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SITE RESPONSE NONLINEARITY BASED ON CASE STUDIES

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ABSTRACT

In recent years, during the major earthquakes in Turkey (1995 Dinar, 1999 Kocaeli, and 1999 Düzce), acceleration time histories were recorded with relatively high peak ground acceleration levels. Boreholes were conducted in the near vicinity of these recording stations with in-hole seismic shear wave velocity measurements during the post earthquake investigations. The soil response nonlinearity is evaluated based on these geological, geotechnical and seismological data for Dinar and Istanbul (Fatih, Zeytinburnu and Atakoy) strong motion stations. The nonlinear site response was first evaluated based on the recorded strong-motion data. The peak horizontal accelerations and spectral amplitudes recorded on soil and on nearby rock outcrop sites were compared during main shock and aftershocks and when appropriate reference rock site was not available the spectral ratio of horizontal to vertical ground motion were used to assess site response nonlinearity. The results obtained are discussed with respect to soil nonlinearity and the level of ground shaking intensity that would induce nonlinearity.

Keywords: site response, nonlinear soil behaviour, strong motion

INTRODUCTION

Acceleration records obtained during recent earthquakes have demonstrated that certain source factors such as fault type, rupture mechanism, rupture directivity, and fault orientation as well as geotechnical site conditions such as soil stratification, depth of ground water table, and properties of soil layers could have significant influence on strong motion characteristics. The parameters used in the conventional seismic design and analysis, design spectrum and design acceleration, may not characterize this complexity of the earthquake generated strong ground motions. Dynamic analyses performed using site specific acceleration time histories may be better suited to model earthquake ground motions.

The seismic hazard analysis involves the estimation of earthquake characteristics on the ground surface at the selected site to be used for the engineering analysis. The first option to account for the effects of local soil conditions in hazard analysis is to use contemporary attenuation relationships formulated in terms of site and source classifications. The second option is to use empirical amplification factors like site parameters as suggested by Borcherdt (1994) and Crouse and McGuire (1996). The third option is to adopt a comprehensive approach in estimating site specific earthquake characteristics based on site response analysis using a more detailed site characterization (Heuze et al., 2004). Taking into consideration the possible differences in soil profiles even within relatively short distances and observations in previous earthquakes that site conditions are important (Field & Hough 1997, Hartzell et al. 1997), it may be more reliable to adopt the third alternative for the assessment of site-specific ground motion characteristics.

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One of the important issues in specifying site specific input design motion is to account for nonlinearity in site response which will be dependent on expected earthquake source and existing site characteristics. This issue has been source of debate among researchers (Idriss, 1991; Aki, 1993; Yu et al., 1993; Wen, et al., 1994; Elgamal et al., 1995; Kazama, 1996; Chin and Aki, 1991; Beresnev and Wen, 1996; Aguirre and Irikura, 1997; Su et al., 1998, Beresnev et al., 1998; Higashi & Sasatani, 2000; Bonilla et al., 2005).

Soils behave nonlinearly when subjected to strong levels of ground shaking. The effect of nonlinearity is to reduce the amount of amplification as the input ground-motion level is increased. This phenomenon is due to the increase in hysteretic damping and degradation and softening in soils with strain accumulation. At low strain levels, the relationship is essentially elastic.

In geotechnical engineering field, it is well established by laboratory and field tests that stress – strain relationships of soils is strain dependent, nonlinear and hysteretic, especially for large shear strain levels. However, evidence of nonlinear site response in seismological observations has been observed more recently with increasing number of good quality strong motion data.

The purpose of this paper is to evaluate the site response nonlinearity at some recording stations during the recent major earthquakes in Turkey based on available geotechnical and strong motion data. The acceleration time histories recorded during major earthquakes in recent years in Turkey Dinar 1995 and Kocaeli 1999 were evaluated for estimating site response nonlinearity.

