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Site Effects Estimation in Tehran City by Using Empirical Methods

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ABSTRACT

In this paper, site effects assessment in Tehran city, the capital of Iran, were estimated by using empirical methods. Both spectral ratio of the horizontal components of sedimentary site to rocky site (Hs/Hr) or site/reference, and Horizontal to Vertical Spectral Ratio (HVSR) methods have been used for estimation the site effects parameters. For this purpose, the recorded motions in BHRC (Building and Housing Research Center) acceleration stations were analyzed. These motions were recorded from Changureh-Avaj (2002), Tehran (2003), Firozabad-Kojour (2004) and Kahak-Qom (2007) earthquakes, which have been occurred near to the Tehran city. Some of these motions recorded in rocky stations and were used for site/reference (Hs/Hr) analysis. Site predominant frequency and soil amplification factor in various frequency ranges were estimated in each station by using calculated amplification functions by two empirical techniques. The results reveal a large contribution of site effects on ground motion at the majority of the studied sites. The value of predominant frequency in southern part of city is less than northern part. Therefore, the level of damage in southern part might be increased and short frequency structures, such as high-rise buildings and long span bridges might be strongly affected by the site effects in this part of the city.

INTRODUCTION

During an earthquake surface sedimentary layers can significantly intensify earthquake motion parameters; this phenomenon is known as site effects. The effect of soil characteristics in earthquake is one of the most important factors in geotechnical earthquake engineering. Soft sedimentary layers can strengthen or weaken intensity of earth movements in specific frequency ranges under the influence of earthquake. Strengthening or weakening of frequency range under the effect of local sediments depends on thickness and shear wave velocity of soil layers. Also, strong ground motions event in a small distance leads to significant changes in dynamic properties of subsurface layers (Boatwright et al., 1991).

Different methods have been proposed for site effects assessment and analysis, which are employed both for seismic microzonation and earthquake risk evaluation in special structures (Ghayamghamian, 1997). Generally there are two major methods for site effects assessment, empirical and theoretical methods. In the empirical methods, which are often based on spectral ratio analysis in the frequency domain, dynamic characterization of surface layers is determined. There are various types of spectral ratios for estimation of site amplification characteristics using earthquake data, such as standard site/reference method (Borcherdt, 1970), HVSR (Nakamura, 1989), and uphole to downhole spectral ratio in downhole arrays (Ghayamghamian and Kawakami, 1996). In these methods dynamic characteristics of surface layers such as amplification function and dominant frequency are calculated directly from analysis of earthquake data, microtremor measurements, and downhole arrays in specific area. Whereas, in theoretical methods which are based on boring investigations, the results of geotechnical and geophysical tests such as shear wave velocity profile, layer thickness and density are used in numerical modeling and site effects assessment. In most cases, boring investigations which are costly and time consuming are needed to accurate formulating of soil characteristics and models. Therefore, in an area if sufficient real data such as recorded earthquake motions or microtremor measurements be available, empirical methods can be appropriate for site effects analysis.

Considering the high population density, high seismic activity, and political situation it was necessary to study the site effects for Tehran city, the capital of Iran. Different investigations had been focused on site effects assessment and seismic microzonation studies in Tehran (JICA, 2000; Jafari et al, 2002). In most of these studies site effects analysis performed based on theoretical method, then by using geotechnical and geophysical tests site effects assessment results were given in terms of site amplification factor, dominant frequency, and seismic microzonation map. In addition, due to lack of the recorded data from previous earthquakes, the accuracy and validity of these analyses have not been verified. Recently most researches have been directed towards using empirical methods in analysis of recorded data from recent instrumental earthquakes.

In this study, data from acceleration stations belonging to the BHRC (Building and Housing Research Center) were analyzed. Acceleration data were analyzed in the range 10-40 cm/s^2 from Changureh-Avaj (2002), Tehran (2003), Firozabad-Kojour (2004) and Kahak-Qom (2007) earthquakes, which recently occurred near to the Tehran. Two empirical methods, standard site / reference (Hs/Hr) and horizontal to vertical spectral ratios (HVSR) or H/V were employed to evaluate the site characteristics. The results reveal a large contribution of site effects on ground motion at the majority of the studied sites.

ACCELERATION STATIONS AND SITE EFFECTS ESTIMATION

The Iranian Strong Motion Network (ISMN) stations are mostly equipped with digital instruments (SSA-2 and Guralp CMG-5TD) by Building and Housing Research Center (BHRC), which is responsible organization for ISMN. During the past five years, the acceleration stations were increased from 850 to more than 1100. In Tehran city, the numbers of acceleration stations were increased from 5 to 41 surface stations including 6 stations on different levels of important buildings. It is also planned to increase the number of acceleration stations in Tehran for providing reliable information regarding PGA distribution and generating shake map during an earthquake. Up to now, Tehran acceleration network was able to record Changureh-Avaj (2002), Tehran (2003), Firozabad-Kojour (2004), and Kahak-Qom (2007) earthquakes, which triggered 1, 1, 21, and 14 acceleration stations of the network, respectively, depending on the size and location of the earthquakes. The specifications of the acceleration stations and recorded surface PGAs for each earthquake are shown in Table 1.

