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RESEARCH ARTICLES

Seismic microzonation of Mashhad city, northeast Iran

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ABSTRACT

Mashhad city has a substantial risk of earthquakes due to the potential of the underlying soft soils to amplify ground motions. It is therefore imperative to conduct detailed seismic hazard assessment of the area (seismic microzonation). Seismic microzonation of big cities, like Mashhad, provides a basis for site-specific hazard analysis. In the present study, microtremor observations were carried out at 90 sites in the east part of Mashhad city. The predominant frequency and spectral ratio amplitude of the ground were determined by the Nakamura technique, and a microzonation map was developed for Mashhad on the basis of the variations of the predominant frequency and spectral ratio amplitude of the ground. Soil texture and N-value standard-penetration-test (N-SPT) maps and sections were prepared for different depths below the city, by analysis and interpolation of data collected in the study area from 169 boreholes. Then the predominant frequency variations were compared with soil texture and N-SPT variations for four sections in different directions in the study area. This comparison shows that with decreasing soil softening and N-SPT values, the soil predominant frequency also decreases.

1. Introduction

During earthquakes, variations in ground motion according to geological site conditions make it necessary to perform detailed seismic hazard assessments for large cities. Mashhad city, in northeastern Iran, is situated in a region with high seismic potential and it has experienced several destructive earthquakes in its history. In consideration of this seismicity history, there is always the possibility of destructive earthquake events in this region.

Mashhad city is situated on a large plain that is underlain by thick alluvial sediments. Therefore there is the possibility for amplification of ground motion, as studies of important earthquake events around the World have shown that alluvium characteristics can have strong effects on intensity and distribution of earthquake damage. These characteristics can act like filters against seismic waves, and they can cause amplification or damping of seismic waves at certain frequencies. Nowadays, surface-layer effects on seismic waves are known as site effects, which are functions of many factors, including the geology of the underground layers, the site topography, and the incoming wave-field properties [Bard 1995, Fah et al. 2003, Ansal 2004, Apostolidis et al. 2004]. Studies of earthquake damage around the World have shown that local ground conditions can substantially affect the characteristics of incoming seismic waves during earthquakes [Borcherdt and Glassmoyer 1992, Field et al. 1995, Miyakoshi et al. 1998, Trifunac and Todorovska 2000, Ozel and Sasatani 2004, Ergin et al. 2004, Jafari et al. 2005].

Mashhad city is the second largest city in Iran. Mashhad was built on alluvium beds in a region with high seismic potential. Therefore, comprehensive studies need to introduce suitable solutions for prevention and minimizing of earthquake damage that might happen in the future. In the present study, the Nakamura method [Nakamura 1989] was used to evaluate the predominant frequency of the ground vibrations in the study area, which is located within latitudes 36° 14′ 29″ N and 36° 21′ 25″ N, and longitudes 59° 31′ 34″ E and 59° 43′ 49″ E (Figure 1). This method is cheap, quick and simple for urban areas, and recently it has seen widespread application for site effect studies around the World. Therefore, to investigate the relationships between the alluvium characteristics and the frequency obtained in the study area, variations in the ground vibration predominant frequency and variations in the soil texture and blow counts (N-values) of the standard penetration test (N-SPT) were investigated along four sections.

2. Geology and seismicity of Mashhad city

Mashhad city is situated on a large plain (Mashhad Plain) that is underlain by thick alluvial deposits, between Koppet-Dagh basin in the north and Binaloud mountain range in the south. Mashhad Plain was formed by tectonic movements of several parallel faults, which extend along the ranges from the northwest to the southeast. The deposits comprising this plain were formed by two main deposition systems: Kashafrud River, the main drainage system of this plain, and

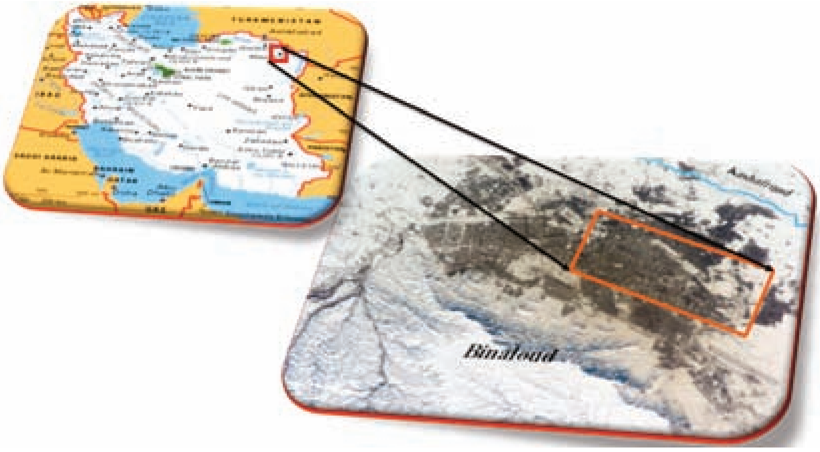

Figure 1. Satellite image of Mashhad City, in the north-east of Iran.