NONLINEAR SOIL BEHAVIOUR

Observations indicate that properties of soil layers could be modified due to cyclic stresses induced by earthquake ground motion. Cyclic tests conducted on undisturbed samples as well as the field evidence have shown degradation of soil stiffness and shear strength characteristics of local soil layers with shear strain accumulation. In evaluating the behaviour of soils under cyclic stresses, one alternative is to consider stress-strain and shear strength properties separately. Dynamic shear modulus, damping ratio, and their variation with shear strain may be regarded as the dynamic stress-strain properties of soils. Cyclic stress amplitudes and number of cycles leading to failure or excessive deformations may be defined as dynamic shear strength characteristics. The results obtained from cyclic laboratory tests conducted on undisturbed samples subjected to different shear stress amplitudes and different loading patterns indicate the presence of threshold cyclic shear stress amplitudes with respect to elastic, elasto-plastic and plastic behaviour. In addition, the degradation of soil stiffness and accumulation of excess pore pressures may cause significant reduction in shear strength and may induce bearing capacity and slope failures as well as additional settlements as observed in many locations after the 1999 Kocaeli earthquake.

An important interpretation of the observed cyclic soil behaviour was the suggestion of two shear strain threshold levels, the first one as the beginning point of nonlinear behaviour and the second one as the beginning point of inelastic behaviour (Vucetic, 1994). Another important observation was the effect of soil plasticity expressed in terms of plasticity index on the degradation of dynamic shear modulus and damping ratio with respect to shear strain amplitude (Vucetic and Dobry, 1991).

A series of stress controlled multistage triaxial tests were conducted on normally consolidated undisturbed clay samples obtained from a boring in Izmit after the 1999 Kocaeli Earthquake (Okur and Ansal, 2004). The maximum shear modulus, G_{max}, as well as the modulus reduction and increase of damping ratio for each sample were determined to evaluate the threshold cyclic shear stress levels as shown in Figure 1.

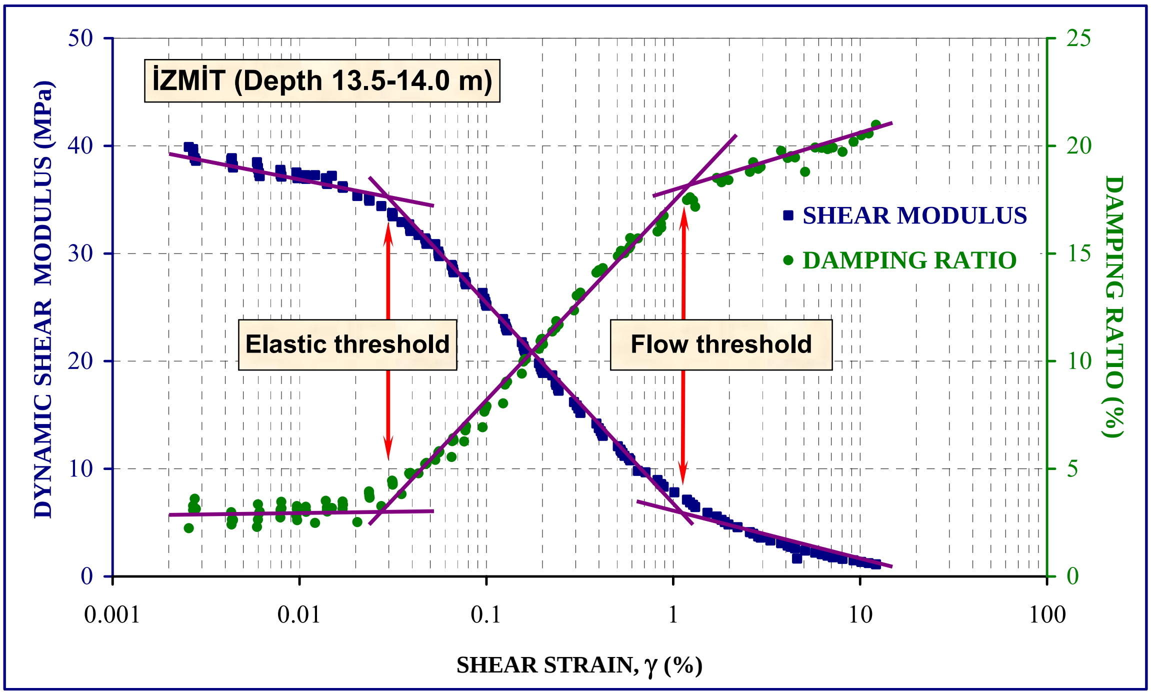

Figure 1. Variation of shear modulus and damping ratio with shear strain for a soil sample

