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MODELING THE OBSERVED SITE RESPONSE FROM ISTANBUL STRONG MOTION NETWORK

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ABSTRACT

An extensive site investigation study was carried out in the European side of Istanbul as part of the large-scale microzonation project for the Istanbul Metropolitan Municipality. 2912 borings mostly down to 30m depth with approximately 250m spacing were conducted within an area of 182 sqkm to investigate local site conditions. 55 stations of the Istanbul Rapid Response Network and Ataköy vertical array are located in this area. There have been few small earthquakes in the recent years with local magnitude slightly over M=4. One of these earthquakes took place on 12/3/2008 in Yalova with local magnitude of M=4.8. Vertical array stations at 4 levels (ground surface, at depths of 50m, 75m and 140m) and 23 of the 55 Istanbul Rapid Response Network stations recorded this earthquake. Based on the recorded acceleration time histories on the engineering bedrock at Ataköy vertical array, the remaining recorded acceleration time histories are modeled based on empirical site amplification relationships proposed by Borcherdt (1994) and based on a modified version of Shake91 (Idriss and Sun, 1992). An attempt is also made to model the recorded acceleration time histories during the M_w=7.4, 1999 Kocaeli Earthquake recorded at Ataköy, Fatih and Zeytinburnu stations located in the same area.

INTRODUCTION

Within the framework of the Istanbul Microzonation Project for the European side (Ansal et al., 2009a,b), the investigated region was divided by a grid system of 250m×250m and site characterization was performed for each cell based on borings and insitu measured seismic wave velocities for defining representative soil profiles with shear wave velocity values extending down to the engineering bedrock.

Geotechnical data is composed of boring logs of at least 30m depths for each cell with Standard Penetration Tests (SPT), seismic wave velocity measurements, and laboratory soil classification test results. In addition 25 deep boreholes were drilled to locate the engineering bedrock with PS-Logging inhole seismic wave velocity measurements (OYO, 2007). Geological data together with seismic measurements provided engineering bedrock (Vs > 750m/s) depths for all the cells. Variations of shear wave velocities with depth for the soil profiles are determined from SPT blow counts using empirical relationships proposed in the literature and based seismic wave velocity measurements. The calculated shear wave velocity profiles are compared with respect to velocity data obtained from in-situ borehole seismic wave velocity measurements and are modified when necessary.

There have been few small earthquakes with local magnitude slightly larger than M=4 that was recorded by the Ataköy vertical array as well as by some of the Istanbul Rapid Response Network (IRRN) stations. One of these earthquakes took place on 12/3/2008 in Yalova with local magnitude of M=4.8. Vertical array stations at 4 levels (on the ground surface, at 50m, 75m and 140m depths) and 23 of the 55 Rapid Response Network stations recorded this earthquake.

Even though the level of ground shaking is very low with maximum PGA in the order of 9mg, an effort was made to model the recorded acceleration time histories at the three upper levels of the Ataköy vertical array, as well as the 23 acceleration records obtained from the IRRN stations using the acceleration record obtained at 140m depth, on the engineering bedrock at the Ataköy vertical array.