minor streams that originate in the southern parts of Mashhad city. Generally, with respect to the sources of sedimentation, from the margins of the southern heights towards the center of the plain, and also from the west to the east, the soil grain size decreases and the soil texture becomes finer [Akbari 2007]. Using information obtained from 169 boreholes and their analysis and interpretation using the RockWorks 2006 software (http://www.rockware.com) according to the Kriging method, in the study area, variations in the soil texture were obtained for different depths beneath the city. As can be seen in Figure 2, the soil texture at the surface of Mashhad city in the study area is 70% fine grain, 25% medium grain, and 5% coarse grain. From a seismotectonic viewpoint, Mashhad city is located between the Koppet-Dagh and Central Iran seismotectonic provinces, both of which have the potential for large and strong earthquakes [Berberian et al. 1999]. Mashhad city is thus situated in a high seismic hazard zone, with 0.30-0.35 *g* maximum acceleration (Figure 3). Among the destructive earthquakes that have occurred in Mashhad city, there were

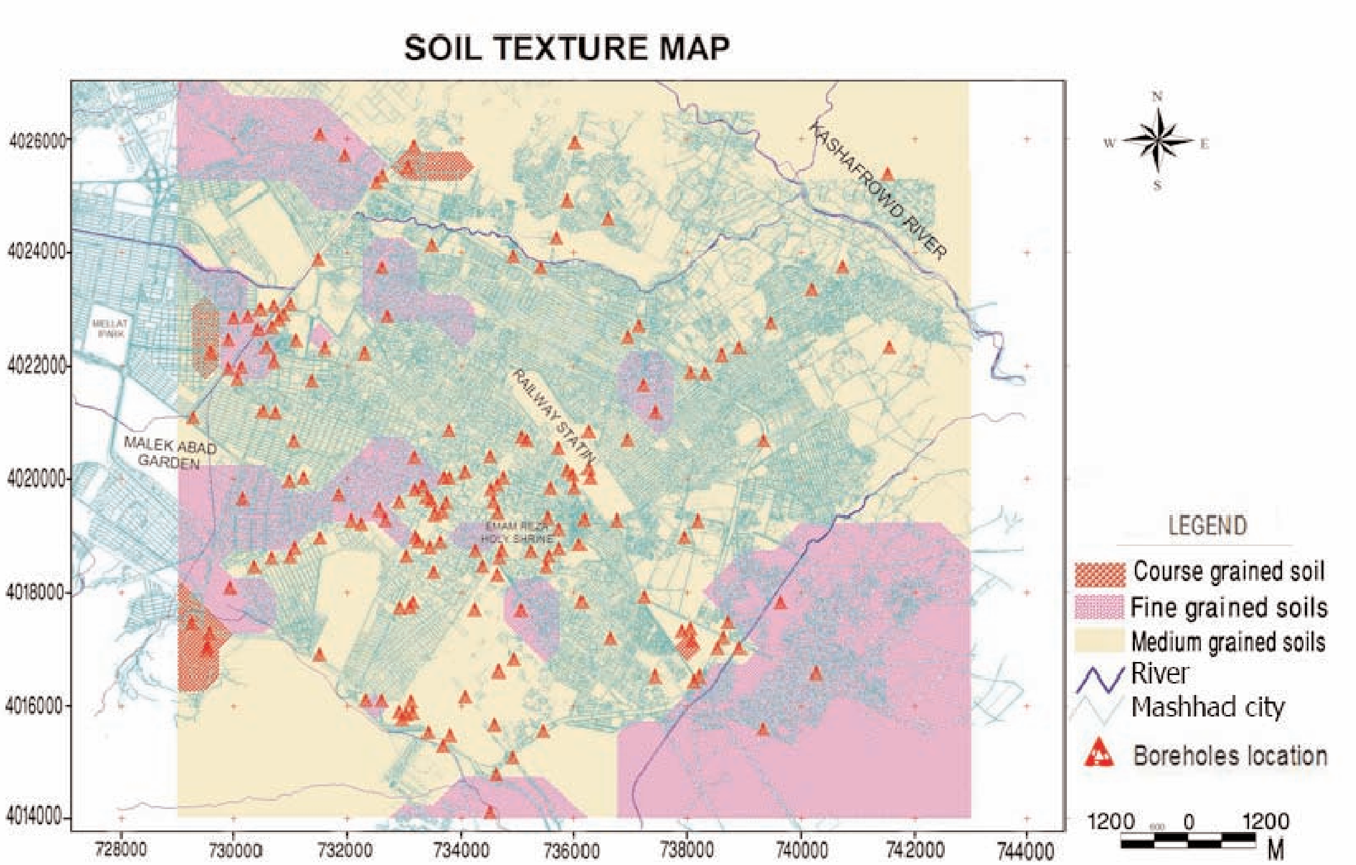

Figure 2. Surface soil texture for Mashhad city.