It appears suitable to treat the cyclic stress-strain behaviour of soils in three consecutive stages. In the first stage, the soil sample will respond elastically without any significant reduction in its stress-strain and shear strength properties. The imposed cyclic stresses are small thus induced cyclic strain amplitudes are insignificant. If the imposed cyclic stress levels were lower than the elastic threshold, the reduction of the dynamic shear modulus as well as the post cyclic shear strength would be negligible. Once the elastic threshold is exceeded, the soil sample will respond in elasto-plastic manner. This can be considered as the second stage in the cyclic behaviour of soils. During this stage the induced cyclic shear strains would lead to strain softening, particle structure breakdown, and pore pressure accumulation leading to rapid deterioration of stress-strain and shear strength characteristics up to the flow threshold. If the flow threshold is exceeded, the soil sample would experience large strain amplitudes due to the significant reduction of the dynamic shear modulus. This third stage can be considered as the transition to the steady state in the cyclic behaviour of soils.

NONLINEARITY IN SITE RESPONSE

Due to the nonlinear behaviour of soils, amplification factors are dependent on the intensity of shaking. This can be demonstrated by comparing the amplification factors for a soil site with respect to a reference rock site using acceleration time history data of different magnitudes representing weak and strong motions. Reference station is selected as a nearby site of outcropping rock. The amplification factors are reduced with increasing shaking intensity, resulting from reduced shear modulus and increased damping. The relationship between peak accelerations on soil sites with respect to reference rock sites is also an indicator of nonlinearity in site response. The increased nonlinearity of soft soil response at higher accelerations reduces the amplification factors.

When a suitable reference rock site could not be found in an acceptable vicinity of the soil site of interest, another technique not depending on reference site named as horizontal to vertical spectral ratio method (HVSR) can be used to assess site amplifications. Recent search results imply that the HVSR technique is sensitive to ground-motion intensity and can be used to detect and study nonlinear site response (Dimitriu et al., 2000; Wen et al., 2006).

The frequency content of strong motion on the ground surface is much more affected by site conditions. From an engineering perspective, the shift in the predominant frequency of strong ground motions can be evaluated based on spectral ratio methods.

Dinar Case Study

The earthquake sequence that affected Dinar was composed of small to medium size foreshocks, main shock, and aftershocks. The foreshocks started on September 26, 1995 and the main shock (M_s=6.1) took place on October 1, 1995 followed by large number of aftershocks. Table 1 lists the data for the selected events recorded in Dinar station. The fault plane solutions indicate a normal faulting with a strike of N130E and a dip of 41°. The hypocenter of the earthquake was located right under Dinar with a focal depth of 24 km (Eyidogan and Barka, 1996; Durukal et al., 1998).

A detailed geotechnical investigation composed of in-situ penetration tests; seismic wave velocity measurements by suspension PS Logging technique were carried out to determine the soil stratification and soil properties by the Dinar strong motion station (Ansal et al. 1997). The ground water table is almost at the ground surface. As shown in Figure 2, the soil profile consisted mostly of sandy, silty clay layers with shear wave velocities ranging between 150-250 m/sec in the top 42 m. Very stiff and dense sandy clayey gravel layer with shear wave velocities around 600 m/sec was encountered below this depth (Ansal, 1999).

Fourier Amplitude Spectra of some events selected from Table 1 with magnitude range of M=4.0 to M=6.0 are shown in Figure 3. Shift of the fundamental frequencies to lower values can be observed with increasing magnitudes.