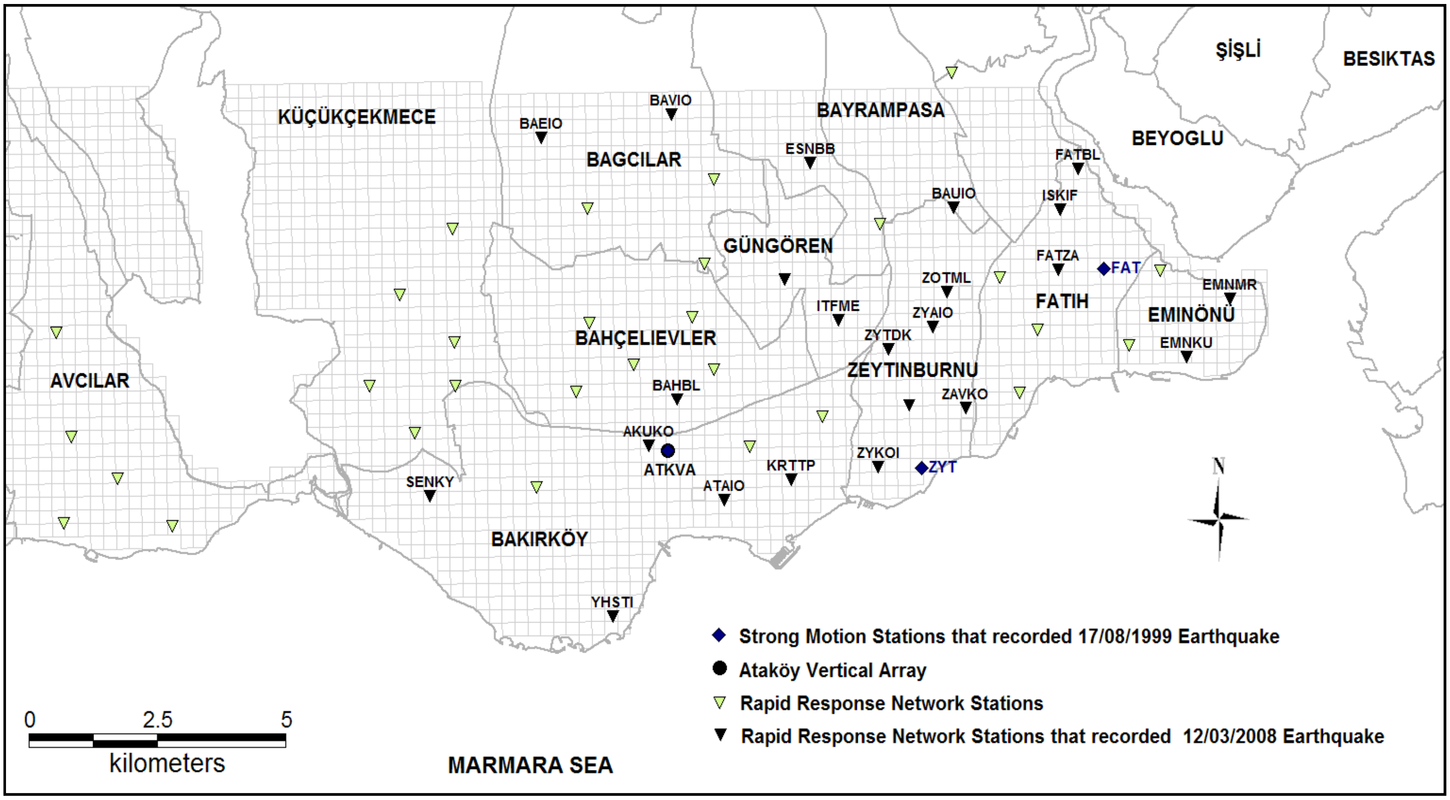

Fig. 1. Strong motion stations of Istanbul Network in the European Side that recorded 12/3/2008 earthquake

An attempt is also made to model the acceleration time histories recorded at Fatih, Zeytinburnu and Ataköy strong motion stations during the 17 August 1999 M_w=7.4 Earthquake based on the detailed soil profiles obtained recently and using the Maslak station record which was situated on the bedrock outcrop.

ISTANBUL RAPID RESPONSE NETWORK

The Istanbul Rapid Response Network is composed of 100 strong motion stations distributed more or less evenly with the metropolitan city of Istanbul. Strong-motion instruments are generally located at grade level in small and medium-sized buildings, such that the motion recorded corresponds to that on the ground in the surrounding area. The main data processing center is located at the Department of Earthquake Engineering - Kandilli Observatory and Earthquake Research Institute of Bogazici University. Full-recorded waveforms at each station can be retrieved using GSM and GPRS modems subsequent to an earthquake (Erdik et al., 2003). Out of 100 rapid response network strong motion stations 55 stations are located within the area where detailed microzonation study was conducted.

Fortunately during the recent years, Istanbul has only experience minor earthquakes. Among these, the highest ground shaking was produced by the M=4.8 earthquake that took place in Yalova (40.84N, 28.99E at 10km depth) on 12/03/2008/18:53:38.5. This event was recorded by 23 Istanbul Rapid Response Network stations out of the 55 that were located in the investigated area as well by the Ataköy vertical array shown in Fig.1. The variations of the PGA values for these 23 stations including the surface record from the vertical array (ATKVA) are shown in Fig.2.

Even though the recorded maximum PGA values are in the order of 9mg, the differences among different stations are significant indicating the effects of site conditions. Similar observations are reported by Hartzell et al., (1997).

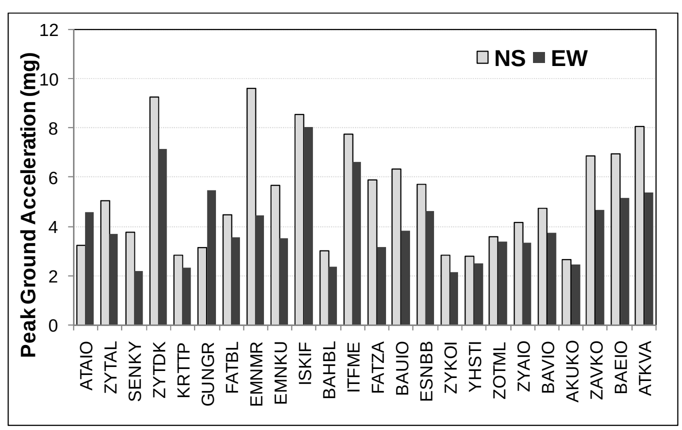

Fig. 2. Variation of PGAs recorded by the 24 stations during 12/3/2008 earthquake

Based on the detailed site investigations conducted for the Istanbul Microzonation Project, it was possible to establish detailed soil profiles with shear wave velocities extending all the way down to engineering bedrock (Vs>750m/sec) for all these 23 stations. One alternative in identifying the site conditions is to adopt average (equivalent) shear wave velocity for the top 30m for each station based on the borings conducted in the near vicinity of all stations as shown in Fig.3.

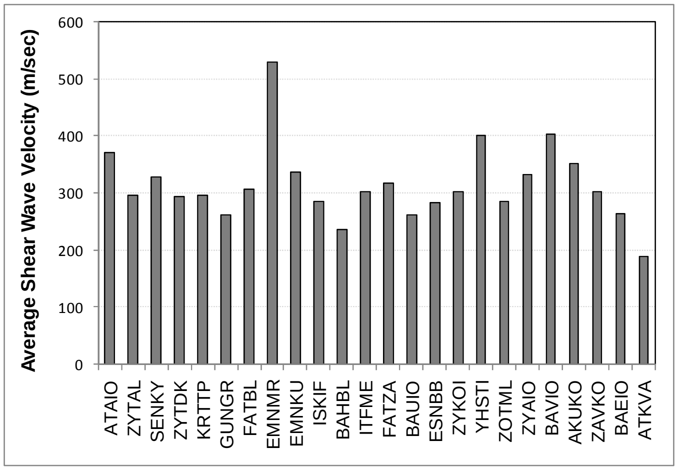

Fig. 3. Variation of average shear wave velocities at 24 stations that recorded 12/3/2008 earthquake

MODELING 12/03/2008 M=4.8 EARTHQUAKE

There are two alternatives in modeling the observed earthquake characteristics on the ground surface. One option is to adopt an empirical approach based on amplification factors such as suggested by Borcherdt (1994) even though the excitation level is very low and not within the suggested range of bedrock excitations. The second option is to use site response analyses using the bedrock motion recorded at 140m depth from the vertical array.

