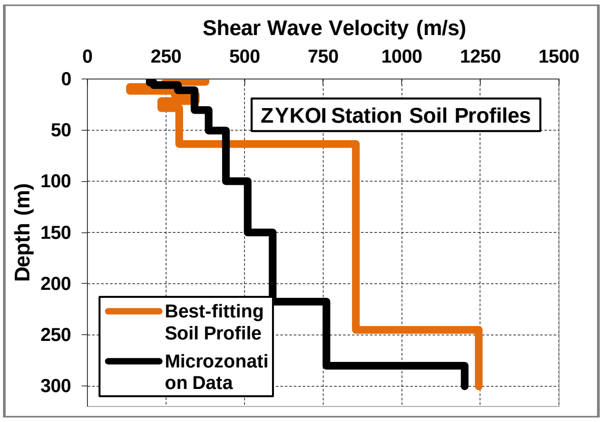

Figure 6. Real soil profile and Best-fitting soil profile at ZYKOI rapid response station

Optimized soil profile indicated a better match with the recorded response at ZYKOI station for the earthquakes 16.11.2015, 27.11.2013 and 28.10.2015 (Figure 7). However, it should be noted that the optimized models cannot be regarded as accurate models of the site stratification.

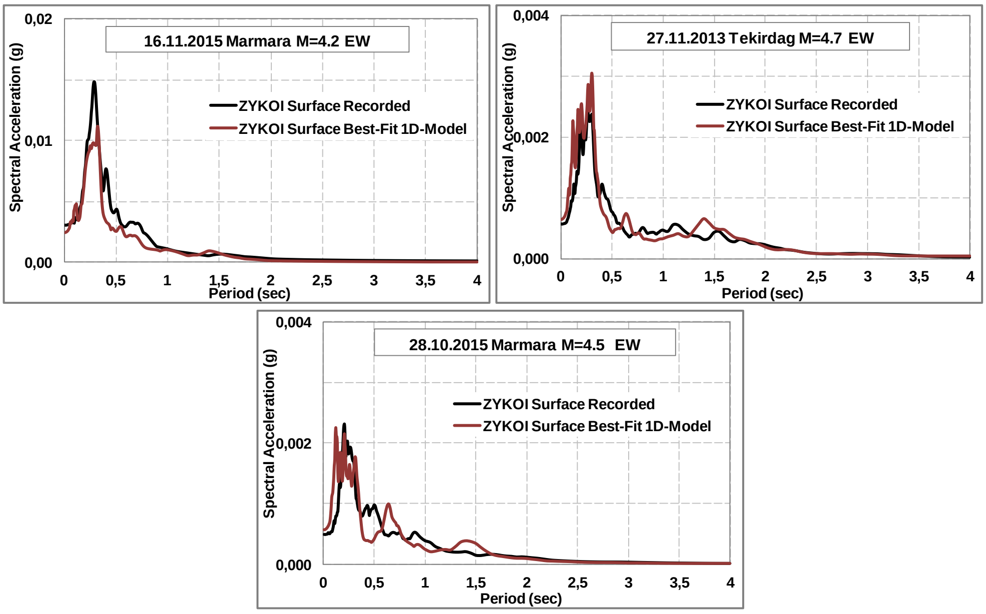

Figure 7. Comparison of the recorded and modeled response spectra at ZYKOI station for the events of 16.11.2015 Marmara Sea, 27.11.2013 Tekirdağ, 28.10.2015 Marmara Sea.

3.2 2D Site Response Analysis

The purpose of 2D site response analysis is to account for the horizontal change in site response along the cross section given in Figure 1, through ATAIO, KRTTP, ZYKOI stations of IRRN and ZYT vertical array. Borehole data obtained in the Istanbul Microzonation Project for each 250m x 250m cell, enabled to make correlation between the boreholes on the predefined cross section line (Figure 8). By correlation, lateral continuity of soil formations and layer thicknesses were determined and then a horizontally continuous soil profile was proposed (Figure 9). Borehole logs given in Figure 8, presented the first 30 m of the soil profile which was mainly composed of fill, clay and limestone units. Down to the bedrock, five different rock layers were defined according to the REMI tests. Equivalent linear modelling was applied in QUAKE/W finite element dynamic analysis software (QUAKE/W, 2016) and the model was constituted by 10 m mesh size containing 11349 nodes