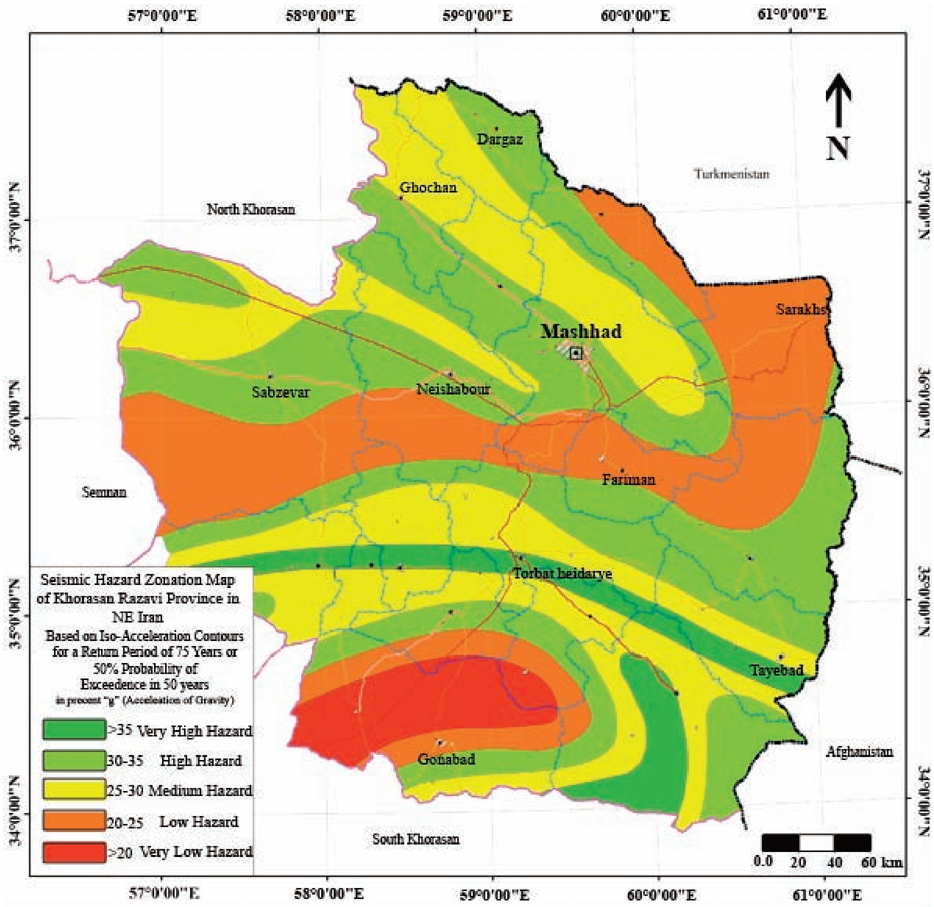

Figure 3. Seismic hazard zonation map of Khorasan Razavi province in north-eastern Iran.

the 1598, 1676 and 1678 A.D. earthquakes. The most important historical earthquake in the Mashhad area was the earthquake on July 30, 1673, which destroyed about two third of Mashhad city and killed about 4,000 people [Ambraseys and Melville 1982].

3. Predominant frequency of ground vibration

The predominant frequency of ground vibration is one of the dynamic features of soil that is important to know for reliable seismic hazard estimation and planning of earthquake-resistant structures. The importance of determining the predominant frequency of a site is that if the natural vibration frequency of a structure is the same as the predominant frequency of its site, the structure might undergo severe damage. On the other hand, the natural frequency of a structure is a very important factor in computations for seismic planning of such structures. Therefore, determination of this predominant frequency of a structure should take into account the predominant frequency of the site. Chopra [1981] defined three cases for soil structure interactions based on the relationships between natural frequency of vibration of buildings (ω) and the forcing frequency of external forces (ω_0):

1. If $\omega_0/\omega \cong 0$, i.e., the forcing frequency is much smaller than the natural frequency, then dynamic effects are negligible and maximum responses depend on the structure stiffness.

2. If $\omega_0/\omega > 1$, i.e., the forcing frequency is much higher than the natural frequency, then responses approach zero and depend mainly on the mass.

3. If $\omega_0/\omega = 1$, i.e., the forcing frequency is equal to the natural frequency of the buildings, then response is maximum and governed by the damping ratio.

Therefore, in the present study, we wanted to obtain the predominant frequencies of site vibrations in the study area. For this reason, from numerous available methods, horizontal-to-vertical (H/V) spectral ratios (HVSRs) of microtremors were used, in what is known as the Nakamura method. This method is useful for the evaluation of sites in urban areas, and nowadays it is a method well recognized in site-effect vibration studies [Nakamura 1989, 2000]. In spite of some doubts of its theoretical basis, because this method is cheap and quick, and as it allows easy collecting of data and is easy to use in low seismicity or nonseismic areas, it has wide application for site-effect evaluations [Bard 1999, Cara et al. 2003, Panou 2004]. This method can effectively eliminate source and path effects using microtremor measurements, and it can evaluate the predominant frequency of a site, especially in urban areas with high noise levels [Field and Jacob 1995, Lachet et al. 1996, Nguyen et al.

2004]. Thus, for predominant frequency evaluation for site-effect determination in eastern Mashhad, microtremors were used in association with the Nakamura method.

4. Microtremor measurement and data analysis

4.1. Instrument specification

Microtremor observations were performed using portable microtremor equipment. One Kinemetrics solid-state recorder (SSR-1) and three Kinemetrics SS-1 rangers were used for the data acquisition. The SSR-1 is a highly flexible digital seismographic event recorder. It has an amplifier, filter and digitizer, and it recorders all in one. We used only three of its six available recording channels. The SSR-1 has a 16-bit A/D converter with a dynamic range of 96 dB. This recorder also has a built-in, first-order RC high-pass filter at a 0.01 Hz corner frequency [Kinemetrics Systems 1990a, Trnkoczy and Standley 2009].