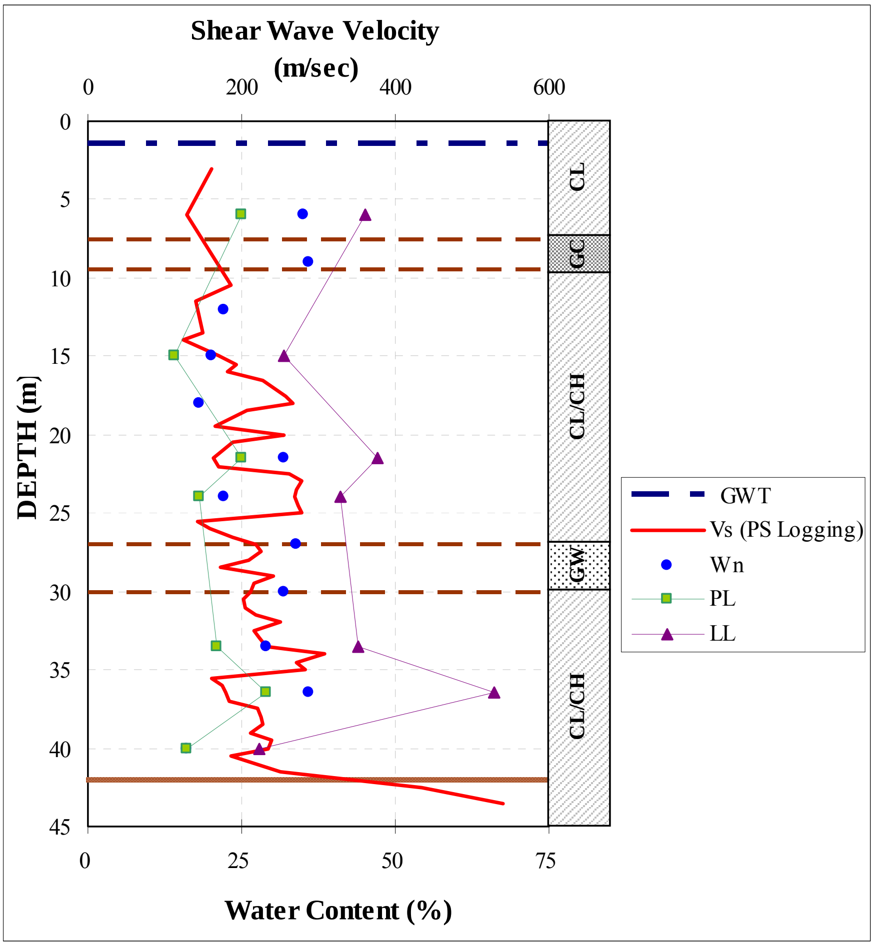

Figure 2. Soil profile at Dinar strong motion station

Table 1. Selected events recorded at Dinar Station

TIME		M_L	PGA (g)	
			NS	EW
"Strong"	26/9/14:58	4.6	0.100	0.182
	27/9/14:15	4.7	0.089	0.188
	1/10/15:57	6.0	0.279	0.356
	1/10/18:02	4.9	0.214	0.116
	1/10/21:14	4.2	0.084	0.174
	3/10/7:38	4.3	0.070	0.146
	5/10/16:15	4.6	0.092	0.137
	6/10/16:15	4.4	0.090	0.170
	4/4/98/16:17	4.6	0.137	0.135
	26/9/15:18	4.6	0.100	0.182
"Weak"	26/9/15:18	4.1	0.056	0.085
	28/9/13:26	4.0	0.037	0.036

