Site Effect Classification in East-Central of Iran

A. Komak Panah[1], N. Hafezi Moghaddas[2], M.R. Ghayamghamian[3], M. Motosaka[4], M.K. Jafari[5], and A. Uromieh[6]

1. Assistant Professor, Dept. of Civil Engineering, Tarbiat Modares University, Tehran, I.R. Iran
2. Ph.D. Student, Dept. of Engineering Geology, Tarbiat Modares University, Tehran, I.R. Iran
3. Assistant Professor, Dept. of Civil and Architectural Engineering, Tohoku University, Japan
4. Professor, Dept. of Civil and Architectural Engineering, Tohoku University, Japan
5. Assistant Professor, International Institute of Seismology and Earthquake Engineering, Tehran, I.R. Iran
6. Assistant Professor, Dept. of Engineering Geology, Tarbiat Modares University, Tehran, I.R. Iran

ABSTRACT: *The site effects in East of Iran have been studied using Iranian Accelerograph Network data recorded at 50 stations. The geological and geotechnical investigations have been conducted to determine the characteristics of soil profiles in the 20 sites. The horizontal to vertical ratio (HVSR) have also been employed in order to recognize the site transfer function. The dominant frequencies of the site transfer functions calculated based on the 1D model were found to be in agreement with those identified by horizontal to vertical spectral ratio. Additionally, a good correlation has been found between the dominant frequencies with averaged S-wave velocity over the upper 30m. Based on the identified dominant frequency, average of shear wave velocity in upper 30m of soil and geological condition, a site classification is proposed for the stations under study.*

Keywords: Site effect; Site classification; Spectral ratio; East-Central Iran

1. Introduction

Several techniques have been proposed for the estimation of site amplification characteristics using surface seismograms. The spectral ratio of sediment site, with respect to a reference site is classically applied in site effect studies. Recently, the horizontal to vertical spectral ratio (*HVSR*) have been used for such purposes [15, 9, 4, 25]. However, the theoretical background of this technique for application to earthquake records is not fully understood. Nevertheless, the *HVSR* technique provides a powerful tool for site effect estimation and classification based on the surface accelerograms.

In this research, an effort is made to evaluate site amplification characteristic in East of Iran based on the surface accelerograms recorded in 50 stations. The accelerograms records were provided by the Building and Housing Research Center of Iran (*BHRC*), which is the official body in charge of Iranian Accelerograph Network. The soil profiles have been determined using geophysical and geotechnical prospecting at 20 sites. The theoretical transfer functions are identified based on 1*D* model at these sites. The *HVSR* technique have also been employed to estimate the transfer function for all sites.

When compared, at the most sites a good agreement between theoretical transfer functions and identified ones based on *HVSR* have been found. Therefore, the *HVSR* have been used for site effect estimation at the remaining sites where there was no geotechnical information available. Finally, a classification system was proposed based on predominant frequency of *HVSR*, average of seismic velocity over 30 of soils, V_s^{30}, and geological condition of the sites.

2. Seismotectonic of Study Area

The study area is located in East Iran and include Khorassan and Kerman provinces. This region, being a part of the Alpine-Himalayan orogenic belt, has a complex tectonic history of repeated folding, magmatism and metamorphism and is surrounded by a fault dissected ophiolite ring [22, 17]. The area has experienced many major earthquakes in the past decades (e.g., Tabas Earthquake 1978, *Ms*7.4; Qaen Earthquake 1979, *Ms*7.1; Golbaf Earthquake 1981, *Ms*7.0; Qaen Earthquake 1997, *Ms*7.3). The last important earthquake (Zirkuh-e-Qaen Earthquake) occurred in May 1997 and as a result of which at least 1588 people died, 2600 injured and approximately 50000 people became homeless.

The major earthquakes have usually been associated with surface faulting. The recent earthquakes mainly concentrated in the three following zones: 1) Systan suture zone, 2) Sirch-Golbaf (Gowk) zone and 3) Tabas zone (Figures (1) and (2)). The Systan suture zone is a tectonically border that separates East-Central of Iran from Afghan block to the east. This zone is an important seismotectonic boundary at East of Iran. Most of segment faults located in the north part of this zone (e.g., Abiz fault, Dasht-e-Bayaz fault, Nauzad fault and Ferdos fault) has been ruptured in the last century [1]. The Sirch-Golbaf or Gowk zone is another active zone of this area where four major earthquakes with magnitude greater than 6.5 occurred in the past two decades. Tabas region located between Dasht-e-Bayaz fault and Nayband fault in the west. This region is formed of horst and graben structures that are strongly folded. The Tabas reveres fault controlling one of the graben structures and has been ruptured during Tabas Earthquake in 1978 [19].