The SS-1 ranger seismometer is a short-period field seismometer which is frequently used as a sensor for ambient vibration measurements of buildings, bridges, foundations and offshore platforms. The natural period of this sensor is 1 s. The operating range frequency of the seismometer is approximately 0.1 Hz to at least 50 Hz. The frequency response amplitude is asymptotically flat above a 1 Hz resonant frequency, and decays below this with −40 dB/decay slope [Kinemetrics Systems 1990b]. Generally, seismometers are sensitive enough to record ambient noise to be discriminated on H/V curves, even at low frequencies. The problem is that when at low frequencies (below 1 Hz), the natural frequency of the seismometer is much higher than the H/V peak. In this case, deviations at low frequencies do not affect the H/V curves if and only if [Guillier et al. 2008]:

- these deviations are instrumental parameter dependant;
- these deviations are the same on all three components;
- the signal-to-noise ratio is strong enough to allow extraction of ambient vibrational signals from the electronic noise.

4.2. Data acquisition and processing

Microtremor observations were carried out on squared nets of 700 m × 700 m at 90 sites. The guidelines of the SESAME European research project were used for the implementation of the HVSR technique for microtremors. These practical guidelines recommend procedures for observation point selection, field experiment design, data processing, and interpretation of results [Bard et al. 2004].

The duration of the recorded time series at each site was 20 min, with a sampling rate of 100 Hz. The recorded time series data were divided into 29 segments, each of 40.96 s duration. For each site, 20 segments of the data were chosen, omitting the segments that were influenced by very near noise sources. These 20 segments were used for the calculations. The study used the Programmable Interactive Toolbox for Seismological Analysis (PITSA) software for filtering; PITSA is a flexible and powerful system for signal processing with digital seismic data [Scherbaum et al. 1999]. A Butterworth band-pass filter was applied, in frequency intervals from 0.125 Hz to 20 Hz, and also the linear regression method for offset correction. The Fourier amplitude spectrum calculation, Fourier spectrum smoothing, and Fourier spectral-ratio calculation of 40.96 s for the horizontal to vertical components of microtremors were performed on 20 segments which were related to each observation point in MATLAB software. The Parzen window, with a 0.3-Hz bandwidth, was used for smoothing the Fourier spectra. Several other types of digital filters are often used in seismic engineering studies, such as Hanning, Hamming and Barlet windows. The resulting spectra obtained by using any of these digital filters did not show any significant differences [Konno and Ohmachi 1998, Rodriguez and Midorikawa 2002].

The Fourier spectral-ratio calculation was performed according to the Nakamura method, as follows [Nakamura 1989]:

$$R(f) = \frac{\sqrt{F_{NS}(f) \times F_{EW}(f)}}{F_{UD}(f)}$$

where $R(f)$ is the HVSR, F_{NS}, F_{EW} and F_{UD} are the Fourier amplitude spectra of the NS, EW, and vertical components, respectively.

After obtaining the H/V spectra for the 20 windows, the average of the spectra were obtained as the H/V spectrum for each particular site. The peak frequency of the H/V spectrum plot shows the predominant frequency of the site (Figure 4).

5. Results of the microtremor measurements

Many authors have stressed the significant stability of estimates deriving from this Nakamura [1989] approach. A commonly accepted opinion is that single components of ambient noise can show large spectral variations as a function of natural and cultural disturbances, but the HVSRs are stable *versus* daily (human activity cycles) and long-term (meteorological) variations, and tend to remain invariant, preserving the peak at the fundamental resonance of a site. In this method, the peak frequency is relatively stable even when the measurements are repeated at different times, although the peak amplitude of the HVSR (the amplification factor) indicates the relative variations from site to site [Lermo and Chavez-Garcia 1993, Mucciarelli et al. 2003, Almendros et al. 2004, Parolai et al. 2004].

The H/V spectra were obtained for all of the 90 sites and the predominant frequencies of ground motion for these sites were identified. A number of the Fourier spectral ratios