Based on Amplification Factors

The first option adopted was the empirical procedure suggested by Borcherdt (1994) where the peak spectral acceleration for the short period (T=0.2 sec) were determined based on average (equivalent) shear wave velocity using the empirical relationship;

$$S_a = \left(760/v_{s30}\right)^{m_a} * S_S \qquad (1)$$

where S_S is the spectral acceleration at T=0.2s on the rock outcrop, V_{s30} is the average shear wave velocity, and the power coefficient $m_a = 0.35$ when using the lower bound suggested by Borcherdt (1994).

Assuming PGA=S_S/2.5, the PGA calculated for the 24 strong motion stations is compared with the actual recorded values. The comparison of the results in terms of PGA is shown for both EW and NS components in Fig. 4. Considering the simplicity of the method, the PGAs calculated from the empirical procedure can be assumed as reasonable. However, it is also necessary to point out that even though on the average the predictions are reasonable there are significant differences indicating the weakness of the empirical procedure.

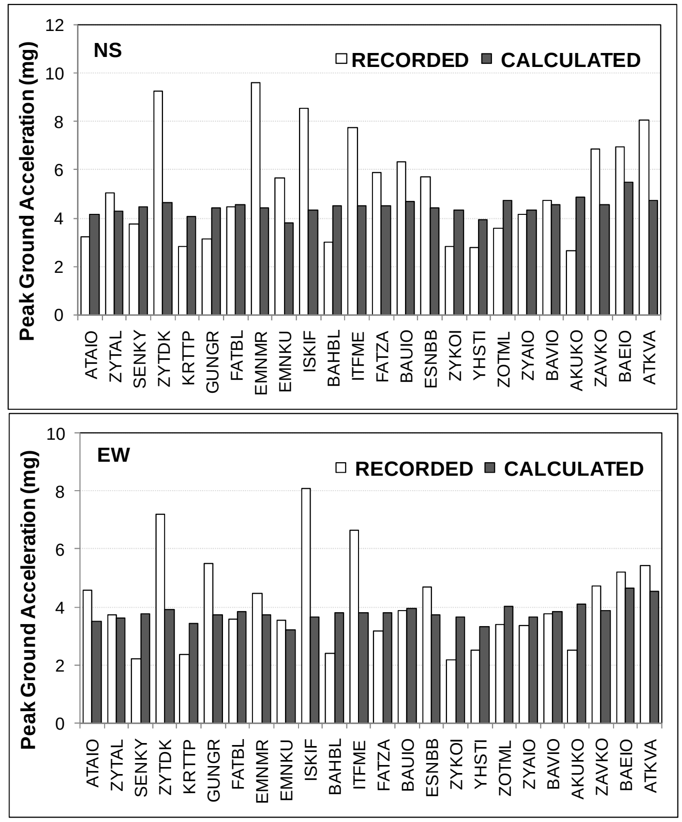

Fig. 4. Comparison of recorded and calculated PGA at 24 stations based on amplification factors

Site Response Analysis

The second option in modeling the observe acceleration time histories on the ground surface is to conduct site response analyses using the acceleration time histories recorded at the engineering bedrock at 140m depth.

Site specific earthquake characteristics on the ground surface for each representative soil profile are calculated using Shake91 (Idriss & Sun, 1992) one dimensional, equivalent linear site response code. One of the issues in one dimensional, equivalent linear site response analyses is the deep soil profiles where even small damping values may affect motion significantly. If site response analysis is to be conducted for large depths, the damping need to be modified such that it reduces with increasing depth, reaching very small values at large depths.

Another issue is related to the effective stress dependency of the modulus reduction and damping relationships used in the analyses. Site response analysis carried out to evaluate the effect of confining pressure dependency on predicted ground motions show that using confining pressure dependent curves results in larger intensity ground motions than those predicted with average generic curves (Darendeli et al., 2001).

Some of the Rapid Response Network stations and vertical array were located on relatively deep soil profiles extending down to 150-200m. Site response analyses were conducted for the soil profiles adopting family of effective stress depending modulus reduction and material damping curves. The curves are developed from the proposed soil model for each sublayer of the soil profiles based on the four parameter model that can be used to characterize normalized modulus reduction and material damping curves developed by Darendeli (2001). This model was based on the hyperbolic soil model originally developed by Hardin and Drnevich (1972).

The four model parameters (reference strain, curvature coefficient, small strain material damping and scaling coefficient) are calculated for the soil plasticity and loading conditions to estimate the modulus reduction and material damping relationships.

Generally, equivalent linear analysis has a tendency to give larger peak acceleration and shear stress under large earthquakes, and lower amplification in high frequency range. The reason of the latter phenomena is due to the evaluation of damping ratio from the effective strain that happens to be too large for small amplitude (high cycle) vibrations. This effect becomes dominant under the small to medium earthquakes, resulting in smaller accelerations (Yoshida et al., 2002).