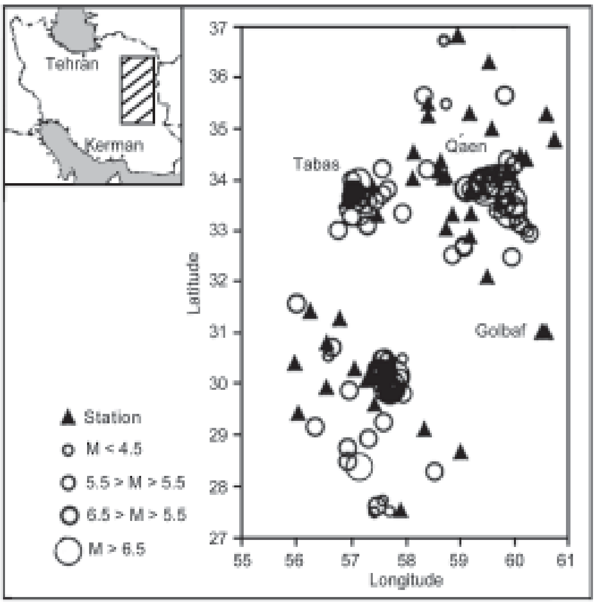

Figure 1. Location of earthquakes and recording stations.

3. Accelerogram Data

The accelerograms recorded by Iranian Accelerograph Network have been used in this study. The present Accelerograph Network of Iran consists of 220 *SMA*-1 analog and more than 800 *SSA*-2 digital accelerographs. Among them, only a few numbers of instruments were installed in the rock outcrop. In this study a total of 270 surface accelerograms (three components) recorded in 50 stations have been selected for site effect studies. Among them, 170 accelerograms recorded by *SSA*-2 instruments, and the remaining by *SMA*-1 instruments. The maximum peak ground acceleration (*PGA*) of data was about 1000*gal* that recorded by Tabas station during Tabas earthquake in 1978. Some statistics of selected records are summarized in Table (1). The data are

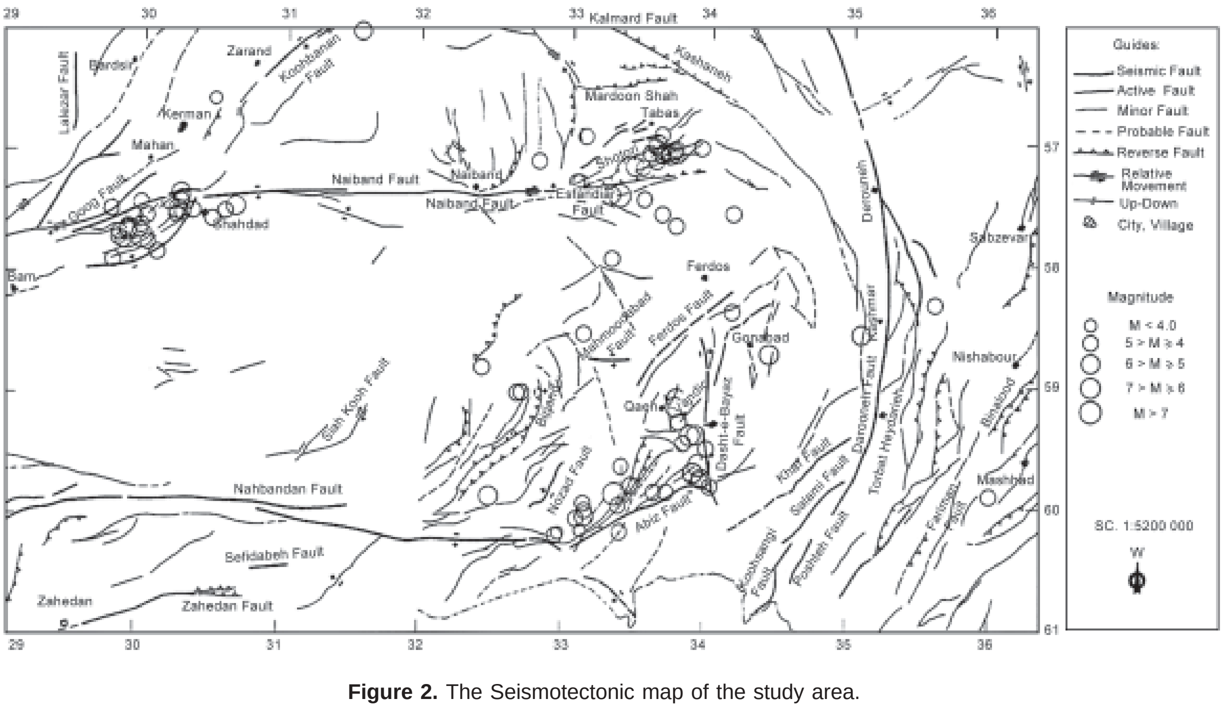

Figure 2. The Seismotectonic map of the study area.

Table 1. Statistics of earthquake data of the stations.

Magnitude	Number of Earthquakes	Number of Records
< 4.0	5	5
4.0-4.5	18	18
4.5-5.0	73	85
5.0-5.5	20	23
5.5-6.0	5	15
6.0-6.5	7	5
6.5-7.0	7	30
7.0-7.5	4	42
---------	---------	49
Total	119	270

corrected for base line drift and filtered mostly from 0.3 to 20*Hz* using butterworth (*FIR*) filter.

