Estimation of subsurface structure using microtremor in Karaj city, Iran

Nastaran EHSANI (1), Mohammad Reza GHAEMGHAMIAN (1), Mohsen FAZLAVI (2) and Ebrahim HAGHSHENAS (1)

(1) International Institute of Earthquake Engineering and Seismology, Tehran, Iran
E-mail: n.ehsani@iiees.ac.ir
(2) Imam Khomeini International University, Qazvin, Iran

Abstract

In order to estimate the site effects in Karaj city, microtremor H/V spectral ratios were used in 37 locations of the city along the north-south-west profile. The results show that the dominant frequency changes in the range of 0.4 to 2 Hz. 1-D numerical simulation was performed using Deepsoil software based on the linear method at low strain levels and results of theoretical response were compared with fundamental frequencies obtained from microtremor measurements. The obtained modelling results are indicative of an effective contrast at depth of 200 to 300 meters and deep contrast at a depth of about 2 kilometers due to difference in bedrock type. Finally, using the results and according to the geological conditions of the region, subsurface structures in Karaj city were examined in two-dimension along the studied profiles.

Keywords: Site effects, Microtremor, spectral ratio H/V, Dominant frequency, 1D site modelling

1. Introduction

The earthquake is one of the most devastating natural disasters that always threats human societies in terms of health and financial issues. Iran is one of the most seismic prone countries of the world due to locating on Alpine- Himalayan Orogenic belt. On the other hand, growing population and increased construction of tall buildings, increases the damages caused by large earthquakes, especially in large cities. Karaj is one of the most populous cities in Iran which there has been considerable industrial and economic development in recent years.

When an earthquake occurs, seismic waves radiate away from source and travel rapidly through the earth crust. When these waves reach the ground surface, they produce shaking that may last from several seconds to a few minutes. During earthquakes, different alluviums with different structures show various reactions. It is well-accepted that, besides the earthquake magnitude and fault distance, local geologic conditions, known as site effects, can also exert significant influences on characteristics of the seismic waves such as amplitude, frequency content and duration of strong ground motion at a given location (Kramer, 1996). The seismic ground motion at any site is influenced by the type of soil in that region. Younger and softer soils usually amplify ground motion more than older soils or bedrocks (Purnachandra Rao et al., 2011).

There are theoretical and experimental methods to evaluate the site response. In the present study, the Nakamura's H/V spectral ratio method has been used to evaluate the resonance frequency in 37 locations at Karaj site. In addition, a preliminary 1-D site response modelling has been conducted using Deepsoil program according to downhole, array and geology data. Site frequencies obtained from modelling are presented and compared with site frequencies obtained through microtremor measurements.

2. Geology and Seismicity of Karaj

Karaj city is situated 20 km west of Tehran, at the foothills of the Alborz Mountains. It is the fourth largest and most populous city in Iran which has been developed on disaster-prone areas and tectonically active region according to the seismic hazard map of Iran.

The tectonics of the Alborz Mountain is characterized by boundary conditions, due to convergence between Arabia and Eurasia, which probably began in the Cretaceous simultaneously with establishment of the Alpine-Himalayan orogeny. Andesitic and clastic rocks of the Karaj Formation were composed as the result of the Pyrenees phase in the Eocene with a thickness of more than 3300 m. Continental sediments of the Red Formation was deposited between middle-upper Miocene, which consists of conglomerate, sandstone and siltstone and has been located with disconformity on older rocks, particularly on Tuffites of the Karaj Formation. The Red Formation is considered as the bedrock in south and west of the Karaj site. The last dominant orogenic movements in Alborz occurred during the late Pliocene-early Pleistocene due to the Pasadenian phase which lead to faulting and mild thrusting in the Alborz Mountain. Conglomerate tall hills of Hezardareh Formation (or A Formation) were composed as the result of this orogeny (Rieben, 1966). The lower part of this Formation has a low porosity (Berberian et al., 1985) which can be considered as the bedrock in north of Karaj site.

The Alborz Mountains have been eroded due to the activities of Karaj and Kordan rivers as well as the rivers and seasonal floods originating from the valleys since the late Pliocene until now. Therefore, Quaternary alluvial sediments were deposited on the southern slopes of the Alborz Mountains with an area of 210 km^2 and the Karaj city has been developing on these soft and young deposits. Stratigraphy and lithology features as well as age of the Quaternary alluvial deposits were studied by Rieben (1955) as Kahrizak formations (B), alluvial sediments of Tehran (C) and recent sediments (D).