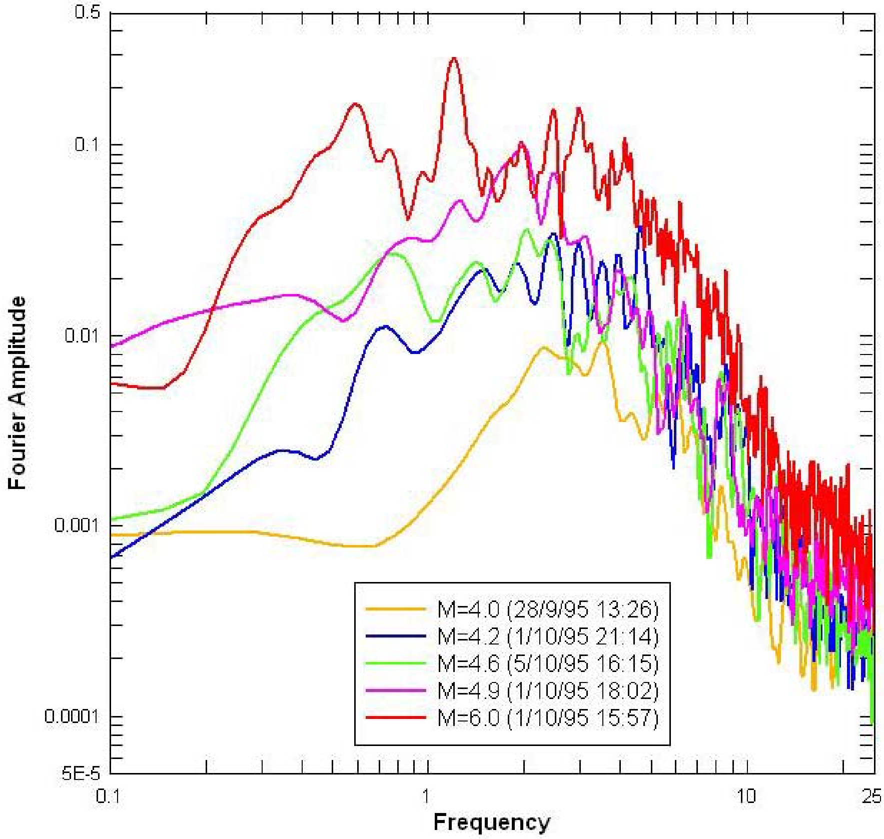

Figure 3. Fourier Amplitude Spectra at Dinar strong motion station for the main event-selected foreshock and aftershocks

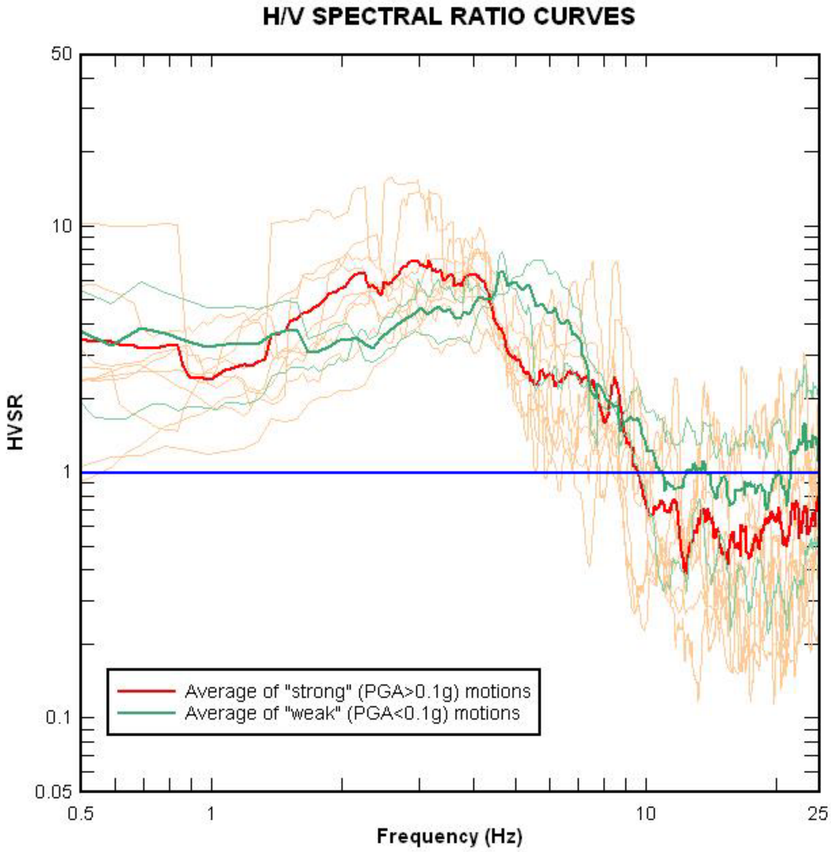

Figure 4. Mean HVSR curves for the strong and weak motions recorded at Dinar station listed at the right of the figure