4. Geological and Geotechnical Investigations

From geological point of view, the study area mainly covered by sedimentary rocks (limestone, sandstone, shale and marl) with limited outcrop of the igneous and metamorphic rocks. The vast fan deposits, sand dunes, flat desert and rugged mountains are the main morphological features in the area. The thickness of deposits is different from a few meters in slops up to more than few hundred meters at alluvial plains. Based on the geological information, 20 stations have been selected for geophysical and geotechnical prospect. The seismic refraction and geoelectrical methods were used to identify shear wave velocity profiles at 10 sites. For the other 10 sites, the detailed geotechnical studies including boring up to seismic bedrock (mostly up to 30-50*m*), standard penetration test (*SPT*), down hole shear wave velocity measuring and laboratory testing were conducted. The laboratory tests include, sieve and hydrometer analysis, Atterberg limits, density, direct shear and unconfined compressional strength, which performed for undisturbed and disturbed samples. The *S*-wave velocities and *SPT* values are determined for 1.5*m* depth intervals at boreholes. The following relations between *SPT* values (*N* = equivalent bowls for 30*cm* penetration) and *S*-wave velocities (*m/s*) for fine and course materials were found (Figures (3a) and (3b)).

$$Vs = 106\,N^{0.41} \quad \textit{Fine Material (Silt and Clay)}$$

$$Vs = 75\,N^{0.5} \quad \textit{Coarse Material (Sand and Gravel)} \qquad (1)$$

The above relations are used to estimate the shear-wave velocity profile of the sites at which the geotechnical information were available. In Table (2) the results of geotechnical study are summarized. From engineering

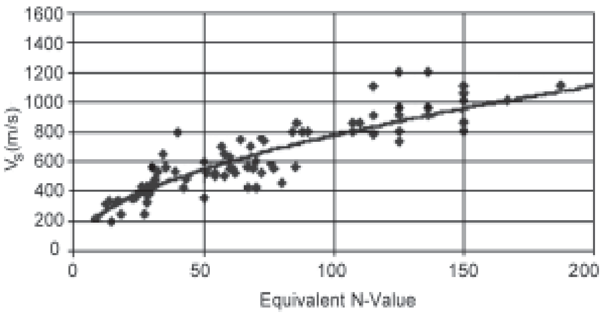

Figure 3a. Relation between equivalent SPT value and S-wave velocity for uncohesive material.

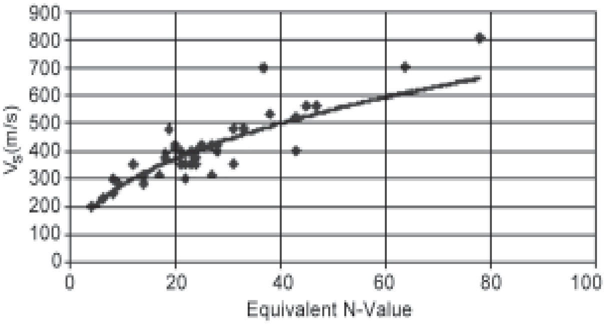

Figure 3b. Relation between equivalent SPT value and S-wave velocity for cohesive material.

geology point of view, the subsurface condition of the studied sites can be generally classified in three groups:

A) Coarse colluvium deposits with thickness less than 20*m*; some sites (Deihok, Afin, Sefidabeh, Hajiabad and Sedeh sites) are classified in this group. Morphologically these stations located in the front of high slopes and soil texture is usually coarse and angular. The fine material as a cohesive agent caused increase of strength.

B) Colluviums deposits with thickness more than 20*m*: The thickness of deposits in the sites (Sirch, Nehbandan, Kohbanan and Birjand sites) that located away from slops is high and usually composed of coarse and fine soils interbeded. The high thickness of soil may be occurred when the border of mountain and plain is faulting zone (Golbaf site).

C) Thick alluvium deposits: many of the sites are classified in this group (Tabas, Qaen, Kerman, Mashad, Gonbad sites). These sites can be divided into two subgroups: the sites, which located on the river deposits, *C*1 (Qaen and Tabas sites), and those located on alluvial plains, *C*2 (Kerman and Mashad sites). The thickness of deposits in both subgroups is generally more than 100 meters and soil texture is interbeded of fine and coarse materials with the higher percent of coarse material (gravel and sand) for the first subgroup. The depth of water table in all of the sites is more than 30*m*.

Table 2. Geotechnical and Specification of the stations.