Subsidence of the Caspian Sea floor and erosion of sediments at one hand, and subduction of oceanic of Caspian Sea crust beneath the Iran crust on the other hand, increases activity of faults in northern Iran. There are many faults, fractures and lineaments in the seismotectonic zones of Alborz. Historical and instrumental studies of earthquakes in Alborz indicated that many areas such as Rasht, Fasham, Damavand, Tehran, Rey and Qazvin were destroyed by large earthquakes. Therefore, the existence of active faults near Karaj city (Figure 1) is a threatening factor in Karaj site (Karaj-Kordan, Mahdasht, North Tehran thrust, Mosha-Fasham, Eshtehard, Kahrizak, and Rey).

Therefore, evaluation of site response and assessment of natural hazard risk is very important in young alluvial sediments with respect to the geology and seismicity at the Karaj site.

3. Microtremor data collection and analysis procedures

Single station microtremor measurements at the Karaj site were carried out by the International Institute of Earthquake Engineering and Seismology (IIEES) in 2012 with a three-component broadband seismometer (Guralp CMG-6TD). In the present study, we have used 37 microtremor data along the north-southwest profile because at this profile, geological section was available and these stations contained geotechnical boreholes data. Figure 2 shows location of microtremor recording stations and geotechnical boreholes in nine sites.

Dynamic range of sensor changes between 0.033 -50 Hz and has a natural period of 1 second. 24-bit analog-to-digital (A/D) converter digitized the recorded data. The recording system was operated continuously for about 30 minutes with sampling frequency of 100 Hz.

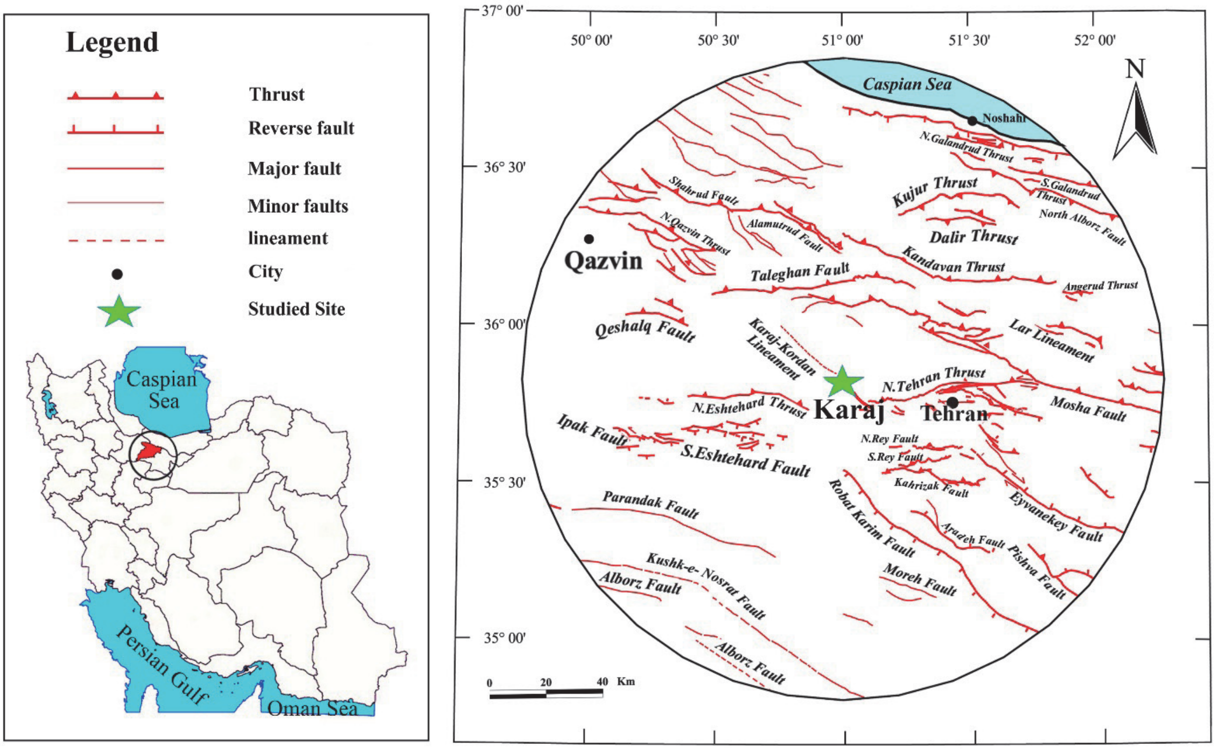


Fig.1 Active faults map of Karaj site.