In this study, site effects were analyzed based on two empirical techniques. Standard site / reference (Hs/Hr) and horizontal to vertical spectral ratios (HVSR) or H/V empirical methods have been used for this purpose. Spectral ratio analysis in frequency domain was used for analysis of different components of acceleration records in each station. The first method compares ground motions with motions from a reference site (usually rock), while the second does not use as a reference site. The second approach has the advantage of being able to incorporate essentially all available earthquake recordings. However, the application of the first one needs to employ the reference site in an appropriate distance from the soil sites that restrict its application. The HVSR, which originally proposed for microtremor measurements, extrapolated to the earthquake ground motion records by Lermo and Chavez-Garcia in 1993. Their study revealed very good matching between earthquake motions based on HVSR estimations and those supplied by the reference site method. The comparison between HVSR for the shear wave of earthquake motion and ideally uphole to downhole spectral ratio using downhole array data also verified a good correlation (Rodriguez et al., 2001; Ghayamghamian, 2005). Furthermore, the HVSR is commonly more stable among different earthquakes because it is more independent of the earthquake source and wave propagation path.

These two methods were applied for estimation of soil amplification characteristics at all strong motion stations. For this purpose, the Fourier amplitude spectra for horizontal and vertical components were generally calculated for 20s time window after S-wave arrival and were smoothed using a rectangular moving average window of bandwidth 0.4 Hz. The smoothing process was applied for local noise removing. There isn't any specific method for this, but it is obvious that excessive smoothing leads to decrease in indicator frequencies and its peak values. Moreover, influence of excessive smoothing on spectral ratio range is the matter that leads to uncertainty in resultant of amplification function. In order to decrease uncertainty, spectral ratio was calculated by using both empirical methods.

In the next step, the HVSR was calculated as an average of N/V and E/V spectral ratios for two horizontal components at each station. Furthermore, different time window lengths and spectral methods (ex. cross-spectrum) were analyzed in the calculation of spectral ratio to assure the accuracy and stability of the results. The calculated HVSR was averaged for different events at a station and was determined as a representative of site amplification function for that station. Finally, the dominant frequency of identified site amplification functions was determined and utilized in site classification of the strong motion stations. In addition, the reference site method was also applied using the same fashion of spectral ratio analysis for the sites. In this method rocky sites have been selected as reference sites, and then source path effects are removed from their. It is believed that path effects are the same for near points and if reference points are free from site effects, it can be concluded that entrance motion to the soil layers and their spectral ratio would be indicative of site effects. Three rocky stations, located in Emamzadeh Davood (T3), Jamshideyeh Park (T30) and Bibishahrbano (T38), were selected as reference stations. Fig. 1 shows the distribution of acceleration stations around the city. The results of spectral ratio calculation in terms of amplification function for each station have been shown in Fig. 2.

Table 1. Specifications of acceleration stations with the maximum peak ground acceleration (P.G.A) recorded in each station.

Earthquake	Station	Long. (ºE)	Lat. (ºN)	Max. Surface PGA (cm/s^2)		
				L	V	T
Changureh-Avaj (2002)	T24	51.155	35.753	16.40	6.74	13.25
Tehran (2003)	T52	51.576	35.739	55.91	12.64	29.87
Firozabad-Kojour earthquake (2004)	T1	51.427	35.592	22.11	20.86	38.49
	T2	51.398	35.726	18.72	19.84	18.56
	T3	51.338	35.877	12.33	19.90	20.88
	T9	51.372	35.745	14.59	13.55	17.38
	T10	51.407	35.764	23.01	15.27	19.63
	T11	51.407	35.761	24.09	17.74	26.88
	T12	51.466	35.827	16.98	14.28	14.65
	T13	51.397	35.647	24.42	20.04	33.87
	T16	51.398	35.711	16.00	16.46	13.26
	T17	51.506	35.669	8.63	8.71	12.56
	T18	51.367	35.741	13.80	9.86	17.04
	T22	51.385	35.739	22.48	14.67	21.81
	T23	51.363	35.741	8.84	11.72	13.75
	T24	51.155	35.753	24.97	17.38	18.99
	T29	51.415	35.684	28.28	25.32	25.53
	T30	51.466	35.827	12.17	12.07	16.83
	T33	51.390	35.791	24.32	19.49	18.90
	T35	51.412	35.704	25.57	13.75	11.63
	T38	51.493	35.591	11.44	6.76	10.51
	T52	51.576	35.739	16.20	16.21	20.06
	T56	51.266	35.722	22.85	25.51	29.11
Kahak-Qom earthquake (2007)	T1	51.427	35.592	13.17	4.93	12.14
	T9	51.372	35.745	6.39	3.93	6.43
	T10	51.407	35.764	10.28	3.41	5.40
	T11	51.407	35.761	11.66	4.35	15.54
	T12	51.466	35.827	7.82	2.49	6.62
	T13	51.397	35.647	16.62	4.51	8.28
	T16	51.398	35.711	7.95	6.45	7.23
	T17	51.506	35.669	8.53	8.18	9.11
	T22	51.385	35.739	8.83	3.69	9.54
	T23	51.363	35.741	9.63	4.35	5.85
	T24	51.155	35.753	6.46	3.52	5.32
	T26	51.353	35.701	7.55	4.04	10.63
	T29	51.415	35.684	6.05	3.04	15.27
	T54	51.503	35.744	5.42	3.67	5.96
	T60	51.428	35.786	5.63	9.75	4.46