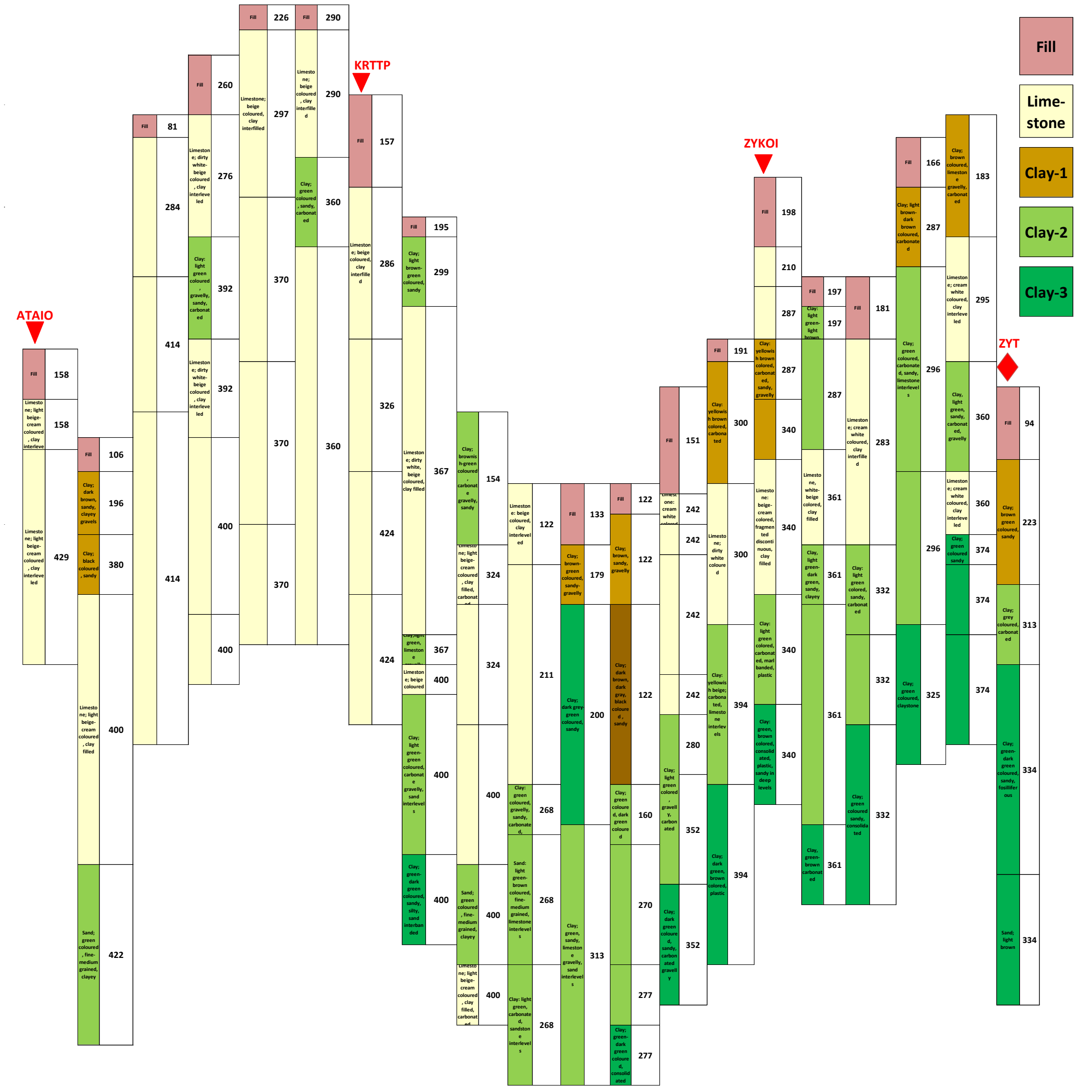

Figure 8. Boring logs along west-east cross section of ATAIO-KRTTP-ZYKOI-ZYT line