Typical nonlinear effects are known as deamplification of strong motion and the decrease of the fundamental frequencies of soil deposits. Deamplification of strong motion was evaluated in Dinar strong motion station data by applying the horizontal-to-vertical spectral ratio (HVSR) technique. Smoothed average spectrum of the two horizontal motions was divided by the vertical motion spectrum (Figure 4). This ratio only reflects site effects in the ground motion, independent of source and path. The recordings given in Table 1 represent 12 earthquakes (M_L=4.0-6.0); PGA varies between 0.036-0.356g. In order to assess nonlinearity, selected recordings for this station were divided into two groups to represent weak and strong motions. Mean H/V spectra curves are calculated for weak (PGA<0.1g) and strong motion (PGA>0.1g). The weak (linear) and strong (nonlinear) motion responses show some differences. Between 1.45 and 4.4 Hz, the nonlinear response exceeds the linear one. Above this frequency, the average strong motion ratio stays below the average of weak motion ratio except for a very short frequency range (8-8.5 Hz). For frequencies larger than 9.5 Hz, nonlinear response drops below unity (deamplification) which may also indicate nonlinearity. As also shown in Figure 4, H over V ratio of events with magnitude range of M=4.0 to 6.0, shift of the fundamental frequencies to lower values can be observed with increasing excitation strength.

Istanbul Case Study

Acceleration time histories were recorded at strong motion stations located in different parts of Istanbul during 1999 Kocaeli Earthquake. Even though the epicentre and related fault rupture were approximately 100km away, peak ground accelerations were in the range that may induce nonlinear soil behaviour at three soil stations namely Zeytinburnu (0.12g), Ataköy (0.16g), and Fatih (0.19g). 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 behaviour can be observed.

In terms of PGA ratios only Fatih station records follow the expected decreasing trend with the increase in the magnitude (Figure 5). 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 is also visible for the records obtained in Fatih station.

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 1999 Kocaeli Earthquake main shock of 17 August 1999.

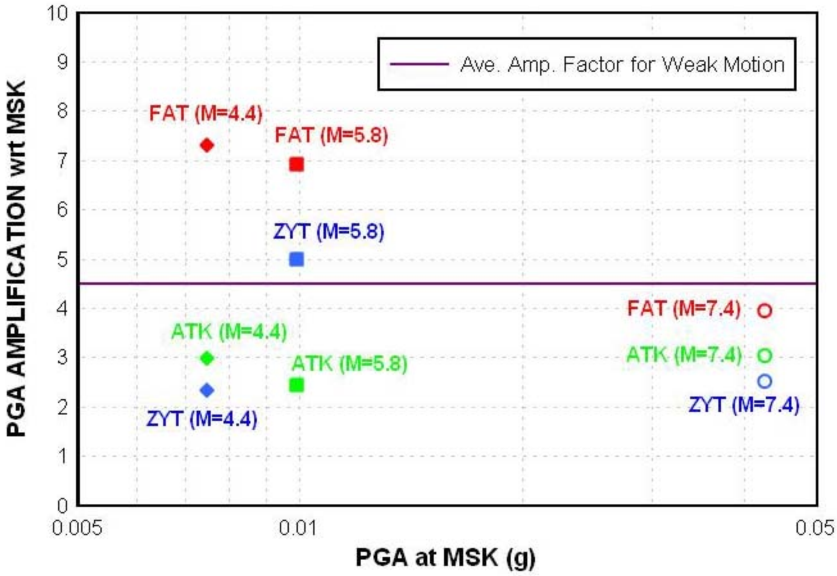

Figure 5. PGA amplification ratios for the Istanbul strong motion soil stations (FAT, ATK, ZYT) with respect to PGA at rock station (MSK) during main event (transparent symbols) and weak ground motion (solid symbols) records

Table 2. Amplification ratios (AR) in terms of PGA 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

Figure 6 shows the spectral amplification ratios for main event (strong motion) to average of the aftershocks (weak motions). Especially, at Zeytinburnu and Fatih stations in EW direction, the amplification factor for strong motion become smaller than those for weak motions. This nonlinear site response evidence can not be observed clearly in the amplification ratio curves for Ataköy.

Even though the difference in the level of peak accelerations recorded at Ataköy (0.157g) compared to Fatih (0.183g) is not significant 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.