Shake91 site response code is modified to account for the frequency dependent characteristics of the modeled ground motions adopting methodology suggested by Sugito et al. (1994). Sugito et al. (1994) improved lower amplification in high frequency range of the equivalent linear analysis by defining frequency dependent characteristics of the effective strain (γ_{eff}) in each frequency component as;

$$\gamma_{eff} = \alpha \frac{F(f)}{F_{\max}} \gamma_{\max} \qquad (2)$$

where *F(f)* denotes Fourier amplitude of shear strain emphasizing its dependence with respect to frequency *f*, and F_{max} denotes maximum value of *F(f)*. Although physical meaning of Eq. (2) is not very clear, this modification sometimes improves equivalent linear analysis significantly. Ueshima and Nakazono (1996) reported that the deconvolution of the vertical array record at Lotung site, Taiwan is well simulated by this method. It was mentioned that this procedure sometimes may not converge when the actual Fourier strain amplitudes are used to calculate the effective strain by means of Eq. (2). Therefore, it may be necessary to smooth the Fourier spectrum to avoid this possibility. However in that case, the results will depend on the method of smoothing.

This modification may improve lower amplification in high frequency ranges in the equivalent linear analysis by defining the effective strain in each frequency component as given in Eq. (2). This approach was adapted to Shake91 code based on the actual Fourier strain amplitude in calculating the effective strain to avoid the effect of smoothing.

Site response analyses were conducted for all 24 soil profiles using EW and NS components of acceleration time histories recorded at 140m depth in the Ataköy vertical array. The observed and calculated results are shown in Fig. 5 for EW and NS directions separately.

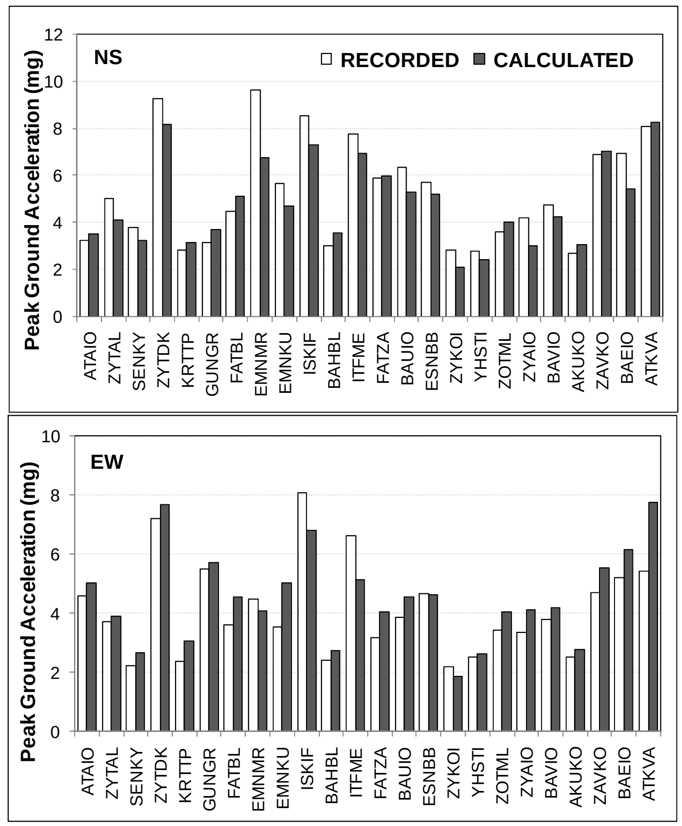

Fig. 5. Comparison of recorded and calculated PGA at 24 stations that recorded 2/3/2008 earthquake

As expected site response analyses gave closer results compared to the empirical approach (Fig.4). This is most likely due to more detailed site characterization in site response analysis while V_{s30} may not be sufficient as a single parameter. However, the empirical relationship formulated by Borcherdt (1994) was based on much higher level of shaking intensity, while the adopted 1D site response analyses is expected to model site response more accurately in elastic range under low acceleration levels (Ansal and Tonuk, 2007).

The calculated and observed ground motion characteristics are also compared with respect to acceleration response spectra as shown in Fig.6. Even though it was possible to model the recorded acceleration response spectra approximately with respect to peak spectral accelerations, it was not possible to model the variation of spectral accelerations with frequency. This may be partly due to the very low level of ground shaking intensity that may be affected by different waves and use of rather simple approach by adopting 1D site response analysis based on shear wave propagation (Ansal, 1999).