Sites	Thickness of Layer (m)	Soil Classification	S-Wave Velocity (m/s)	V_s^{30} (m/s)	Geological Classification	Dominant Frequency (Hz) F_{HVSR}	F_{SEIS}	Site Classification
*Kerman	16	CL-ML	310	371	C2	1.6	2.0	III
	4	ML	420					
	20	CL-ML	450					
	10	Soft Marl	480					
*Mashhad	5	ML	330	453	C2	2.7	2.7	IIB
	10	SM-ML	400					
	15	SM-ML	530					
	20	SM	670					
	10	SM	860					
		SM	930					
*Qa'en	7.5	GM-SM	250	610	C1	4.7	5.5	IIA
	3	GM-GP	455					
	9.5	GM-GP	550					
	5.5	GM-GP	730					
		GP	800					
*Deihok	10	GP	420	950	A	7.5	7.0	I
	12	GP	850					
	23	GP	1400					
		Rock	1800					
*Hajiabad	9.5	GM	420	760	A	8.2	8.0	III
	11.5	GP-GM	900					
		GP	1200					
*Tabas	7.5	SP-SM	290	476	C1	4.8	4.3	IIB
	8.5	GM	375					
	4	SP	560					
	10	GM-GW	800					
*Joshan	7	GP	560	930	A	9.8	8.5	I
	9	GP	850					
		Sandstone	1200					
**Afin	6	CL	390	520	A	6.4	6.0	IIA
	12	GP	650					
		GP	940					
*Kohbanan	12	CL-ML	350	450	B	3.6	4.5	IIB
	8	SM-ML	480					
	20	GM	700					
		GM	800					
*Sefidabeh	13	GP	740	1025	A	14.2	13.0	I
	6	GP	950					
		Marl	1400					

Table 2. Continued ...

*Sirch	2	CL-ML	430	760	B	8.2	8.0	I
	6	GM-SM	650					
	12	GP	800					
		GP	850					
**Birjand	4	CL-ML	380	590	B	5.9	6.0	IIA
	8	SM	495					
	10	SM	600					
		GM-GP	780					
**Vandic	4	SM-ML	200	597	B	7.1	7.5	I
	8	GM	450					
	18	GM-GP	850					
		GP	1300					
*Golbaf	8	SM-CL	350	430	C1	3.7	3.5	IIB
	14	SP-GM	420					
	11l	GM	700					
		GPl	850					
**Bardeskan	8	CL-ML	200	345	C1	3.4	3.5	IIB
	10	CL-ML	315					
	15	SM	470					
		SM	590					
**Torbat Heydarieh	4	CL	115	475	B	4.7	4.0	IIB
	10	CL-ML	390					
	14	GM	740					
		GM-GP	910					
**Chenar	7.5	CL	170	400	C2	3.0	3.4	IIB
	12	CL	380					
	10	SM-SP	620					
		GM	750					
**Khazri	5	CH-CL	190	330	C2	2.3	2.2	III
	11	CL	300					
	19	SM	480					
		SM	650					
**Gonabad	7	CL-ML	250	420	C2	3.4	4.0	IIB
	15	CL-ML	420					
	9	SM	570					
		SP	750					
**Kashmar	4	CH-CL	100	330	C2	2.3	2.0	III
	12	CL-ML	240					
	10	ML-SM	450					
		GM	520					
**Nishabour	3	CL	170	525	C1	3.9	3.5	IIB
	12	ML-SM	460					
	18	SP-SM	650					
		GM	770					

* The soil profile was determined by geotechnical and down hole studies.
** The soil profile was determined by Geophysical prospecting.

5. Site Effect Evaluation

The site effects were studied by using 1*D* equivalent linear analysis and *HVSR* techniques. In both methods, the *S*-wave portions of the records were used. The window length of 5, 10, and 15sec was selected for the events with $Mw < 5$, $6.5 > Mw > 5.0$ and $Mw > 6.5$, respectively.

The 1*D* equivalent linear analysis at 20 sites, which geotechnical and geophysical studies were carried out, are computed by Proshake program [10]. The shear modulus reduction and damping ratio curves proposed by Seed and Idriss [20], Seed et al [21] and Idriss [10] were used for Sand, Gravel and Rock, respectively. The Vucetic and Dobry [26] shear modulus reduction and damping ratio curved were used for stiff clays, whereas for soft clays those proposed by Sun et al [23] were used.

The *HVSR* technique, which is in fact a combination between seismological methods (called the receiver function, *RF*, technique), used by Langston [13, 14] to determine crustal structure and by Nakamura [18] to analyse site effect using microtremores. It is based on the assumption that the microtremore generates mainly by Rayleigh wave and vertical component is not affected by the surface layers [11]. Although the above assumption may not be valid for earthquake records, but many researchers have empirically shown that this technique gives a reasonable estimation for the site predominant frequency [9, 4, 25, 12].

The *HVSR* technique was applied for all 50 stations. For this purpose, the Fourier spectrums of horizontal and vertical components are calculated. The calculated spectral were smoothed using hanging window, then the transfer function is estimated using resultant horizontal to vertical spectral ratio and averaged for the events at the sites. In Figure (4), the estimated transfer functions of some stations are shown. The good correlation between site geology and identified dominant frequencies of transfer function can be seen in this figure. The Khari, Kerman and Mashad sites, which are located on the alluvial plains (*C*2), show dominant frequency at the range of 1.5, 2.5 and 2.7*Hz*, respectively. Accordingly, Vandic, Hajiabad, Sefidabeh sites, which are located in the slope of mountains (A), show dominant peaks at the frequency greater than 7*Hz*. Figure (5) shows the comparison between transfer functions calculated by using Proshake and those estimated by *HVSR* technique. In addition, the correlation between dominant frequencies obtained by two methods is shown in Figure (6). Figure (7) also shows the relation between dominant frequencies of both