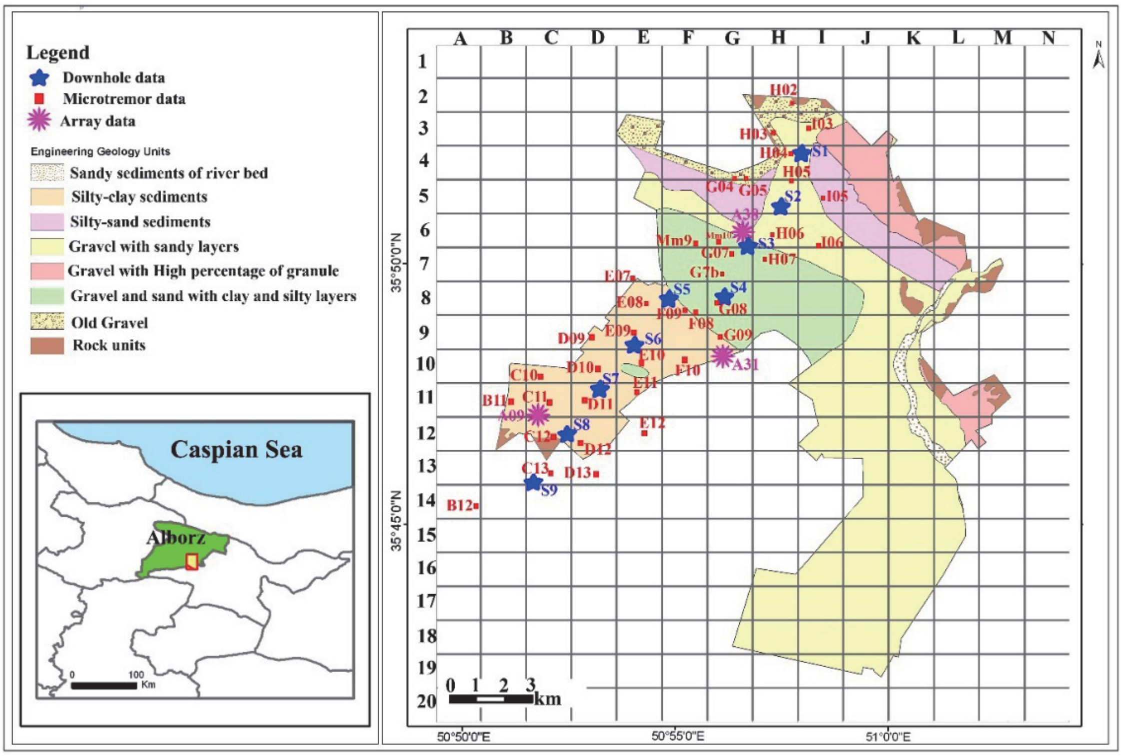


Fig.2 Karaj engineering geology map and location of microtremor recordings stations, array and downhole data.

The use of ambient vibrations for analysis of the local site effects has been studied in detail in the framework of the European research project SESAME (Site Effects Assessment Using Ambient Excitations). The recommended guidelines on the H/V spectral ratio technique are the result of the comprehensive and detailed analysis performed by the SESAME participants during three years of investigations (2001-2004).

H/V spectral ratio was carried out by the Geopsy software (Wathelet, 2007). The process starts by converting data from binary format to ASCII format. After DC offset removal, eighth order Butterworth band pass filter used within the range of 0.1 Hz to 50 Hz. The Anti-triggering algorithm STA/LTA has been selected to reject energetic transients from ambient vibration recordings, so STA and LTA were considered respectively 1 and 30 second. Minimum and maximum STA/LTA thresholds were selected between 0.2 and 2.5. For each station, the time-series of the record is divided into windows of 40 to 100 seconds in three components with an overlap of 50%. Also, a cosine taper with the length of 5% of the total window length was used at each end.