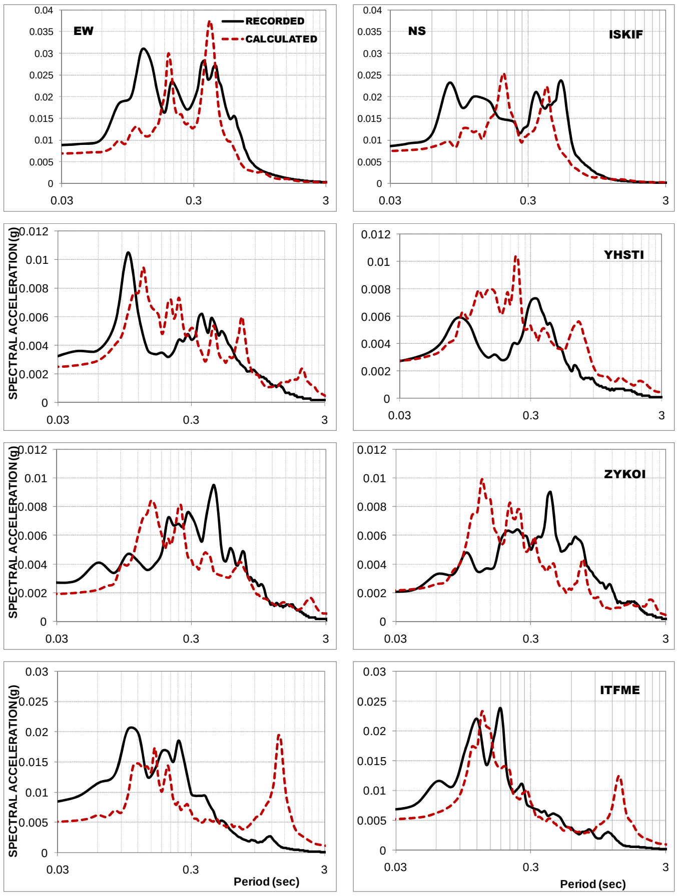

Fig.6. Comparison of recorded and calculated acceleration response spectra based on site response analyses

VERTICAL ARRAY

Ataköy vertical array is composed of four downhole triaxial accelerometers located at the depths of 50m, 75m, 140m and one on the ground surface. The modeling studies for this array are limited to the recorded small magnitude earthquakes. EW and NS components of 12/03/2008 M=4.8 and 27/04/2009 M=4.1 Yalova earthquakes recorded by the vertical array is modeled using Shake91 (Idriss & Sun, 1992) that was modified to account for stress and frequency dependence of the modulus reduction and damping relations.

One of the options in utilizing the vertical array records obtained during small earthquakes is the potential to fine tune the soil shear wave velocity profiles to improve the site models. This approach was adopted in modeling the recorded acceleration time histories at the depths of 50m, 75m and on the ground surface using the recorded acceleration time history at 140m depth as input. The site conditions at the vertical array station were studied in detail based on in-situ PS Logging tests and microtremor array measurements (Parolia et al., 2009a; 2009b; Bindi, et al., 2009). The modeling study for the Ataköy array is performed based on EW and NS components of 12/03/2008 M=4.8 earthquake. Modeling of all recorded six acceleration time histories is achieved by trial and error procedure by slightly modifying the insitu measured shear wave velocity values without changing the soil stratification and layer thicknesses.

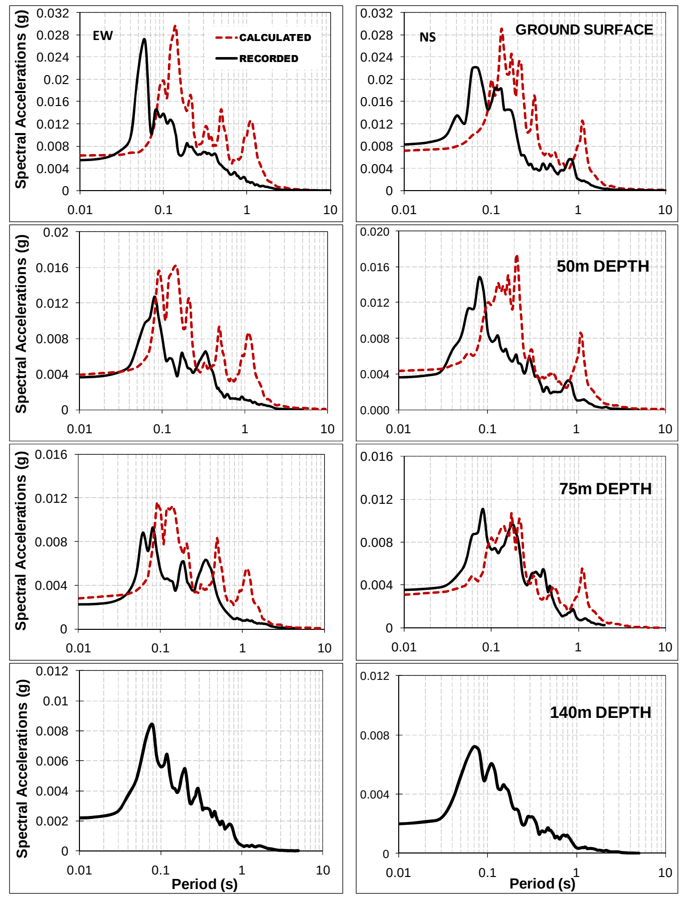

Fig. 7. Calculated and observed acceleration response spectra for the 12/03/2008 M=4.8 earthquake in the Ataköy vertical array at the ground surface, -50m and -75m

Since the recorded earthquakes are of small magnitude, only elastic amplification was observed in the vertical direction with no shift of the spectral peaks due to soil nonlinearity. As shown in Fig.7, it was possible to model approximately spectral amplitudes, but it was not possible to model the elastic acceleration response spectra very accurately. Even though acceleration response spectra at 140m depth were very similar in EW and NS direction, this similarity is not observed in the other records obtained on the ground surface, at 50m and 75m depths. Thus mathematically it is very difficult to model this change in the spectral shapes using the same soil profile and similar input acceleration time histories. As expected elastic acceleration response spectra calculated at different depths were similar in shape in the vertical direction. There is also difference in the predominant periods corresponding to the calculated peak spectral accelerations which happens to increase in the vertical direction towards the ground surface. This issue needs to be studied in detail to better evaluate the frequency dependence.