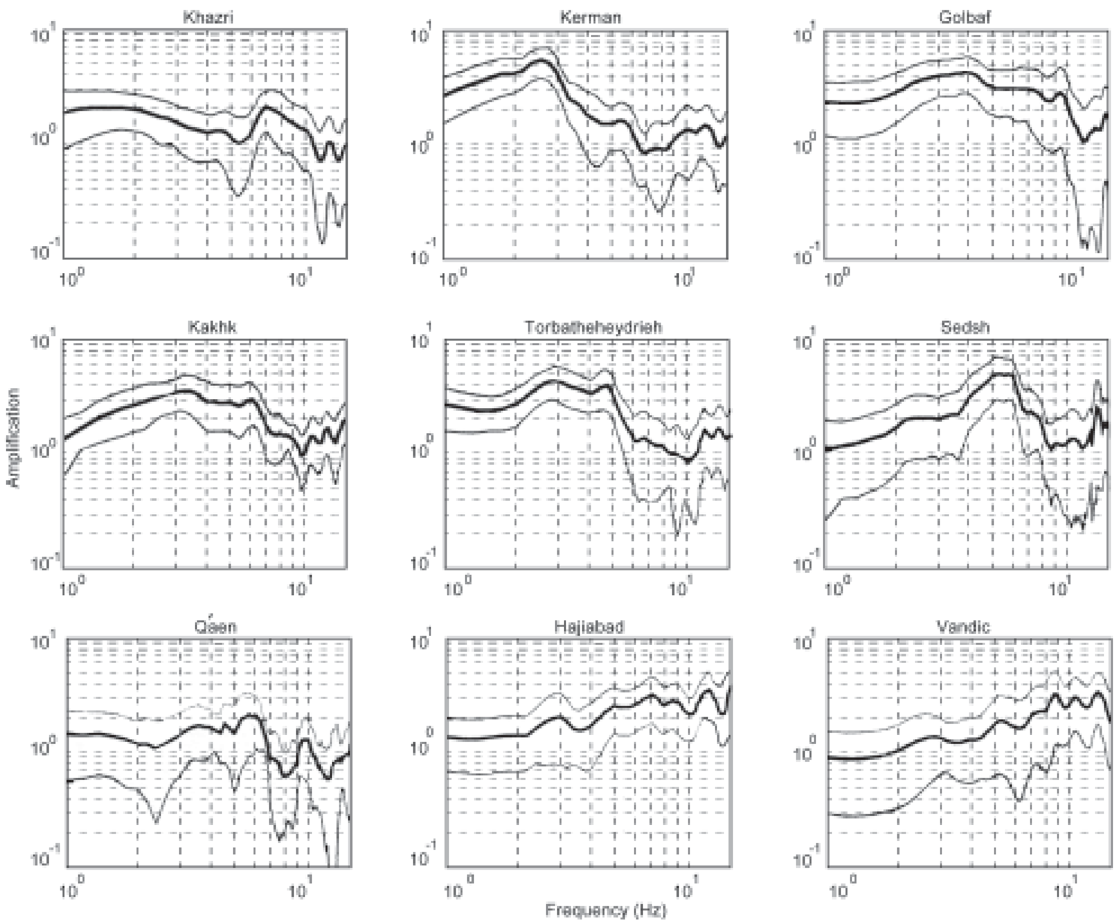

Figure 4. The transfer fucntions of some sites estimated by HVSR technique.

methods with respect to V_s^{30}. Generally, a fairly agreement between the results can be seen in these figures. However, the correlation of estimated site amplification between *HVSR* and Proshake shows under estimation of site amplification by *HVSR* technique. The depth of seismic bedrock (by assuming the shear wave velocity of 750*m/s* for seismic bedrock) in the studied sites are different from 9*m* up to 60*m* with average of 33*m*. In Figure (8), shows the relation between F_{hvsr} and F_{seis}. F_{seis} estimated based on average of S-wave velocity over seismic bedrock (V_s^b) and depth of Seismic bedrock(F_{seis}) using the following equation: are shown.

$$F_{seis} = V_S^b / 4h_b \tag{2}$$

It is noted that, the correlations of results become much better than those in Figure (6). The results also validate the application of *HVSR* for site dominant frequency estimation in study area.

6. Site Classifications

Extensive site effect studies have been undertaken over the past decades and many site classification systems have been proposed. The most recent classification system usually uses of V_s^{30} as a key parameter [2, 6]. The recent works based on the results from Northridge and Lomaprieta earthquakes confirmed the importance of depth of sediment in the site classification [5, 3, 11]. The Table (2) the characteristics of all sites including F_{hvsr}, F_{seis}, V_s^{30}, geotechnical condition and geological classification are shown. Based on the information of this table it is possible to classify the studied sites into 3 categories. A description of proposed classification is given in Table (3). There was no hard rock or very soft soil in sites under study, therefore the proposed classification does not include upper and lower limit classes. The classification of remaining 30 sites, in which geotechnical information were not available, is carried out based on identified dominant frequency using *HVSR* and geological information. In Figure (9) the average of transfer functions for different classes of stations (for all 50 stations) estimated using *HVSR* technique are shown. The variation of dominant frequency between categories verify proposed classification for study area.