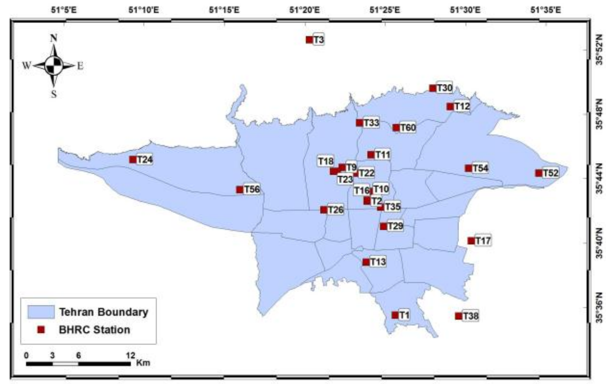
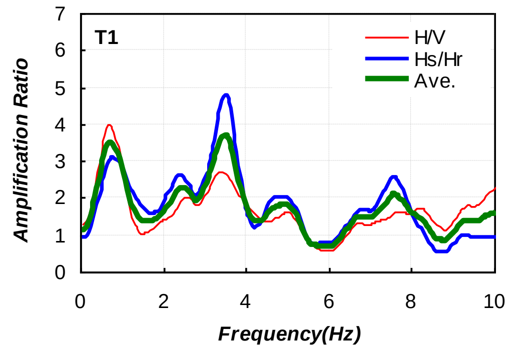
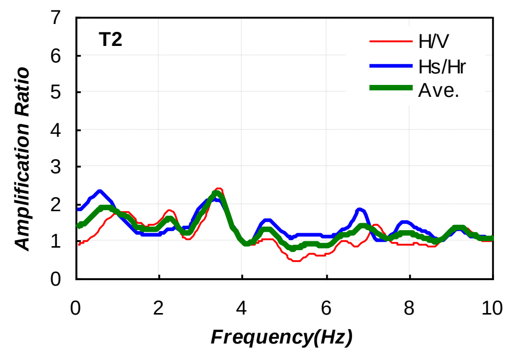


Fig. 1. Distribution of acceleration station around the city.