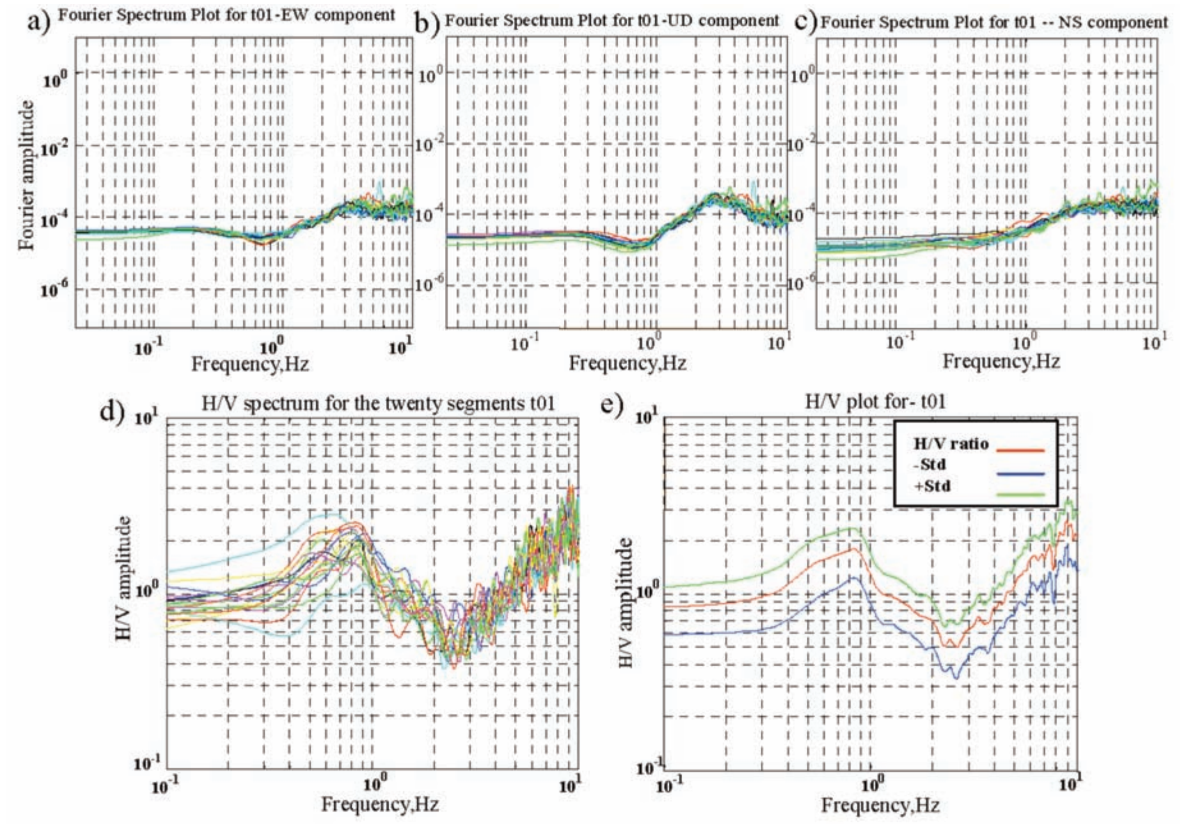

Figure 4. (a-c) Fourier spectra of horizontal and vertical components of microtremors. (d) The calculated Fourier spectral ratios related to he 20 windows. (e) The mean of the Fourier spectral ratios.

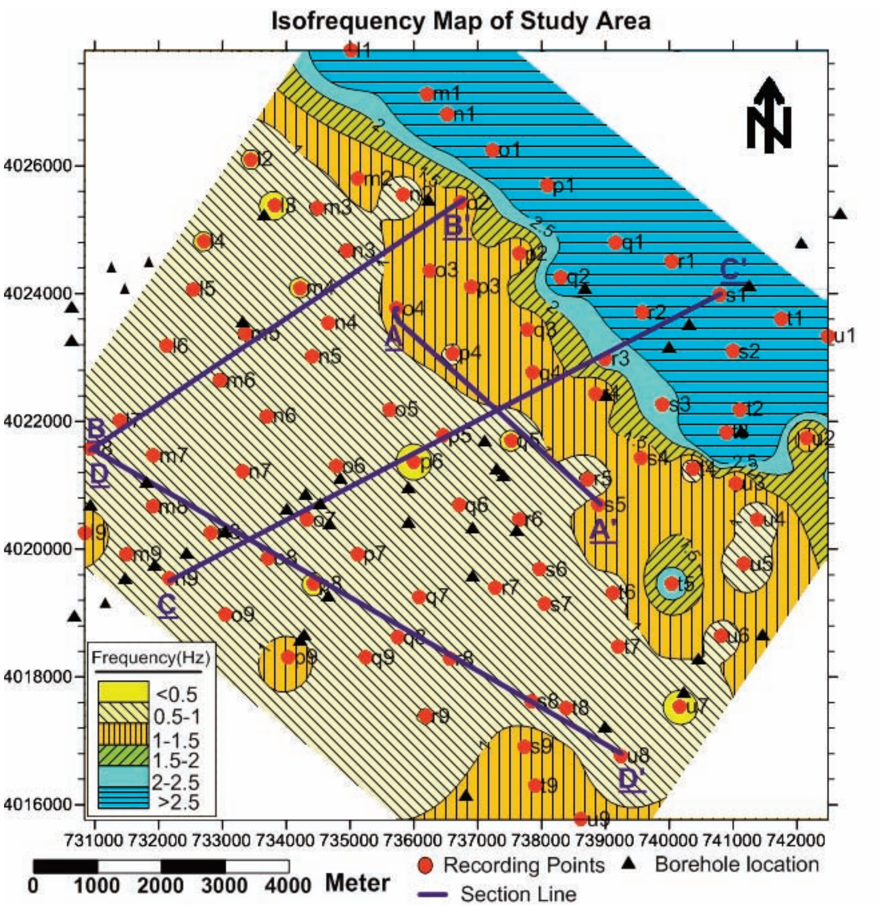

Figure 5. Iso-frequency map and locations of the boreholes (black triangles) and microtremor recording points (red circles) and the cross-sections discussed (thick black lines) for the study area.

along the studied sections are shown in Appendix 1.