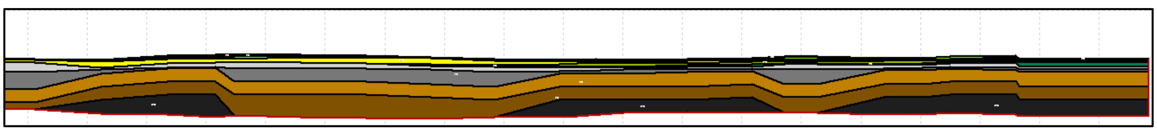

Figure 9. 4.5 km long cross section of ATAIO-KRTTP-ZYKOI-ZYT line

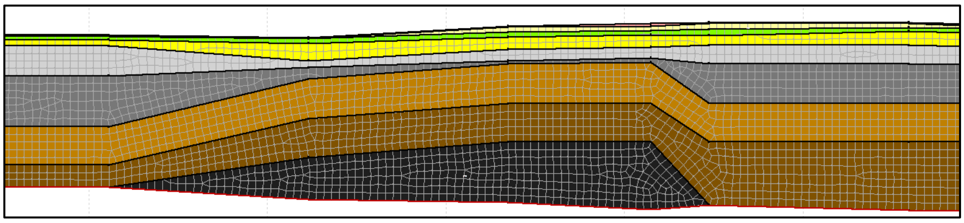

Figure 10. First 1.2 km of 4.5 km long cross section.

and 10954 elements (Figure 9 and Figure 10). For ATAIO and ZYT stations, spectral accelerations were presented in comparison to 1D, 2D modeling results and recorded motions on the surface just for the earthquakes 27.11.2013 and 28.10.2015 (Figure 11). 2D modeling results indicated quite lower values than the recorded ones, interestingly for 27.11.2013 earthquake, some long period peaks were observed. PGA distributions along the horizontal distance through east-west cross section were presented for 16.11.2015 Marmara Sea, 27.11.2013 Tekirdağ and 28.10.2015 Marmara Sea earthquakes in Figure 12, Figure 13 and Figure 14. Highest accelerations were observed for 16.11.2015 M4.2 Marmara Sea earthquake which was the closest one to the site though the magnitude was lower. For all of the earthquakes, 1D site response results matched better with the recorded components while 2D site response mostly underestimated the recorded ones. It should be noted that, in 2D site response modeling, continuity of the soil layers and the change in layer thicknesses in the horizontal direction, reflection of the shear waves in the vertical direction and boundary conditions contribute to more complex results to comment on. Different from 1D analysis, effect of these multiple parameters should be studied well by further modeling.