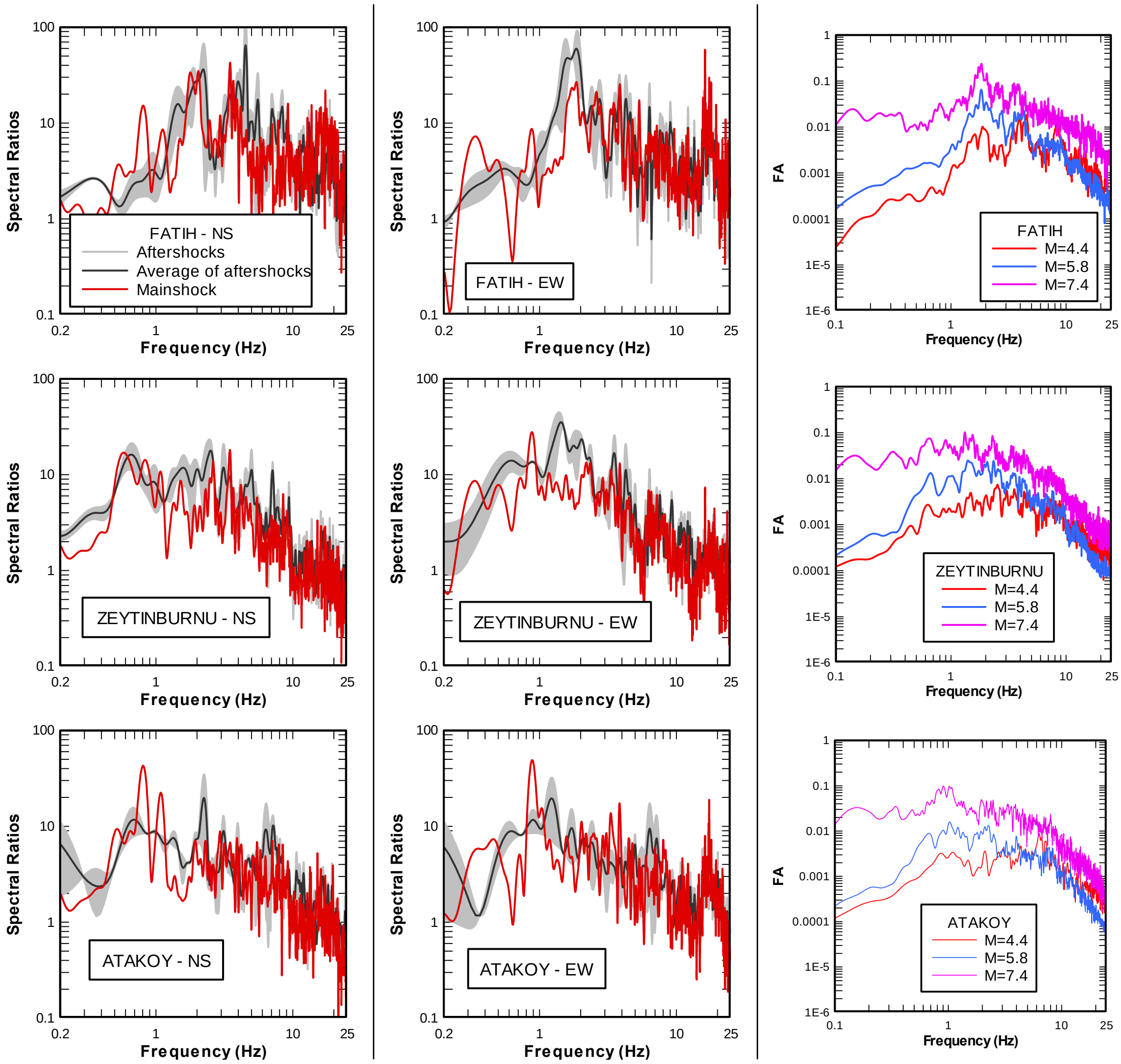

Figure 6. Spectral ratios for the Istanbul strong motion stations (FAT, ATK, ZYT) for strong and average of weak ground motion records with respect to Maslak reference rock site, and Fourier Amplitude Spectra at these stations

CONCLUSIONS

The earthquake strong motion characteristics on the ground surface are affected by the local site conditions especially in the case of softer alluvial deposits. Soil layers depending on their properties could demonstrate nonlinear response even under relatively low acceleration levels thus modifying the strong ground motion on the ground surface.

Typical nonlinear effects are deamplification of strong motion and the decrease of the fundamental frequencies of soil deposits. It is possible to observe the nonlinear site response in terms of amplification ratios with respect to peak ground accelerations or spectral amplitudes calculated for weak and strong ground motion records. The spectral ratio technique can be selected as SSR or HVSR according to the absence of reference rock site.

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