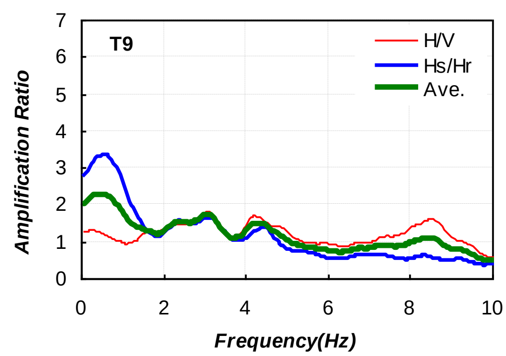
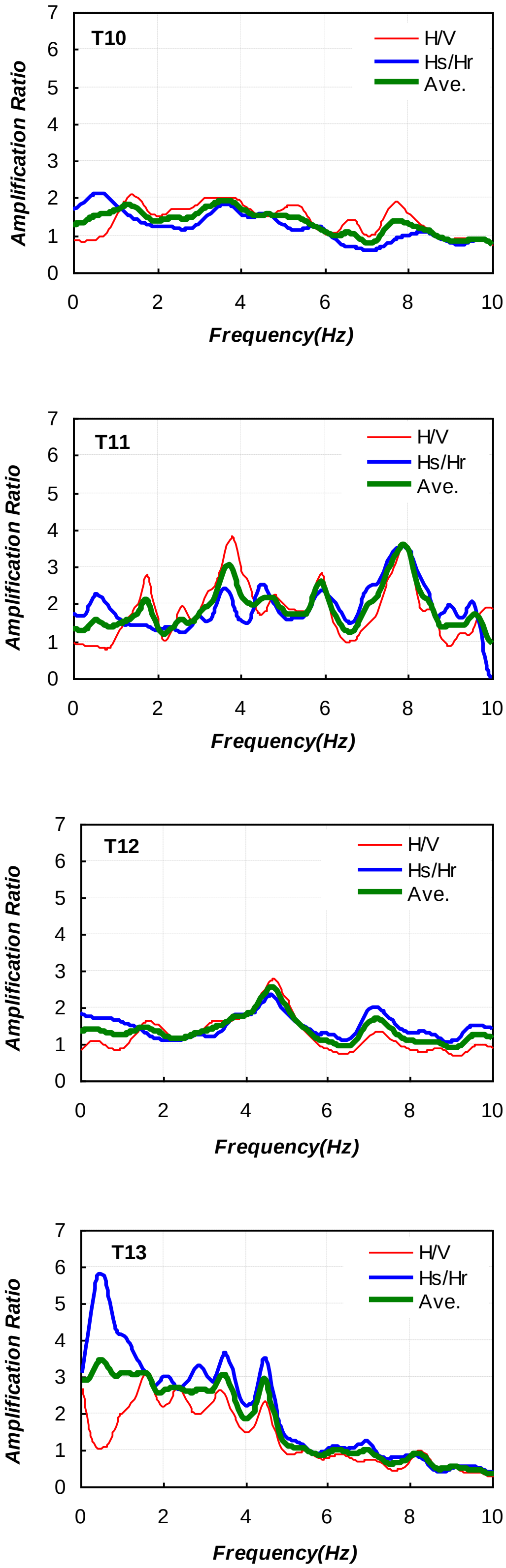


Fig. 2. Result of spectral ratio calculation in terms of amplification function for acceleration stations.



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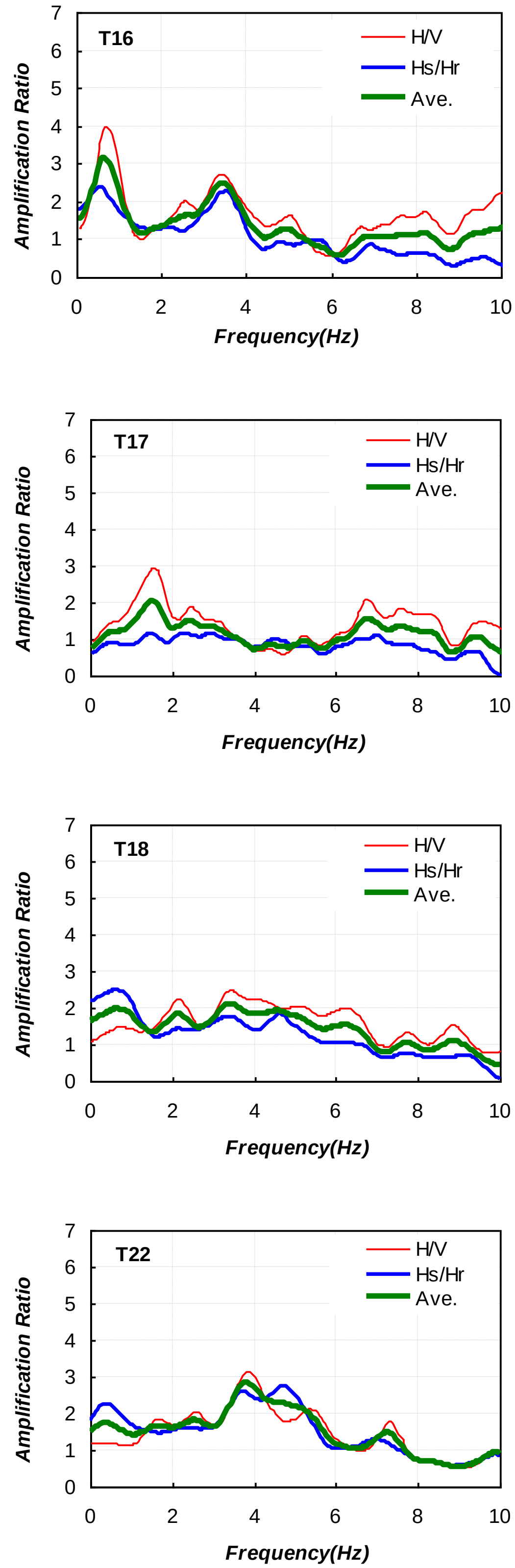