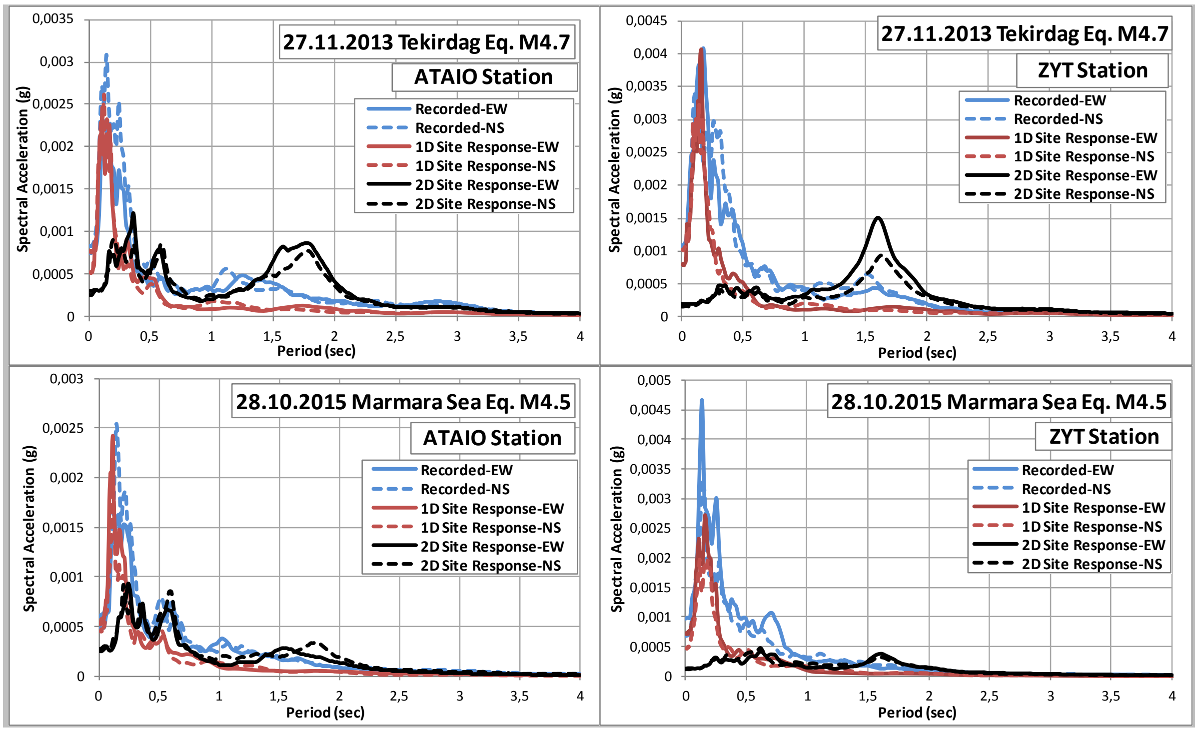

Figure 11. Calculated and recorded spectral accelerations on the surface for ATAIO and ZYT stations

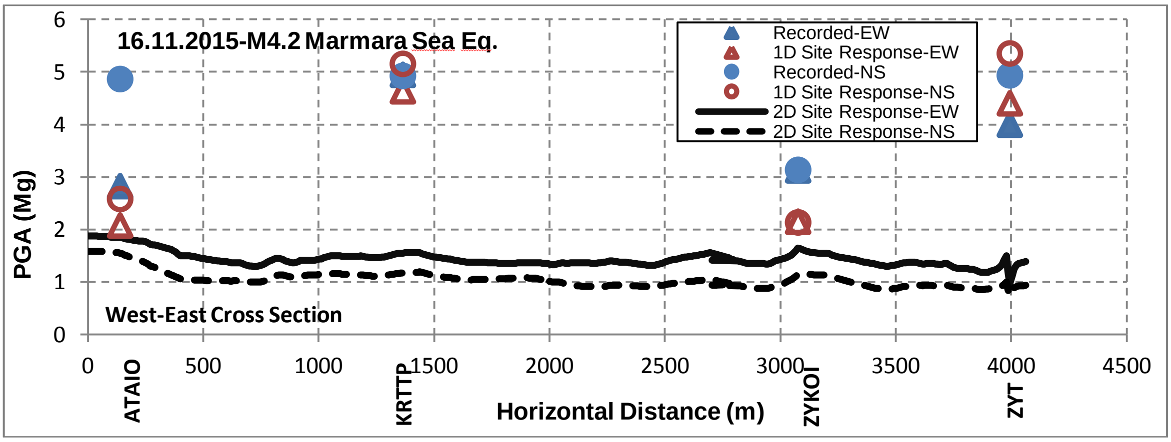

Figure 12. PGA distribution at IRRN stations, ZYT vertical array and horizontal distance along west-east cross section for 16.11.2015 Marmara Sea Earthquake.