An attempt is made to model acceleration time histories recorded by the vertical array during the 27/04/2009 M=4.1 Yalova earthquake based on the soil shear wave velocity profile that was defined by modeling the acceleration time histories recorded during the 12/03/2008 M=4.8 earthquake as shown in Fig.8. The EW and NS components on the bedrock level was significantly different for this event as demonstrated in Fig.8 even though the epicenter locations of both events are very close to each other which to a certain extend eliminates the effect directivity. As can be observed, the calculated acceleration response spectra at 75m depth are very similar to the acceleration response spectra of the recorded acceleration time histories. However, this good agreement is not observed at 50m and on the ground surface.

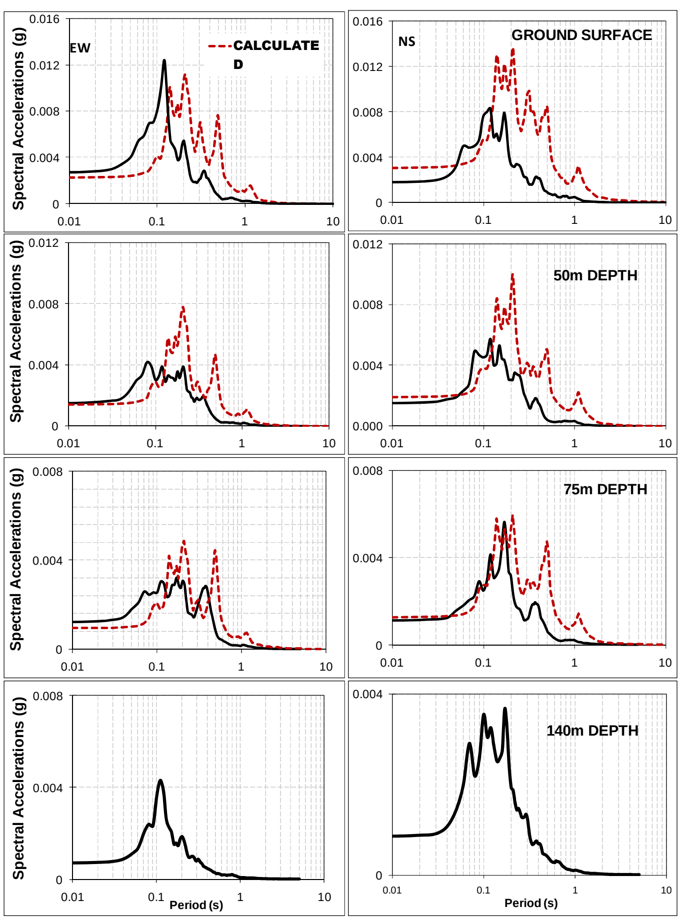

Fig. 8. Calculated and observed acceleration response spectra for the 27/04/2009 M=4.1 earthquake in the Ataköy vertical array at the ground surface, -50m and -75m

MODELING 17/08/1999 M=7.4 EARTHQUAKE

Acceleration time histories were recorded at strong motion stations located in different parts of Istanbul during 1999 Kocaeli Earthquake. Even though the epicenter and related fault rupture were approximately 100km away, peak ground accelerations were in the range that may induce nonlinear soil behavior at three soil stations namely Zeytinburnu, Ataköy, and Fatih. The spectral ratios and peak ground acceleration ratios with respect to the reference rock site at Maslak (MSK) for these three stations for the Kocaeli Earthquake main shock (Mw=7.4) and for two aftershocks (ML=5.8 and 4.4) were calculated to determine if nonlinear site behavior can be observed (Ansal &Tonuk, 2006).

In terms of PGA ratios only Fatih station records follow the expected decreasing trend with the increase in the magnitude (Fig.9). However, strong motion amplification ratios for three soil sites are below the average value of weak motions. This can be regarded as one indication of soil response nonlinearity (Higashi and Sasatani, 2000). In terms of spectral ratios, the same trend was also observed for the records obtained in Fatih station.

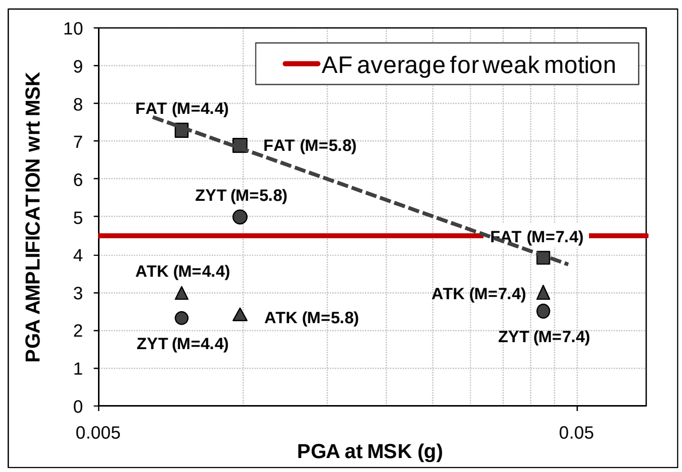

Fig. 9. PGA amplification ratios for the Istanbul strong motion soil stations (FAT, ATK, ZYT) with respect to PGA at rock station (MSK) during main event and weak ground motion records

Table1. PGA amplification ratios (AR) with respect to MSK

Station	Direction	PGA (g)	AR (M4.4)	Ratio of [AR (M7.4)/AR (M4.4)]
Zeytinburnu	NS	0.104	1.7	1.349
	EW	0.111	3.3	0.825
Ataköy	NS	0.099	2.8	0.798
	EW	0.157	3.3	1.184
Fatih	NS	0.183	7.5	0.552
	EW	0.151	7.0	0.530

In terms of PGA amplification ratios as given in Table 1, there was no nonlinearity in the site response in Zeytinburnu and Ataköy stations however nonlinearity was observed at Fatih during the Kocaeli Earthquake main shock of 17 August 1999.