Variations in the predominant frequency in the study area are shown in Figure 5, which shows that the predominant frequency in the city center was below 0.8 Hz, and that it increases in the S-SW and N-NE directions of the city. So, in the northeastern part of the city, the predominant frequency is increased significantly. The predominant frequency in this area, which included Golshahr, Panjtan end, Altimur, and Tabarsi Northern end and Khajeh-Rabee, is sometimes more than 2.5 Hz, and in some areas, it is greater than 8 Hz. Variations in the predominant frequency depend on the local site conditions, such as thickness of the soil layer, shear-wave velocity, type of soil, and variation in the topography. Since low frequency is related to thick or very soft deposits, and high frequency is related to very thin deposits or weathered rocks [Ansal 2004], it can be concluded that from the center of the study area towards the north and south the alluvium thickness decreases, or it becomes very compact. It can be seen that the predominant frequency increases towards the north-northeast of Mashhad city. This increase in the predominant frequency is because of the large decrease in bedrock depth. So these intense variations can be related to the existence of an obscured fault in this direction. The trend of this fault is the same as for Tus fault (NW-SE), which is covered by alluvial deposits. Based on geomorphologic, geophysical, geodesy and geotechnical studies, Azadi et al. [2009] reported that the Tus fault has a reverse mechanism, with a dip direction to the south-west, towards the populated area of the city. They showed that this fault enters into Mashhad from the north-west, near the town of Tus, and passes through the Khajeh-rabee (obscured fault) to the Golshahr area in the eastern part of the city.

6. Relationship between predominant frequency distribution and variations of soil texture and N-SPT

The main purpose of the SPT is to provide an indication of the relative densities of *granular* deposits, such as *sand* and *gravel*, from which it is virtually impossible to obtain undisturbed samples. Despite its many flaws, it is usual practice to correlate the SPT results with the soil properties that are relevant for geotechnical engineering design. The reason for this is that the SPT results are often the only test results available, and therefore the use of direct correlations has become common practice in many countries. On the other hand, the site effects are a function of many parameters, like surface geology, rock-sediment interface geometry, underground-layers geology, site topography and incoming wave field properties [Fah et al. 2003, Ansal 2004, Apostolidis et al. 2004]. Therefore, in the present study, according to the available information, the predominant frequency relationship with the soil texture and the N-SPT were investigated. The borehole depths at which the information was collected were between 5 m and 45 m. In the study area, with respect to the available borehole data, variations in the soil texture and N-SPT were modeled using the Rock Work 2006 software. Then, cross-sections of this model were developed in the desired directions. In the study area, the variations of the predominant frequency with soil texture and N-SPT were investigated using four different sections along which the borehole data were available (Figure 5). Table 1 shows the variations of the N-SPT with depth in the various soils in the study area.

Depth (m)	N60					
	Fine grain soils		Medium grain soils		Coarse grain soils	
	Range	Mean	Range	Mean	Range	Mean
0-5	3-43	14	3-58	19	13-44	26
5-10	5-48	15	5-57	19	12-54	28
10-15	3-44	17	7-53	20	15-54	28
15-20	5-42	18	3-47	22	16-50	30
20-25	5-45	21	6-48	25	26-54	34
25-30	8-41	22	10-57	26	13-35	20
30-35	6-38	22	8-42	29	39-59	48
35-40	9-44	22	5-51	27	--	--
40-45	28-47	39	--	--	--	--

Table 1. Variations of the N-SPT with depth in the study area.

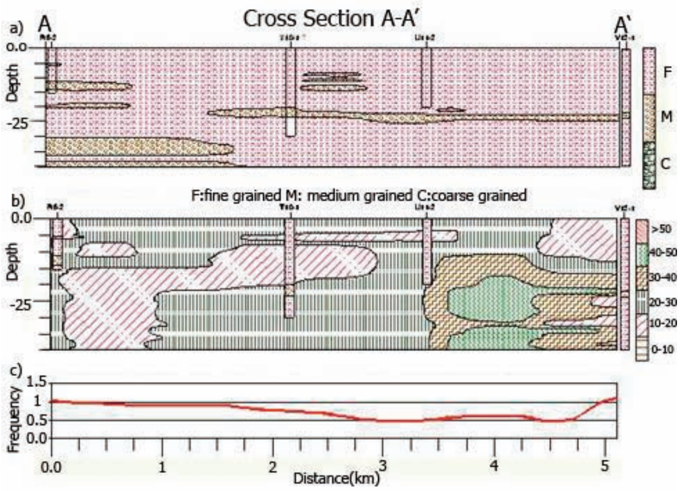

Figure 6. A-A` cross-section. Variations in the soil texture (a), N-SPT (b), and predominant frequency (c).