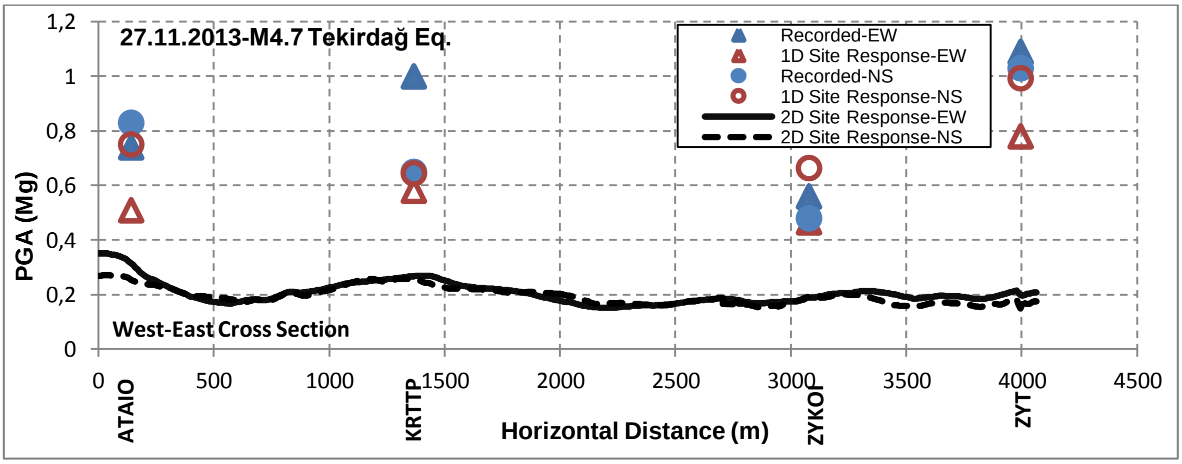

Figure 13. PGA distribution at IRRN stations, ZYT vertical array and horizontal distance along west-east cross section for 27.11.2013 Tekirdağ Earthquake.

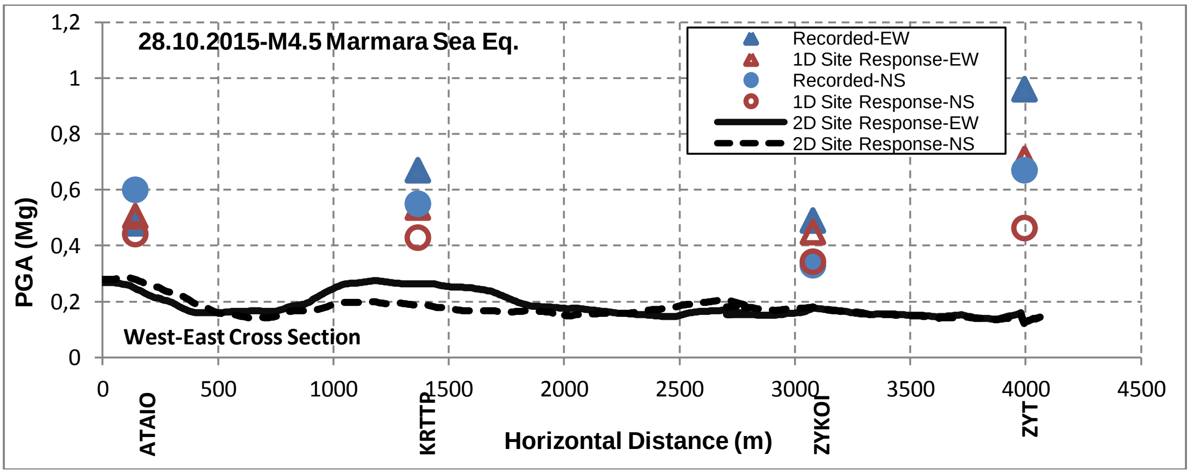

Figure 14. PGA distribution at IRRN stations, ZYT vertical array and horizontal distance along west-east cross section for 28.10.2015 Marmara Sea Earthquake.

4. CONCLUSIONS

Among the earthquake database recorded by IRRN and vertical seismic array, it was possible to compile just a total number of 7 earthquakes when excluding the unrecorded stations. By 1D site response analysis, it was intended to test the soil parameters revealed from the microzonation project. Though they were not exactly fitting to the recorded motions in terms of spectral accelerations, they showed quite close values in terms of PGAs. By optimization, best-fitting soil profile produced compatible results with the recorded ground motion by estimating the least square difference between them. In order to observe the site effects in two dimensional soil profile, 2D site response analysis was conducted by comprising the rapid response stations near ZYT vertical array and by using the tested soil parameters in 1D site response models. However, the 2D models unexpectedly indicated quite lower results than the 1D model results signing out the parameters of the laterally continuous layers, varying layer thickness in horizontal axis, varying bedrock depths and reflecting SH waves in horizontal axis were needed to be investigated independently. As a further investigation, it was decided to generate best-fitting soil profiles for the other seismic stations and by the correlation between adjacent stations, it would be possible to make a correlation to reveal a 2D soil profile.