7. Conclusions and Discussion

The 50 sites of Iranian Accelerograph Network located in East Iran have been selected for site effect studies. The geotechnical and geophysical prospecting were conducted for 20 sites and geological mapping was performed for all sites. The site transfer functions were identified based on

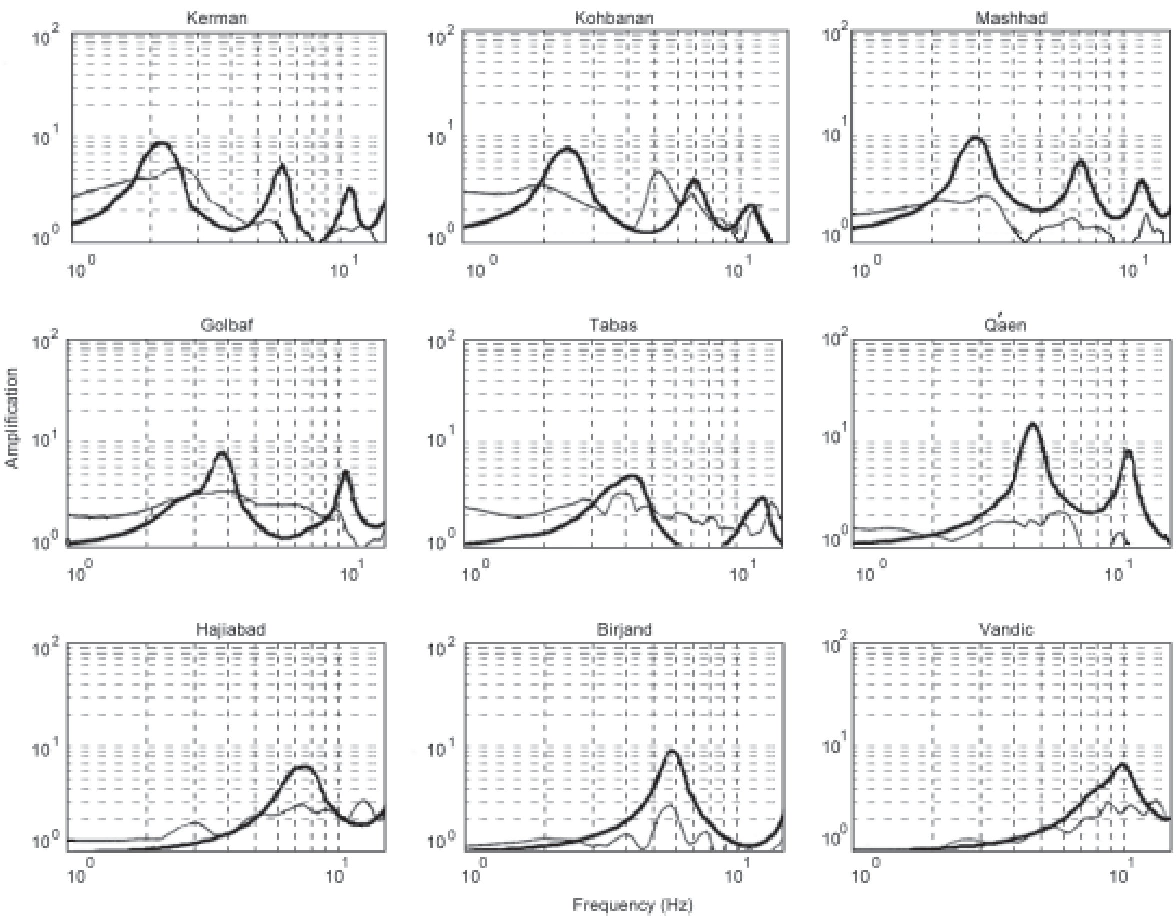

Figure 5. Comparison of transfer functions estimated by HVSR and calculated by theoretical method.

the 1*D* model and horizontal to vertical spectral ratio at the sites where geotechnical and geophysical investigations were carried out. The good agreement between theoretical and identified ones base on *HVSR* is found for the dominant frequency at the sites. Further, it is found that, there is a good agreement between F_{hvsr} and F_{seis}. These results validate the application of *HVSR* technique for site dominant frequency estimation and site classification. Finally, a three-order classification system was proposed based on F_{hvsr}, V_s^{30} and geological condition.

Acknowledgments

The Management and Plan Organization of Iran contributed in searching for the geotechnical and

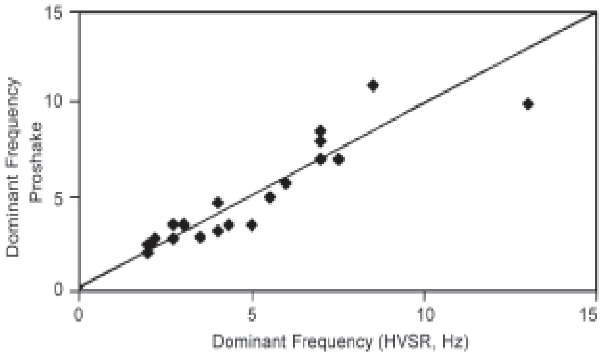

Figure 6. Comparison of dominant frequencies obtained by theoretical and HVSR methods.