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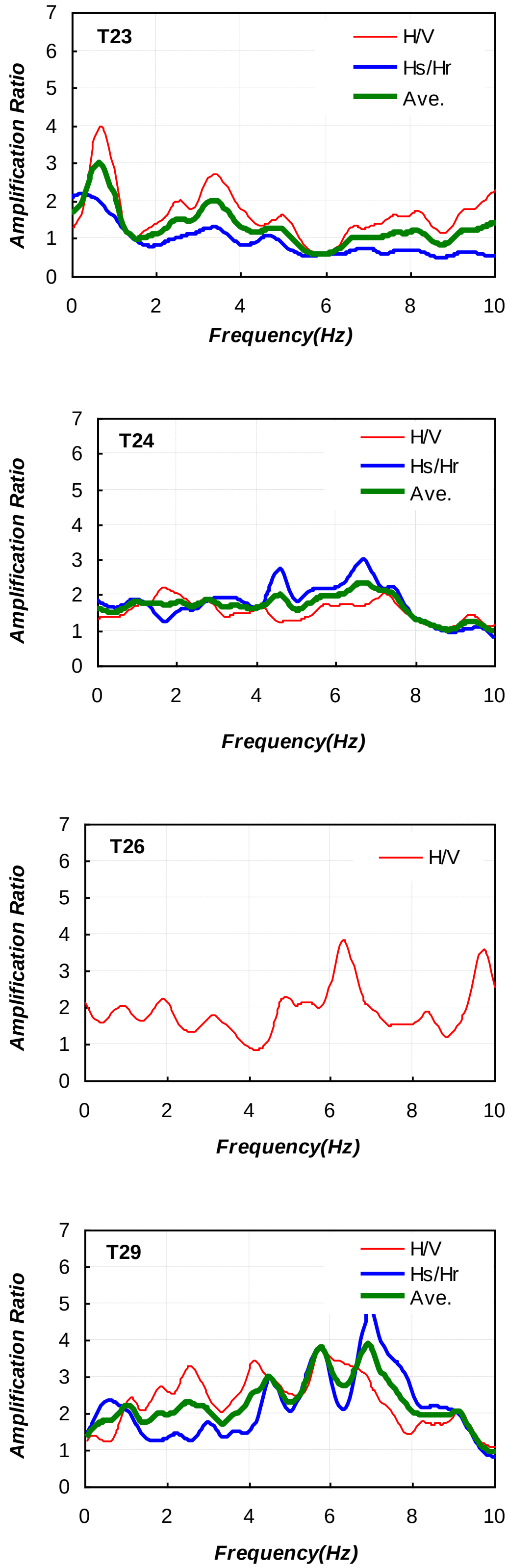

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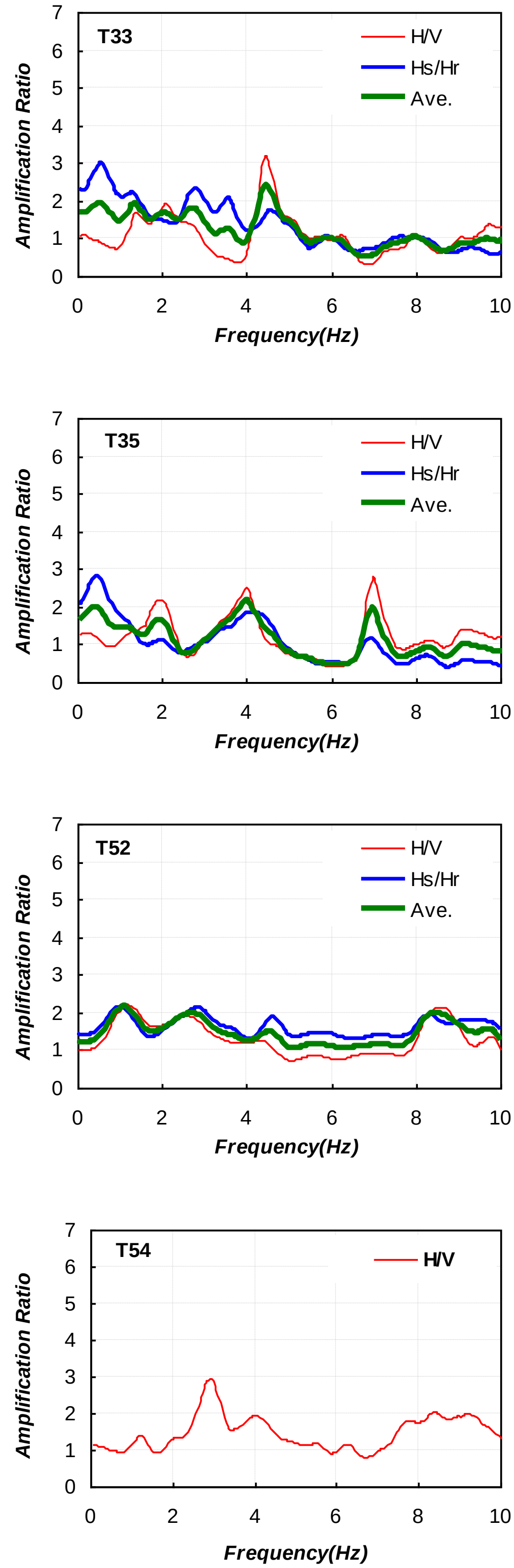