5. ACKNOWLEDGMENTS

The authors would like to acknowledge the Scientific and Technological Research Council of Turkey for supporting the project entitled "Monitoring and Modelling Local Site Response During Earthquakes based on Vertical Strong Motion Array", FP7 Marie Currie Reintegration Project, Urbanquake for supporting Dr.Aslı Kurtuluş and the staff of Bogazici University Kandilli Observatory and Earthquake Research Institute for all their support.

6. REFERENCES

Ansal A, Tönük G, Kurtuluş A, Erdik M, and Parolai S (2010). Modeling the Observed Site Response from Istanbul Strong Motion Network, *Fifth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, San Diego, CA.

Ansal A, Tönük G, Kurtulus A (2014). Site Response From Istanbul Vertical Arrays and Strong Motion Network, *Proceedings of 10NCEE*, nees.org/ resources/12584

Assimaki D, Li W, Steidl JH, Tsuda K (2008). Site amplification and attenuation via downhole array seismogram inversion: a comparative study of the 2003 Miyagi-Oki aftershock sequence. *Bulletin of the Seismological Society of America* 98(1), pp 301-330.

Baise L G and Glaser S D (2000). Fundamental aspects of site response determined from inversion of vertical array data. *12th World Conference of Earthquake Engineering*.

Cadet H, Bard P-Y, Rodriguez Marek A (2012). Site effect assessment using Kik-net data: Part 1. a simple correction procedure for surface/downhole spectral ratios. *Bulletin of Earthquake Engineering* 10, pp 421-448.

Erdik M, Fahjan Y, Özel O, Alcik H, Mert M, and Gül M (2003). Istanbul Earthquake Rapid Response and the Early Warning System. *Bulletin of Earthquake Engineering* 1(1): pp 157-163.

Hashash Y M A, Musgrove M I, Harmon J A, Groholski D R, Phillips C A, and Park D (2016). DEEPSOIL 6.1, User Manual.

Iyisan R (1996). Correlations Between Shear Wave Velocity and In-situ Penetration Test", *Turkish Chamber of Civil Engineers, Digest 96, Teknik Dergi* 7, pp 371-374.

Kaklamanos J, Baise LG, Thompson EM, Dorfmann L (2015). Comparison of 1D linear, equivalent linear, and nonlinear site response models at six Kik-net validation sites. *Soil Dynamics and Earthquake Engineering* 69, pp 207-219.

Kokusho T, Sato K (2008). Surface to base amplification evaluated from Kik-net vertical array strong motion records. *Soil Dynamics and Earthquake Engineering* 28, pp 707-716.Kramer S L (1996). Geotechnical

Earthquake Engineering, Prentice Hall International Series in Civil Engineering and Engineering Mechanics, New Jersey.

Kurtulus A (2011). Istanbul Geotechnical Downhole Arrays, *Bulletin of Earthquake Engineering* 9(5), pp1443-1461.

Kurtuluş A, Ansal A, Şafak E (2011). Geotechnical Arrays Recently Deployed in Istanbul. *Proc. of 4th IASPEI/ IAEE International Symposium: Effects of Surface Geology on Seismic Motion*, Santa Barbara, USA.

Margheriti L, Azzara RM, Cocco M, Delladio A, Nardi A (2000). Analysis of borehole broadband recordings: test site in the Po Northern Italy. *Bulletin of the Seismological Society of America* 90(6), pp 1454-1463.

Nakamura Y (1989). A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. *QR RTRI* 30, pp 25-33.

Ordonez G A (2012). SHAKE2000-A Computer Program for the 1-D Analysis of Geotechnical Earthquake Engineering Problems. Geomotions, LLC; Lacey, Washington, USA.

OYO, Inc. (2007). Production of Microzonation Report and Maps – European Side (South), Report for Istanbul Metropolitan Municipality Microzonation Project.

Safak E (1997). Models and methods to characterize site amplification from a pair of records. *Earthquake Spectra*, *EERI* 13(1), pp 97-129.

Theodulidis N, Bard PY, Archuleta R, Bouchon M (1996). Horizontal to vertical spectral ratio and geological conditions: the case of Garner Valley downhole array in Southern California. *Bulletin of the Seismological Society of America* 86(2), pp 306-319.

QUAKE/W (2016). Finite Element Dynamic Earthquake Analysis, Software, Geo-Slope Office.