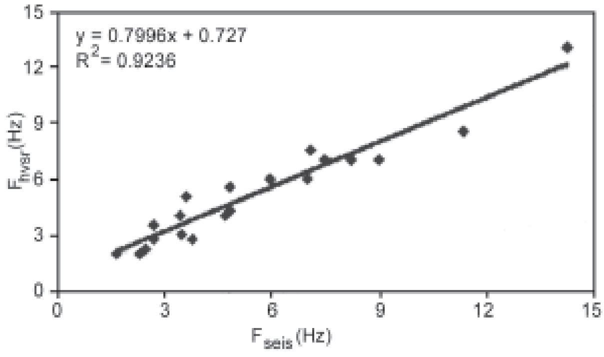

Figure 8. Comparison of dominant frequencies obtained by HVSR technique and F_{seis}.

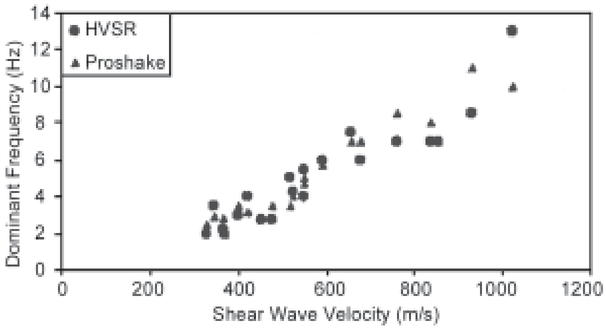

Figure 7. The relation between dominant frequencies estimated by Proshake and HVSR methods with respect to V_s^{30}.

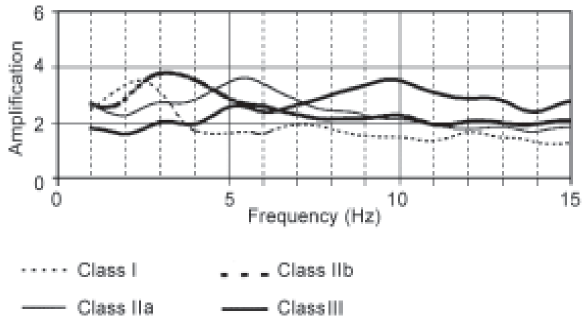

Figure 9. Comparison of average transfer functions for different classes.

Table 3. The proposed site classification system for area under study.

Class No.	Soil Description	Predominant Frequency (Hz)	Vs^{30} (m/s)	Geological Condition	Sites
I	Soft Soil	<2.5	<350	Thick Soft clay or Silty Sandy Clay Mostly Alluvial Plain	Kerman, Khazri, Kashmar, Bam, Gonabad
IIa	Moderately Soft Soil	2.5-5.0	350-550	Interbeded of Fine and Coarse Material, Alluvium Terraces with Weak Cementation	Tabas, Mashhad, Qaen, Golbaf, Sedeh, Ferdos
IIb	Stiff Soil	5.0-7.5	550-750	Thick Old Alluvium Terraces or Colluviums Soils with Medium to Good Cementation	Sangan, Birjand, Afin, Taibad, Khaf, Shahdad
III	Hard Soil Weak Rock	>7.5	>750	Well Cemented and Compacted Soil, Old Quaternary Outcrop	Sefidabeh, Sirch, Deihok, Vandic, Joshan, Hajiabad

geophysical studies. The authors would like to thank *BHRC* (Building and Housing Research Center, Tehran) for providing the raw acceleration data.

References

1. Berberian, M., Jackson, J.A., Qorashi, M., Khatib, M. M., Priestly, K., Talebian, M., and Ghafouri-Ashtiani, M. (1999). “The 1997 May 10 Zirkuh (Qa’enat) Earthquake (Mw7.2), Faulting Along the Sistan Suture Zone of Eastern Iran”, *Geophys. J. Int.*, **136**, 671-694.

2. Borcherdat, R.D. (1994). “Estimations of Site-Dependent Response Spectra for Design”, (Methodology and Justification), Earthquake Spectra, **10**(4), 617-653.

3. Bray, J.D. and Abrahamson, N. (1999). “Characteaization of Site Response: General Site Categories”, *Earthquake Engineering Research Center, PEER*, No. 1999/03.

4. Castro, R.R., Mucciarelli, M., Pacor, F., and Petrungaro, C. (1997). “S-Wave Site-Response Estimates Using Horizontal-to-Vertical Spectral Ratio, *Bull. Seism. Soc. Am.*, **87**, 250-260.

5. Chang, S.W., Bray, J.D., Gookin, W.B., and Riemer, M.F. (1996). “Seismic Response of Deep Stiff Soil Deposits in the Los Angeles”, California.