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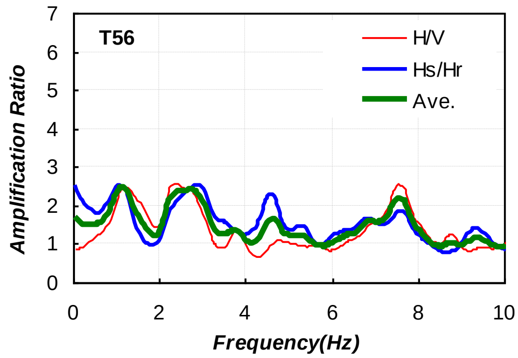


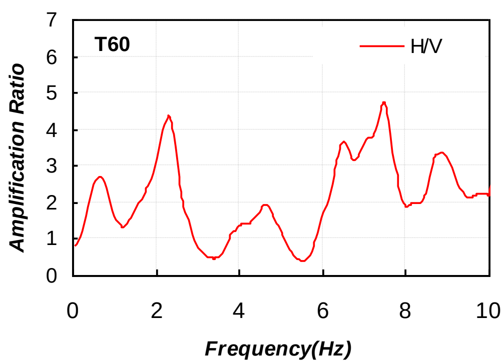


Fig. 2. Continued.

SITE PREDOMINANT FREQUENCY

Site predominant frequency is one of the most important aspects in site effect analysis. Site classification can be one of its applications. Site can be classified based on predominant frequency and mean shear wave velocity in upper 30m. In this study, it is attempted to classify sites based on calculated predominant frequency and mean shear wave velocity in upper 30m. For this purpose, site predominant frequency was extracted from calculated amplification functions, then mean shear wave velocity in upper 30m was calculated by using this equation.

$$f_b = V_{S(30)} / 4H_{30} \quad (1)$$

Where f_b is site predominant frequency, H_{30} is the layer thickness (30m) and $V_{S(30)}$ is the average shear wave velocity in upper 30m.

After calculating shear wave velocity in upper 30m, site was classified based on NEHRP (National Earthquake Hazards Reduction Program) site classification system. Table 2 represents site predominant frequency, amplification factor, estimated shear wave velocity in upper 30m, and site class based on HEHRP. From Table 2, it can be concluded that most part of city are located in C class based on this classification system. In addition, the results reveal a large contribution of site effects on ground motion at the majority of the studied area. The value of predominant frequency in southern part of city is less than northern part. Therefore, the level of damage in southern part might be increased and short frequency structures, such as high-rise buildings and long span bridges might be strongly affected by the site effects in this part of the city.

Table 2. Site predominant frequency, amplification ratio, estimated shear wave velocity in upper 30m, and site classification based on NEHRP for acceleration stations.

No.	Station	Site Dominant Frequency (Hz)	Site Amplification Ratio	Vs_{30}(m/s)	NEHRP
1	T1	2.5	2.3	300	D
2	T2	3.4	2.7	408	C
3	T3	>8.0	1.0	>960	B
4	T9	3.2	1.7	384	C
5	T10	3.8	1.9	456	C
6	T11	3.8	2.9	456	C
7	T12	4.7	2.7	564	C
8	T13	1.7	3.0	204	D
9	T17	1.6	1.9	192	D
10	T18	3.4	2.1	408	C
11	T22	4.0	2.8	480	C
12	T23	3.5	1.5	420	C
13	T24	2.9	1.8	348	D
14	T26	1.9	2.1	228	D
15	T27	4.6	3.0	552	C
16	T29	4.6	2.7	552	C
17	T30	>8.0	1.0	>960	B
18	T33	4.5	2.6	540	C
19	T35	4.0	2.4	480	C
20	T38	>8.0	1.0	>960	B
21	T52	1.1	4.0	132	E
22	T54	2.9	2.6	348	D
23	T56	2.3	2.0	276	D
24	T58	4.1	3.6	492	C
25	T60	2.2	3.4	264	D