Even though the difference in the level of peak accelerations recorded at Ataköy (0.157g) compared to Fatih (0.183g) is not significantly different, most likely due to the differences of site conditions nonlinear response was observed at Fatih site. The average shear wave velocities, $V_{s,30}$ for strong motion sites FAT, ATK and ZYT are computed as 287, 369 and 336 m/sec, respectively. The ATK station with the highest average shear wave velocity can be considered as the site among the others which may behave more linearly under similar shaking intensities.

An attempt is made to model the observed earthquake characteristics on the ground surface for ATK, FAT, and ZYT since detailed soil profiles became available very recently due to the installation of new vertical arrays and soil explorations conducted for the Istanbul Microzonation Project.

In the case of Ataköy (ATK) record during 1999, it was possible to test the validity of the site response methodology and site characterization utilized in modeling the site response during the M=4.8 event that took place on 12/03/2008 (Fig.7). The same soil profile and the same analysis code (Shake91) are used to model the recorded earthquake characteristics during the 1999 M_w=7.4 Kocaeli Earthquake using the Maslak (MSK) record as the input motion on the rock outcrop. The acceleration response spectra of the recorded motion and acceleration response spectra of the calculated surface motion are shown in Fig.10.

The spectra in both EW and NS directions is remarkably similar indicating to a certain extend that the soil profile fine tuned based on small earthquakes could be used for modeling and predicting site response during strong earthquakes. However, as summarized above based on two aftershocks and based on peak ground acceleration ratios, the observed site response at Ataköy was mostly in the linear range with no evident nonlinearity. Therefore this assumption needs to be checked in the case of stronger ground shaking in order to observe it validity in broader range.

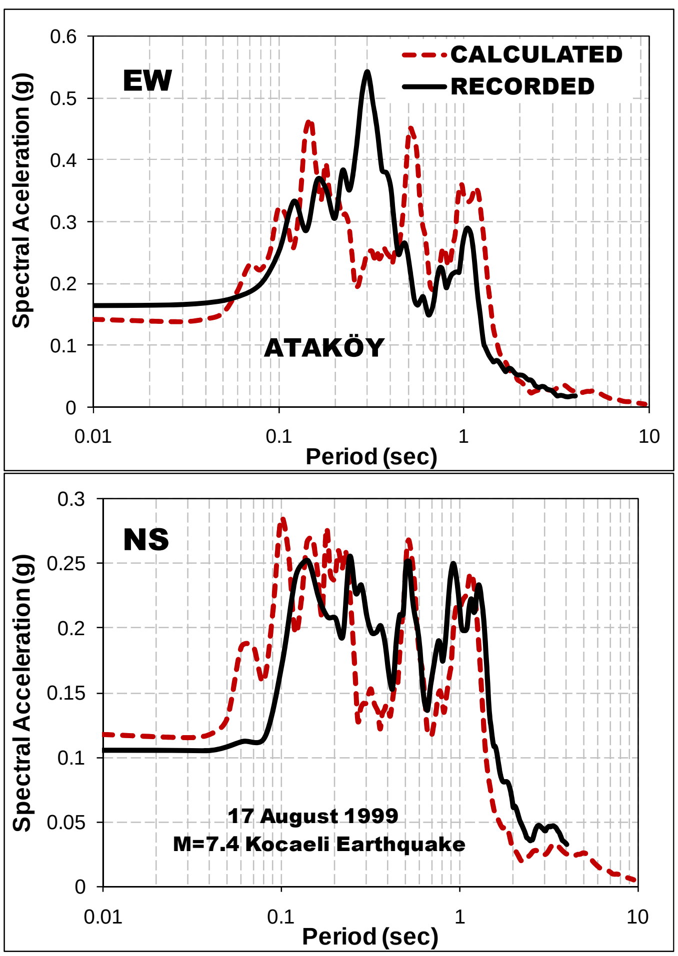

Fig. 10. Calculated and observed acceleration response spectra for the 17/08/1999 M=7.4 earthquake in the Ataköy station at the ground surface