The amplitude spectra of each selected window is computed with a fast Fourier transform (FFT) and smoothed using the Konno-Ohmachi function (Bandwidth=40). Then, two horizontal components are merged by squared average. Finally, the H/V spectral ratio of Nakamura is applied for each individual window, and the final predominant frequency is obtained by averaging the H/V spectral ratio of all windows (Nakamura, 1989).

The presence of clear peak on H/V spectral ratio curve is indicative of the impedance contrast between the uppermost surface soil and the underlying hard rock, where large peak values are generally associated with sharp velocity contrasts, and is likely to amplify the ground motion (Purnachandra Rao et al., 2011). The H/V spectral ratio in some stations shows a clear peak and at the others might show two or multiple peaks which represents the geologically complex areas. The H/V analysis results as well as their average for six stations in site 8 have been shown in figure 3. Calculated dominant frequency changes between 0.4 and 2 Hz. These low values indicate the existence of basement at greater depths and large thickness of sediments on basement (Parolai et al., 2002).

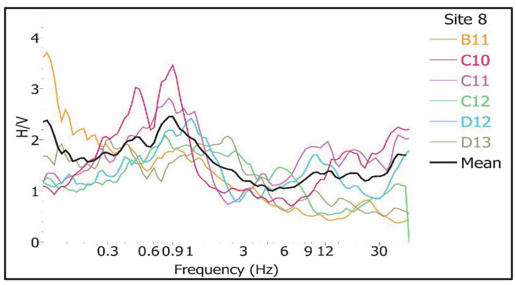


Fig. 3 The H/V results at six stations of site 8 with their mean.

4. Site modelling

The results of H/V spectral ratio are affected by the local geologic structure. Based on this assumption, we can produce theoretical H/V curve with knowledge of the geologic structure in the area (Harutoonian et al., 2010). One-dimensional modelling is a suitable method to evaluation of the site response due to the local geology which requires geotechnical and geophysical data. In the one-dimensional modelling, it is assumed that all boundaries are horizontal in the infinite media and the response of a soil deposit is predominantly caused by SH-wave propagating vertically from the underlying bedrock (Kramer, 1996).

In this present study, one-dimensional modelling was carried out using Deepsoil software (Hashash et al., 2009). Due to the very small deformations in soils by microtremor and producing a low levels of strain, we applied the linear method to evaluate the ground seismic response during mild earthquake shakes. In this software, homogeneous and isotropic soil profile is considered as N horizontal layers. The site response (transfer function) is evaluated by parameters such as layer thickness (m), density (ρ), shear modulus (G), and damping factor of layers (β), which are obtained from available geotechnical boreholes.

Usually, engineering bedrock is considered for the purpose of numerical modelling. According to TC4 (1994), the seismic bedrock was defined as a layer with a shear wave velocity of more than 600 m/s. Shima (1978) recommended that the upper crust with a shear wave velocity of about 3000 m/s, is adopted as bedrock when large scale structures with longer vibration period are being considered. International building code (ICC2000) has defined the seismic bedrock by a shear wave velocity of more than 760 m/s. According to Unified Building Code (UBC97), bedrock is defined into two groups: A (very hard rock with a speed of more than 1500 m/s) and B (rock with a speed of 760 to 1500 m/s). Therefore, the proposed values of the shear wave velocity are different for considering seismic bedrock. In order to consider the uncertainty of the shear wave velocity in the present one-dimensional modelling, three scenarios for the bedrock, were performed with three speeds of 760 m/s (based on engineering bedrock), 1300 m/s (bedrock geology), and 2500 m/s (corresponding to tuff-andesite of the Karaj basement) at different depths, according to the regional geological map. Then, three scenarios of the numerical modelling were compared with microtremor transfer function.

4.1 One-dimensional modelling at the Karaj site using downhole data for engineering bedrock (> 760 m/s)

In order to access the shear wave velocity profile for 1-D modelling, downhole data from 21 boreholes were used in nine sites (Fig. 2) which were available up to the maximum depth of 50 meters at 20 boreholes and 96 meters at A09 borehole (Figure 4). Therefore, low thickness of alluvium (about 17-85 meters) was considered with engineering bedrock (>760 m/s) for numerical modelling. The results represent higher frequency range compared with the microtremor data (Figure 5).