EVALUATION OF VARIOUS FREQUENCY RANGES FOR APPROPRIATE SITE AMPLIFICATION RATIO

Evaluation of various frequency ranges for appropriate site amplification ratio can be another important application of empirical analyses. Assessment the appropriate frequency range and its relevant amplification ratio are the most important factors. The amplification ratio is one of important factor which can be directly multiplied to peak bedrock acceleration ($Acceleration_{Surface}$= Amplification Ratio * $Acceleration_{Bedrock}$). The amount of surface acceleration is related to the frequency content of both amplification function and input motion. In this case, if the frequency range is not appropriately selected the amount of amplification ratio would underestimate. Therefore it is necessary to estimate this appropriate frequency range. To estimate the appropriate frequency range, both bedrock and surface motions are required. For this purpose, data from the Firozabad-Kojour earthquake which were recorded in both bedrock and surface stations were used. Recorded motions in three rocky stations were used as bedrock motions. To estimate an appropriate frequency range, various frequency ranges including 0.5-5, 0.5-7, 1-10, 2-10 Hz were scrutinized. Then based on the calculated amplification ratio in each frequency range, recorded peak bedrock acceleration in rocky stations was multiplied to calculated amplification ratio by this formula ($Acceleration_{Surface}$= Amplification Ratio * $Acceleration_{Bedrock}$), then peak surface acceleration was estimated. Next, the calculated peak surface acceleration was compared with the recorded one in each station. This procedure was conducted for both HVSR and Hs/Hr empirical techniques. The results are shown in Fig. 3 to Fig. 6. The results show that there are good matching between the calculated peak surface acceleration and the recorded one in 0.5-7 Hz frequency range for Hs/Hr empirical technique. Therefore, this frequency range can be used as an appropriate frequency range for seismic design purpose in study area.

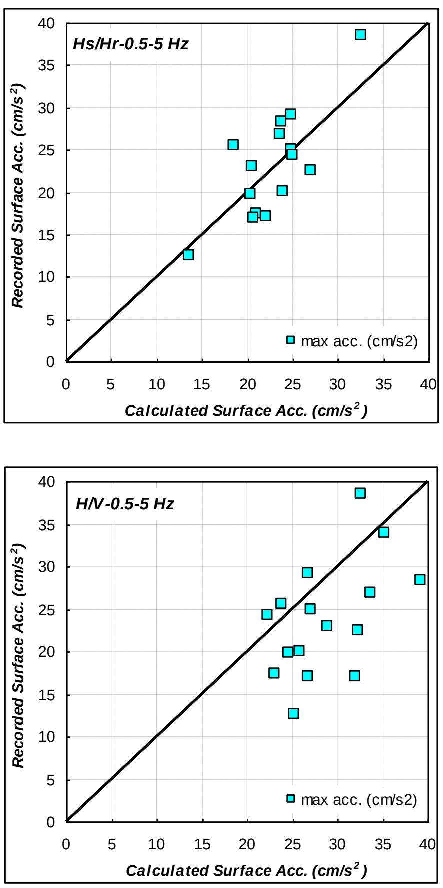


Fig. 3. The comparison between maximum calculated surface acceleration with the recorded one for each station in 0.5-5Hz frequency range for both Hs/Hr and H/V empirical techniques.

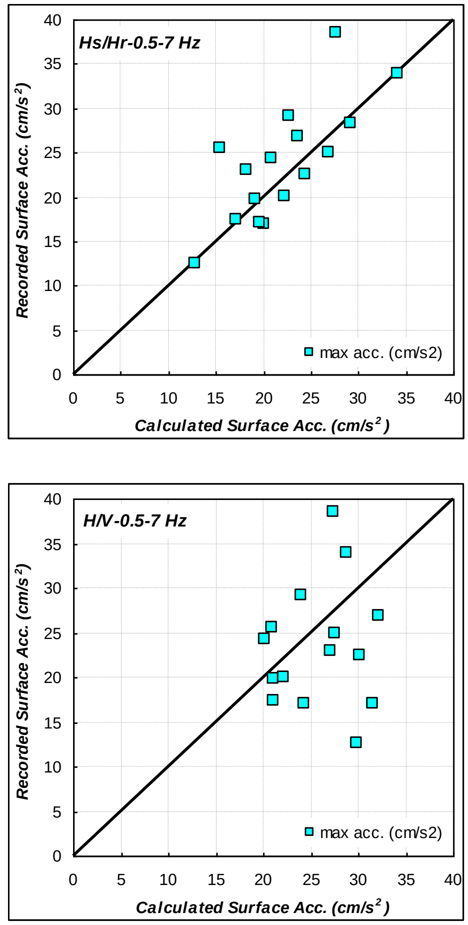


Fig. 4. The comparison between maximum calculated surface acceleration with the recorded one for each station in 0.5-7Hz frequency range for both Hs/Hr and H/V empirical techniques.