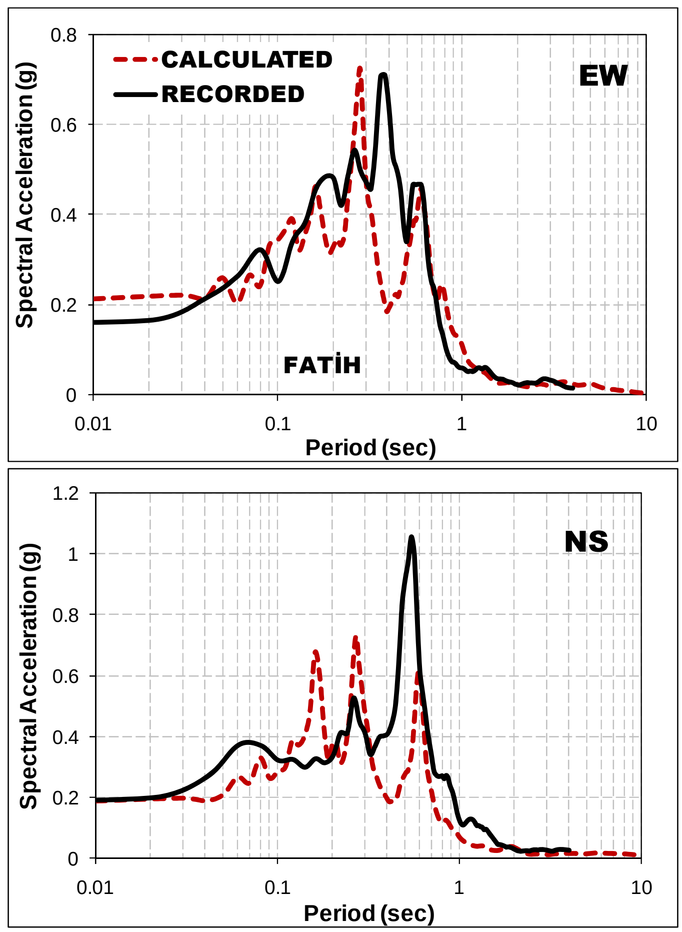

Fig. 11. Calculated and observed acceleration response spectra for the 17/08/1999 M=7.4 earthquake in the Fatih station at the ground surface

An attempt is also made to model the recorded earthquake characteristics during Mw=7.4 Kocaeli Earthquake in Fatih (FAT) and Zeytinburnu (ZYT) using the Maslak record as input motion on the rock outcrop. Unfortunately it was not possible to fine tune the soil profiles based on vertical array records at the present. However, two new vertical arrays are being installed at Fatih and Zeytinburnu and it will be possible to attempt to carry on similar analyses in the future.

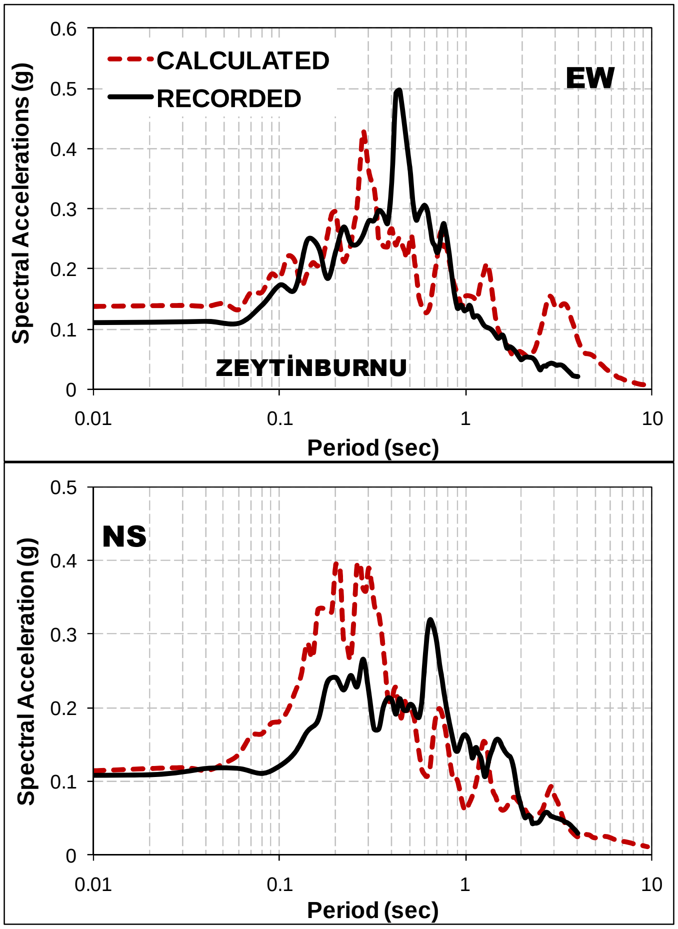

Fig. 12. Calculated and observed acceleration response spectra for the 17/08/1999 M=7.4 earthquake in the Zeytinburnu station at the ground surface

Using the presently available detailed soil profiles, recorded earthquake characteristics during Kocaeli Earthquake are modeled using the modified version of Shake91. The similarity between the calculated and recorded acceleration response spectra at both stations supports the validity of the adopted approach as shown in Fig.11 and Fig.12.

CONCLUSIONS

The extensive site investigation study carried out in the European side of Istanbul was used to define the local site conditions at the 23 stations of the Istanbul Rapid Response Network that recorded 12/3/2008 earthquake with local magnitude of M=4.8. The acceleration time histories recorded by the 23 Rapid Response stations as well by the Ataköy vertical array stations were used to model the recorded motion characteristics in terms of peak ground accelerations and acceleration response spectra using the recorded acceleration time histories on the engineering bedrock. The recorded acceleration time histories are modeled based on an empirical site amplification relationships proposed by Borcherdt (1994) and based on the modified version of Shake91 (Idriss and Sun, 1992). The results indicate the suitability of the site response analyses in modeling the observed variation with respect to peak ground acceleration. The attempt made to model the recorded acceleration time histories during the M_w=7.4 1999 Kocaeli Earthquake recorded at Ataköy station was rather successful indicating the suitability of the vertical arrays in fine tuning the measured shear wave velocity profiles for modeling and prediction at higher ground shaking levels. Preliminary modeling conducted for the Fatih and Zeytinburnu station records during the Kocaeli 1999 Earthquake using the Maslak record as rock outcrop motion gave also reasonable and promising results that could be improved once new vertical arrays are established at these two sites.

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