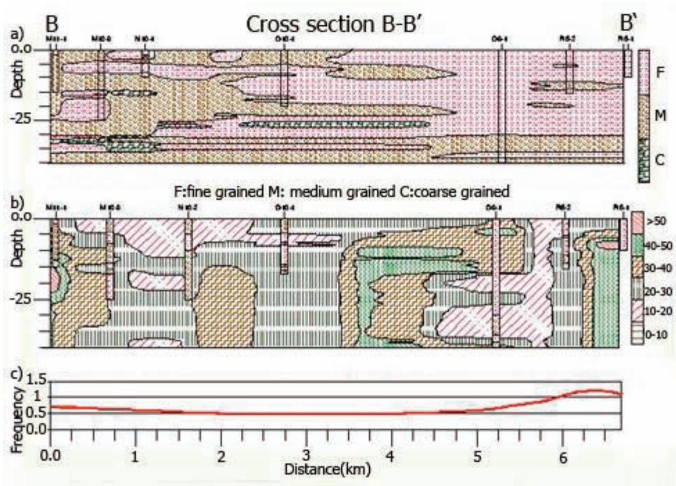

Figure 7. B-B` cross-section. Variations in the soil texture (a) N-SPT (b), and predominant frequency (c).

As Table 1 shows, the soil texture hardened and the N-SPT increased with depth.

Generally, to prepare the soil texture sections and N-SPT maps in this study, the soils were classified into three groups, as: coarse grain (gravel), medium grain (sand), and fine grain (silt and clay).

As is seen along the A-A` cross-section in Figure 6, there are no large variations in soil texture and N-SPT. Along this section, the fine grain texture is predominant. A low N-SPT in this section indicates a soft and fine grain alluvium, which explain the values of the predominant frequency. The predominant frequency in this section does not show significant variations. In addition to the soil texture, the small variations in the predominant frequency would result from thickness variations of the alluvium.

Along the B-B` section, the soil generally has a medium to fine grain texture. In this section, the coarse grain soil increases compared to the previous section. The N-SPT along this section is low and does not show much variation. The predominant frequency level in this section changes from 0.5 Hz to 1.25 Hz. At the end of this section, towards B`, the predominant frequency increases a little, which would result from changes in the alluvium thickness (Figure 7).

Along the C-C` section, for the beginning at C, the soil texture is medium grain; in the middle part, this becomes finer, and towards the end, at C`, it becomes coarser again (Figure 8a). The N-SPT along this section is mostly low. However, at the end, at C`, the N-SPT increases abruptly, which indicates very compact soil (Figure 8b). In this section, the variation of the predominant frequency is very high, and from about 0.8 Hz at C it reaches to about 5.1 Hz at C`. This large increase in the predominant frequency at the end of this section indicates a decrease in the alluvium thickness and a rising of the bedrock, and this cannot be related only to the N-SPT increase in the soil (Figure 8c). As in adjacent areas of C` the predominant frequency is high and as these areas

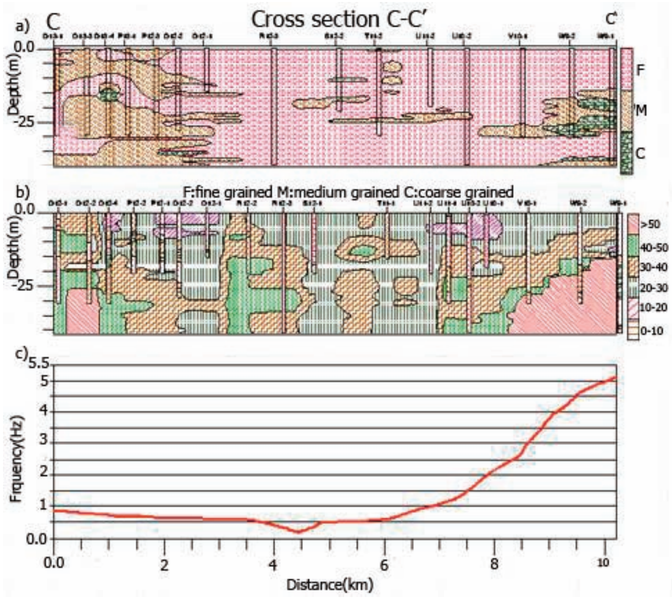

Figure 8. C-C` cross-section. Variations in the soil texture (a) N-SPT (b), and predominant frequency (c).

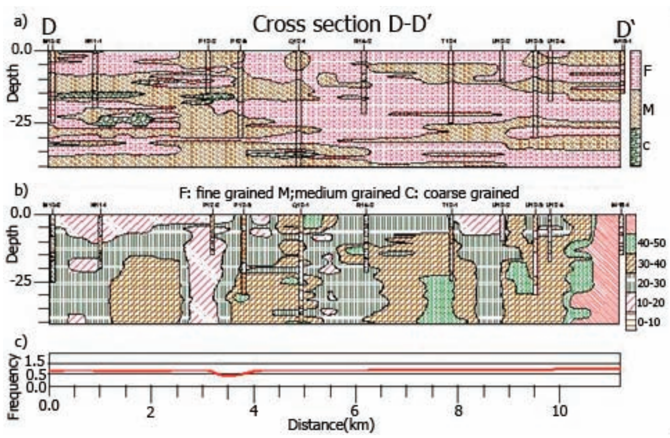

Figure 9. D-D` cross-section. Variations in the soil texture (a), N-SPT (b), and predominant frequency (c).

show a certain direction, and with respect to abrupt and intense variations in frequency in this direction, it is most probable that the bedrock in this area is dislocated by an obscured fault, and hence its depth decreases.

Along the D-D` section, the soil texture is generally fine to medium grain. The N-SPT along this section is mostly low. The variations in the predominant frequency along this section are nearly the same, and are low. This would be indicative of the same geological conditions along this section (Figure 9).