In some previous studies where engineering bedrock had been defined by shear wave velocity values between 700 to 800 m/s in 1-D modelling, the results of the theoretical model is incompatible with experimental results (Kamalian et al., 2008; Jafari et al., 2005). Thus, it seems that it is not suitable to consider the engineering bedrock in 1-D modelling.

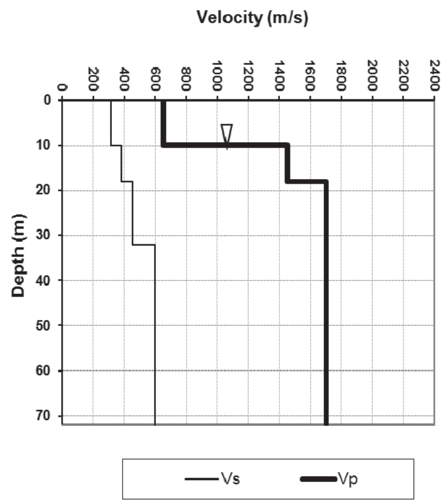


Fig.4 Shear wave velocity profile obtained from downhole test at A09 borehole (site 8).

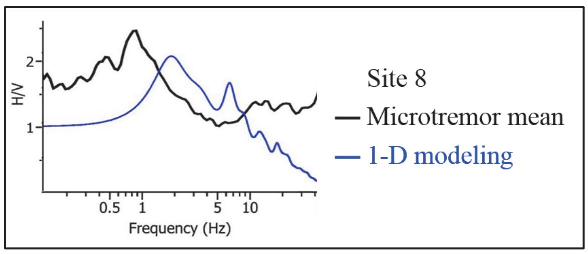


Fig.5 Comparison of empirical and theoretical transfer functions at site 8, by considering the engineering bedrock (>760 m/s) at depth of 85

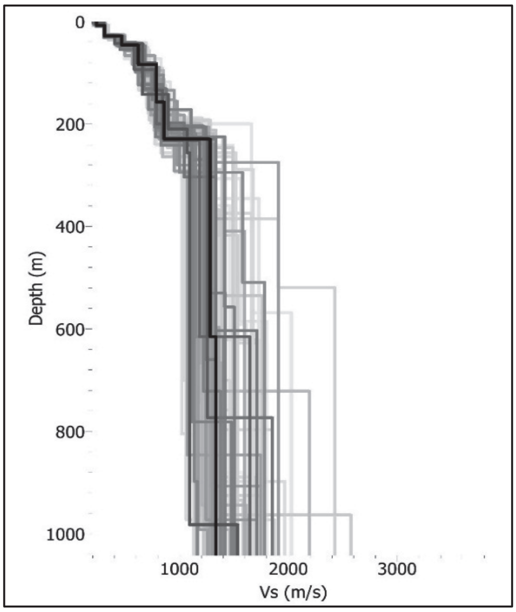
4.2 One-dimensional modelling at Karaj site using microtremor array data for geology bedrock (> 1300 m/s)

By considering the seismic bedrock (>760 m/s) at depths of 17 to 85 meters and calculating the one-dimensional transfer function, the peaks in higher frequency compared with the experimental method is observed. According to reliability of experimental H/V results which has been proved by researchers around the world (Haghshenas et al., 2008), the difference between the transfer function results in experimental and theoretical methods indicates that two variables of shear wave velocity or depth of bedrock and alluvium thickness have not been properly modeled. It seems that in order to get better results, it's necessary to analysis by considering the geology bedrock at greater depth. Tchalenko, et al., (1974) considered lower part of Plio-Quaternary sediments of Hezardareh Formation and Miocene marl-limestone of Upper Red Formation as the bedrock in the Karaj plain. Shafiee and Azadi (2006) computed shear wave velocity characteristics of these geological units throughout Tehran city (table 1). Therefore, a mean velocity of 1300 m/s was considered for the geology bedrock during the modelling.

Table 1. The mean shear wave velocity of geological units throughout Tehran city (Shafiee and Azadi, 2006).