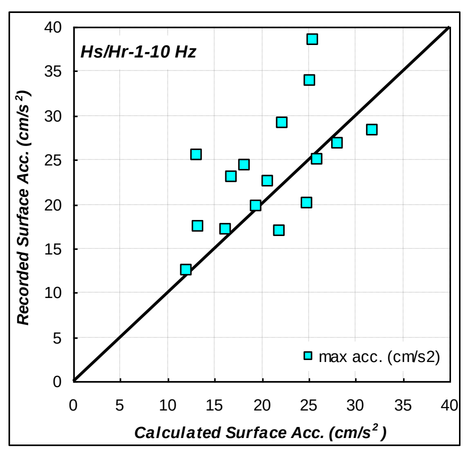
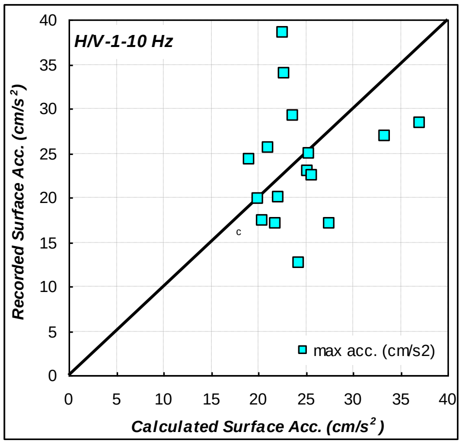


Fig. 5. The comparison between maximum calculated surface acceleration with the recorded one for each station in 1-10Hz frequency range for both Hs/Hr and H/V empirical techniques.



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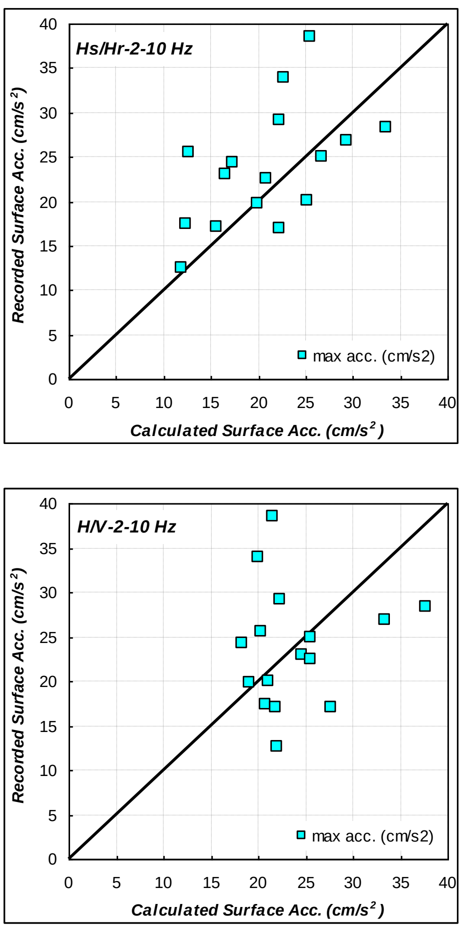

Fig. 6. The comparison between maximum calculated surface acceleration with the recorded one for each station in 2-10Hz frequency range for both Hs/Hr and H/V empirical techniques.

CONCLUSION

In this paper, site effects assessment in Tehran city, the capital of Iran, were estimated by using empirical techniques. Both spectral ratio of the horizontal components of sedimentary site to rocky site (Hs/Hr), and Horizontal to Vertical Spectral Ratio (HVSR) methods have been applied for estimation the site effects parameters. For this purpose, the recorded motions in 25 acceleration stations were analyzed. These motions were recorded from Changureh-Avaj (2002), Tehran (2003), Firozabad-Kojour (2004) and Kahak-Qom (2007) earthquakes, which have been occurred near to the Tehran city. The results are given in terms of site amplification function, site predominant frequency and an appropriate frequency range.

The results from site classification reveal that most part of city is located in C class based on NEHRP site classification system. In addition, the results show a large contribution of site effects on ground motion at the majority of the studied area. The value of predominant frequency in southern part of city is less than northern part. Therefore, the level of damage in southern part might be increased and short frequency structures, such as high-rise buildings and long span bridges might be strongly affected by the site effects in this part of the city. To estimate an appropriate frequency range, various frequency ranges including 0.5-5, 0.5-7, 1-10, 2-10 Hz were scrutinized. Then based on the calculated amplification ratio in each frequency range and recorded peak bedrock acceleration, the peak surface acceleration was estimated. The calculated peak surface acceleration was compared with the recorded one in each station. The results show that there are good agreement between the calculated peak surface acceleration and the recorded one in 0.5-7 Hz frequency range for Hs/Hr empirical technique. Therefore, this frequency range can be used as an appropriate frequency range for seismic design purpose in study area.

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