6. Dobry, R. and Vucetic, M. (1987). “Dynamic Properties and Seismic Response of Soft Clay Deposit”, *Proceedings of International Symposium on Geotechnical Engineering of Soft Soils*, Mexico City, **2**, 51-87.

7. Dobry, R. and Martin, G.M. (1994). “Dynamic Response of Soft and Deep Cohesive Soil during the Loma Prieta Earthquake of October 17, 1989”, A Dissertation Submitted in Partial Satisfaction of the Requirements of the Degree of Doctor of Philosophy in Civil Engineering of the University of California at Berkeley.

8. Dobry, R., Romos, R., and Power, M.S. (1997). “Site Factors and Site Categories in Seismic Codes: A Perspective”, *In Proceedings of the FHWA/NCEERE Workshop on the National Representation of Seismic Ground Motion for New and Existing M.S., and Mayes*, R.L., Eds.

9. Field, E.H. and Jacob, K.H. (1995). “A Comparison and Test of Various Site-Response Estimation Techniques Including Three that are not Reference-Site Dependent,”, *Bull. Seism. Soc, Am.,* **85**, 710-730.

10. Idriss, I.M. and Sun, J.I. (1992). “SHAKE91: A Computer Program for Computing Equivalent Linear Seismic Response Analysis of Horizontally Layered Soil Deposits”, User’s Guide, University of California, Davis, California, 13pp.

11. Lachet, C. and Bard, P.Y. (1995). “Numerical and Theoretical Investigation on the Possibilities and Limitations of the “Nakemura’s Technique”, *J. Phys. Earth.*

12. Lachet, C., Hatzfeld, D., Bard, P.Y., Theodulidis, N., Papaioannou, C., and Savvaidis, A. (1996). “Site Effects and Microzonation in the City of Thessaloniki (Greece): Comparison of Different Approaches”, *Bull. Seis. Soc. Am.*, **56**, 1692-1703.

13. Langston, C.A. (1977). “Corvallis, Oregon, Crustal and Upper Mantel Receiver Structure from Teleseismic P and S Waves”, *Bull. Seism. Soc. Am.,* **67**, 713-724.

14. Langston, C.A. (1979). “Structure under Mount Rainier, Washington, Inferred from Teleseismic Body Waves”, *J. Geophys. Res.*, **84**, 4749-4762.

15. Lermo, J. and Chavez-Garcia F.J. (1993). “Site Effect Evaluation Using Spectral Ratio with Only One Station”, *Bull. Seism. Soc. Am.,* **83**, 1574-1594.

16. Lussou, P., Fukushima, Y., Bard, P.Y., and Cotton, F. (2000). “Seismic Design Regulation Code: A Proposal for Improving Site Effect Evaluation”, *U.S-Japan Workshop on the Effects of Near Field Earthquake Shaking*, March 20-21, 2000, San Francisco, California.

17. Mohajer-Ashjai, A., Behzadi, A., and Berberian, M. (1975). “Reflections of the Rigidity of the Lut Block and Recent Crustal Deformation in Eastern Iran”, *Tectonophysics*, **25**, 281-301.

18. Nakamura, Y. (1989). “A Method for Dynamic Characteristics Estimation of Subsurface Using Microtremor on the Ground Surface”, QR Railway Tech. Res. Inst. **30**(1).

19. Niazi, M. and Kanamori (1981). “Source Parameters of 1987 Tabas and 1979 Qainan, Iran, Earthquakes from Long-Period Surface Waves”, *Bull. Seism. Soc. Am.*, **71**(4), 1201-1213.

20. Seed, H.B. and Idriss, I.M. (1970). “Soil module and Damping Factors for Dynamic Response Analysis”, Report No. EERC, Earthquake Engineering Research Center, University of California, Berkeley.

21. Seed, H.B, Wong, R.T., Idriss, I.M., and Toimatsu, K. (1986). “Moduli and Damping Factors for Dynamic

Analysis of Cohesionless Soils", *J. of Geotechnical Engineering, ASCE*, **112**(11), 1016-1032.

22. Stocklin, J. (1974). "Possible Ancient Continental Margins in Iran", In Geology of Continental Margins, C.A. Burk and C.I. Drake, Editors, Springer-Verlog, New York.

23. Sun, J., Golesorkhi, R., and Seed, H.B. (1988). "Dynamic Moduli and Damping Ratio for Cohesive Soils, Report No EERC-88/15, Earthquake Engineering Research Center, University of California, Berkeley.

24. Takin, M. (1979). "Iranian Geology and Continental Drift in the Middle East", Nature 235, 147-150.

25. Tsuboi, S., Saito, M., and Ishihara, Y. (2001). "Verification of Horizontal-to-Vertical Spectral-Ratio Technique for Estimation of Site Response Using Borehole Seismographs", *Bull. Seism. Soc. Am.*, **91**(3), 499-510.

26. Vucetic, M. and Dobry, R. (1991). "Effect of Soil Plasticity on Cyclic Response", *Journal of Geotechnical Engineering, ASCE*, **117**(7), 89-107.