NEHRP site classification	$\overline{V}_s(30)$ (m/s)	Type of material	Zone
A	1600	Dolomite	Eastern and southern mountains
B	1400	Limestone	
B	1200	Marly limestone	
A	2500	Basalts	Northern mountains
A	2000	Andesites and pyroclastics	
B	1300	Shales and tuffs	

In order to access the shear wave velocity profiles at greater depths, microtremor array stations were designed by seven seismometer with 100 m radius at A09 (site 8) borehole. The results have been illustrated in Figure 6. As it can bee seen, a clear contrast at a depth of about 230 m is observed. Therefore, the modelling was carried out by taking 230 m alluvial thickness on geology bedrock



according to lithology of the region. The result of this modelling has shown a peak at frequency range of 0.87 Hz that is compatible with the microtremor peaks at this site. The results and input data for this modelling are presented in table 2 and figure 7.

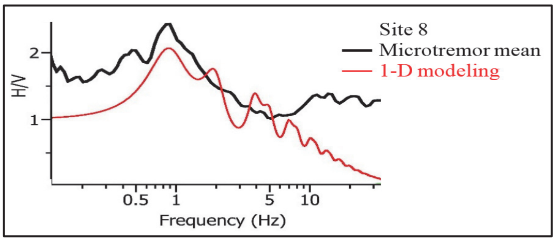


Fig.7 Comparison of empirical and theoretical transfer functions at site 8, by considering the geology bedrock (>1300 m/s) at depth of 230 m.

In other site this modelling was performed using array and downhole data. The results indicated that the first effective contrast occurs at depth of 200 to 300 meters.

Table 2. Input data in order to numerical modeling at site 8.

Thickness of layers (m)	Unit Wight (kN/m^3)	Vs (m/s)	Damp (%)
10	18	235	5
20	19.2	300	5
15	19.5	470	5
40	20	620	5
75	21	786	4
70	21	860	4
Bedrock Depth (m) =230	22	1300	1

4.3 One-dimensional modelling at the Karaj site for basement (> 2500 m/s)

Transfer functions obtained from the previous model, did not cover low frequency peaks in the experimental methods. Therefore, the presence of other low-frequency peaks is either due to the geometry of the sedimentary basin or deep contrast. It seems that due to the geology of the region, tuff-andesite of the Karaj Formation as basement plays an important role in the creation of low-frequency peaks. Therefore, to obtain a better model, deep contrast was considered about 2 kilometers due to differences in the type of bedrock with a shear wave velocity of 2500 m/s (Table 1).

For this purpose, according to the properties of the Upper Red Formation, an average constant speed of 1400 (m/s) was considered in modelling and by changing the thickness of this layer, the modelling was continued in a trial and error manner until the numerical model is consistent with microtremor peaks. The modelling results in nine site indicate that there is basement at the depth of 2000 to 2250 meters. Comparison of empirical and theoretical transfer functions at site 8, are presented at figure 8, by considering the Karaj basement (>2500 m/s) at depth of 2200 m.

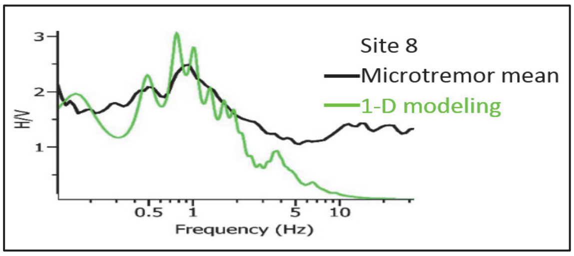


Fig.8 Comparison of empirical and theoretical transfer functions at site 8, by considering the Karaj basement (>2500 m/s) at depth of 2200 m.

5. Two-dimensional model of the Karaj site

Using the one-dimensional analysis and evaluation of the geological map of the area, two dimensional geological structure was rebuilt in studied profiles which is shown in Figure 9. Green and gray tuffs and igneous rocks of Karaj Formation outcrops in north of Karaj and constitute the Alborz Mountains. This Mountains eroded by the action of rivers and were deposited in the form of large alluvial fans. Coarse sandy sediments were deposited near mountains wherein energies of rivers and streams were extremely high (site 1 to 4). Furthermore, fine-grained sediments were deposited at far distances by decreasing in the energy of streams (site 5 to 9). Berberian et al (1985) divided B Formation in two parts: heterogeneous deposits of sand, gravel, rock and clay in north of Tehran (Q_{bn}) and silts and clays of Kahrizak (Q_{bs}) in south of Tehran. According to 1-D modelling, thickness of this layer is about 200 to 300 m which has been deposited on geology bedrock. As mentioned before, lower parts of Hezardareh Formation at the north of Karaj and Upper red Formation in the south west of Karaj are considered as geology bedrock. Upper Red Formation was deposited with unconformity on tuff-andesite of the Karaj basement at depths of 2000 to 2250 meters.