This study shows that there is the possibility of long period ground vibration in the Mashhad city area, and especially in the city center. This would result in severe damage to the long period structures, such as the high-rise buildings.

7. Conclusions

In the present study, microtremor observations were carried out in more than 90 sites in Mashhad city. Mashhad city is situated on the Mashhad Plain between Koppet-Dagh and the Binaloud mountain range. The alluvial deposits in the study area consist of 70% fine grain, 25% medium grain, and 5% coarse grain soils.

The predominant frequencies of the sites were obtained using the HVSR method. With respect to the depicted iso-frequency map, generally the predominant frequency in the city center is below 0.8 Hz and its value increases towards the south-southwest and the north-northeast of the city. The predominant frequency increases when the basement depth decreases. Good correlations were obtained between the predominant frequencies from the microtremor analysis and the variations in the soil texture and N-SPT along the several cross sections in the study area. In the C-C` section, the predominant frequency varied from considerably high values, of about 5.1 Hz at C`, to low values, of less than 0.8 Hz at C. This matches relatively well with the variations in the bedrock thickness. It is probable that the bedrock is dislocated by an obscured fault.

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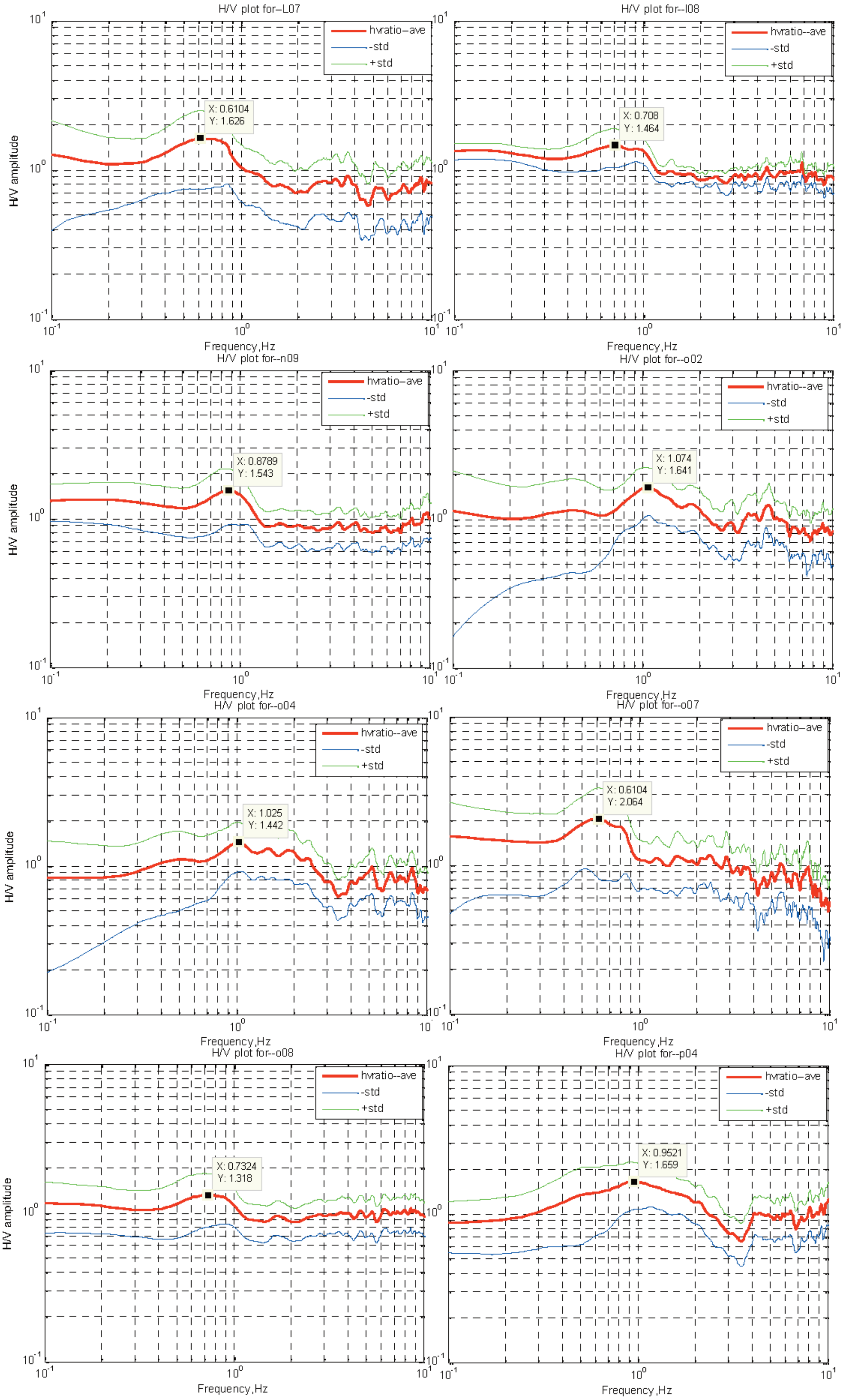
Appendix 1: Some of Fourier spectral ratios along the studied sections.



Appendix 1 (continuation).