6. Conclusions

The use of empirical methods based on microtremor is an efficient way to estimate the site effects in Karaj city, although the use of earthquake records could provide better evidence of the depth and geometry of basement. One-dimensional modelling of shear wave velocity profiles obtained from downhole data and considering the engineering bedrock (> 760 m/s) at depths of 17 to 85 meters, is not a good way to estimate the dominant frequency of alluvium. By considering the greater depth of alluvium and using shear wave velocity profiles obtained from microtremor array, 1-D modelling was carried out for geology bedrock (1300 m/s). Therefore, peak frequency in transfer function at the range of 0.87 Hz has been associated with effective contrast at depths of 200 to 300 meters. It seems that Karaj basement (> 2500 m/s) with about 2 kilometers depth plays an important role in the production of low-frequency peaks in transfer function.

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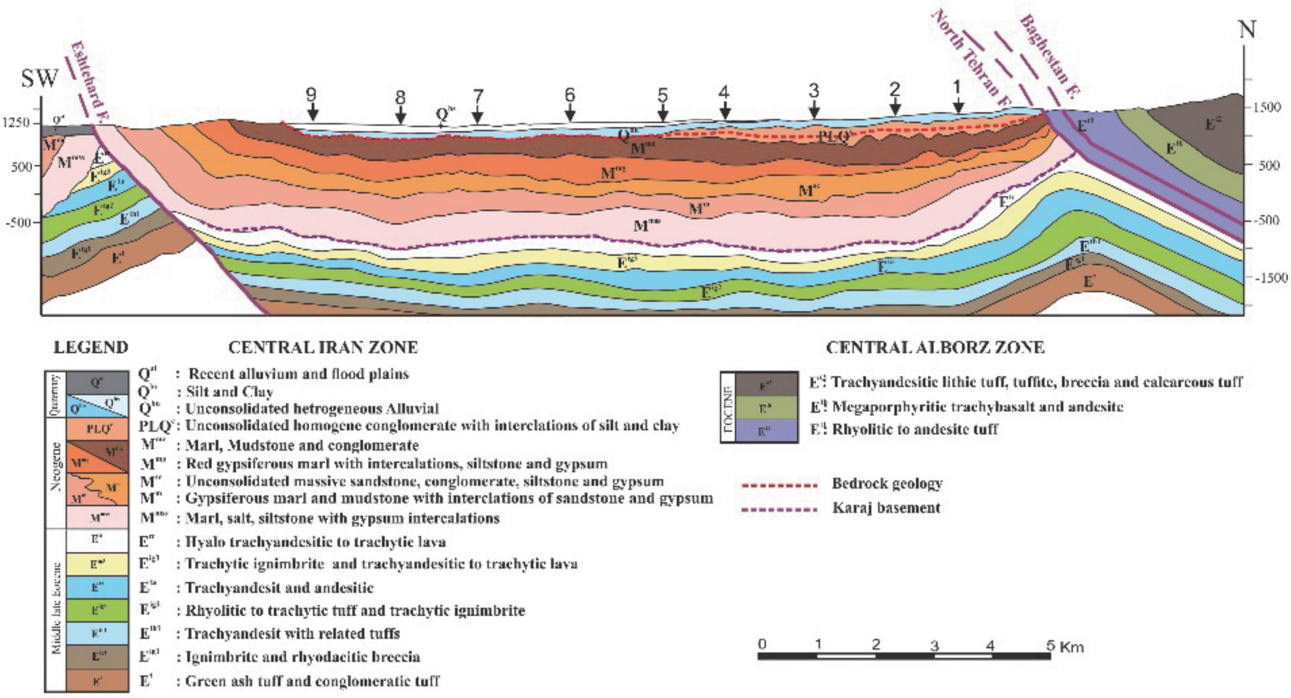

Fig. 9 Two-dimensional model of Karaj subsurface structure (Derived from the geological map with changes)

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