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Site effect microzonation of Babol, Iran

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Abstract. Extensive researches on distribution of earthquake induced damages in different regions have shown that geological and geotechnical conditions of the local soils significantly influence behavior of alluvial areas under seismic loading. In this article, the site of Babol city which is formed up of saturated fine alluvial soils is considered as a case study. In order to reduce the uncertainties associated with earthquake resistant design of structures in this area (Babol city), the required design parameters have been evaluated with consideration of site's dynamic effects. The utilized methodology combines experimental ground ambient noise analysis, expressed in terms of horizontal to vertical (H/V) spectral ratio, with numerical one-dimensional response analysis of soil columns using DEEPSOIL software. The H/V spectral analysis was performed at 60 points, experimentally, for the region in order to estimate both the fundamental period and its corresponding amplification for the ground vibration. The investigation resulted in amplification ratios that were greater than one in all areas. A good agreement between the proposed ranges of natural periods and alluvial amplification ratios obtained through the analytical model and the experimental microtremor studies verifies the analytical model to provide a good engineering reflection of the subterraneous alluviums.

Keywords: site effect; Babol; amplification; DEEPSOIL; microtremor

1. Introduction

During an earthquake, geotechnical properties of shallow soil layers sometimes dramatically influence the characteristics of seismic waves. The soil surface often shows complex heterogeneities in the various directions in three dimensional space. Even though seismic waves generally travel tens of kilometers in rock and less than 100 m in soil, the soil plays a very important role in determination of the characteristics of the ground motions (Kramer 2005).

Microzonation is defined as subdivision of a region into zones in which earthquake effects can be regarded to be relatively similar. Geological, seismological and geotechnical issues are considered by a microzonation process in order to obtain seismic hazard zones that can be used by architects and engineers. Economical, sociological and political issues are regarded in microzonation for obtaining structures less susceptible to earthquake induced damages. General guidelines addressing the types of new structures that are most suited to an area as well as relative damage likelihood data of the existing structures are provided by a microzonation process (SAARC 2011). During previous earthquakes, many civil engineering structures located in high

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seismic hazard zones mainly covered with deep saturated soil deposits have suffered partial or total damage. The 1985 Mexico City earthquake can be given as an example (Finn and Nichols 1988). Therefore, a good understanding of site response under seismic loading and developing well-established constitutive models is an essential need. During the past years, empirical relations for estimating seismic parameters of ground level have been proposed. The first relationship was proposed by Seed *et al*. (1976) as a diagram that could be used for estimating the expected peak ground acceleration of the site. The results of a survey on peak acceleration of the site's alluvial bedrock proposed an earthquake magnitude of about 6.5 for different sites located at the west of America. Later, Idriss (1990, 1991) used the data of more recent devastating earthquakes occurred at Mexico City (1985) and Loma Prieta (1989) along with numerically obtained results to derive advanced curves for estimating ground surface acceleration in alluvial environments. Also, Joyner *et al*. (1981) suggested that the shear wave velocity profile obtained to a depth equal to one fourth of the wavelength at the desired period can be used as a representative of site conditions. Then, Borcherdt *et al*. (1991) showed that there is a significant relationship between the average shear wave velocity to a depth of 30 meters ($V_{s_{30}}$) and intensification of seismic waves. Borcherdt (1994) presented alluviums classification based on the average shear wave velocity in the upper 30 meters. They presented acceleration magnification values for different categories of soil and bedrock regarding both short and long periods. Seed *et al*. (1991) presented another classification based on shear wave velocity of the upper 30 m depth bedrock and other descriptive characteristics of the soil layer. They also introduced charts to estimate ground acceleration for each category according to acceleration of the substrate. The results of these studies, along with studies of Dobry *et al*. (1994) has been used as a basis for site classifications and design spectra provided by valid codes of seismic designs. However, after the 1994 Northridge earthquake, studies showed that decrease in peak ground acceleration by increase in bedrock acceleration was not as high as it was considered before and, therefore, effect of soil interaction on nonlinear seismic response of buildings was revised (Rodríguez-Marek *et al*. 2001). In other words, the coefficients provided by existing codes were shown not to result in an adequate safety margin for accelerations estimated above the bedrock. Therefore, the results obtained by Seed *et al*. (1991, 2001) which were in contrast to other studies, were validated by the experiences of recent earthquakes saying that higher amplification ratios and a more conservative approach have to be determined.

In recent years, some researches, e.g., Shoji *et al*. (2005), Roy and Sahu (2012), Hasancebi and Ulusay (2006), and Rosset and Chouinard (2009), have shown that larger amplification ratios are expected at softer sites compared to those of the harder sites. Moreover, Chávez-García and Tejeda-Jácome (2010) showed that even if the soil structure is quite simple, it is not easy to estimate the properties of the basement which are required to correctly estimate the maximum amplification. Altun *et al*. (2012) performed one-dimensional dynamic site response analyses and provided microzonation maps that addressed maximum surface ground acceleration, amplification factor and ground shaking intensity while also studied seismic hazard distribution. Weimin and Chen (2009) used analytical models for studying the deep saturated soil deposits in Shanghai and approved the ability of the utilized model in capturing fundamental seismic characteristics of the studied deposits and stated the results to be useful for design of engineering structures. Park and Hashash (2005) proposed site coefficients which were lower at short periods and higher at long periods than the 1997 NEHRP site coefficients. Assimaki and Kausel (2002) modified the iterative algorithm for soil amplification and improved it by accounting for strain amplitude alteration resulting from damping with frequency, and the confining effect of the soil pressure on its degradation. Phillips and Hashash (2009) estimated energy dissipation in one-dimensional sites through two new response analysis methodologies. The proposed methodologies were applied and verified in a series of time-domain elastic site response analyses with and without constant damping.

Babol is one of the Mazandaran county's cities located in a region 13 km distant from the Caspian Sea in the southern direction and 10 km away from the Elburz Mountains in the northern direction (Fig. 1). High population concentration of the city and existence of active faults in the vicinity have resulted in the region's high seismic risk which calls for further consideration of city's seismicity in terms of the dynamic response of deep saturated soil deposits of the city for achieving a higher safety in earthquake-resistant designs. Accordingly, a comprehensive study is carried out to assess the seismic hazard of Babol city based on a probabilistic approach. The seismicity and seismotectonic details have been considered within a 150 km radius of the study area. The one dimensional ground response analysis was carried out for 35 representative sites by the equivalent linear method using the DEEPSOIL program in order to estimate the ground motion parameters considering the local site effects. Moreover, through an experimental approach, known as the H/V method ground ambient noise records were used to estimate the site amplification and the fundamental period of the soft soils (Nakamura 1989). In this approach, site effects can be characterized by the ratio between the Fourier spectra of the horizontal and vertical components of microtremors of a station. Following, a number of research studies addressing the H/V method are

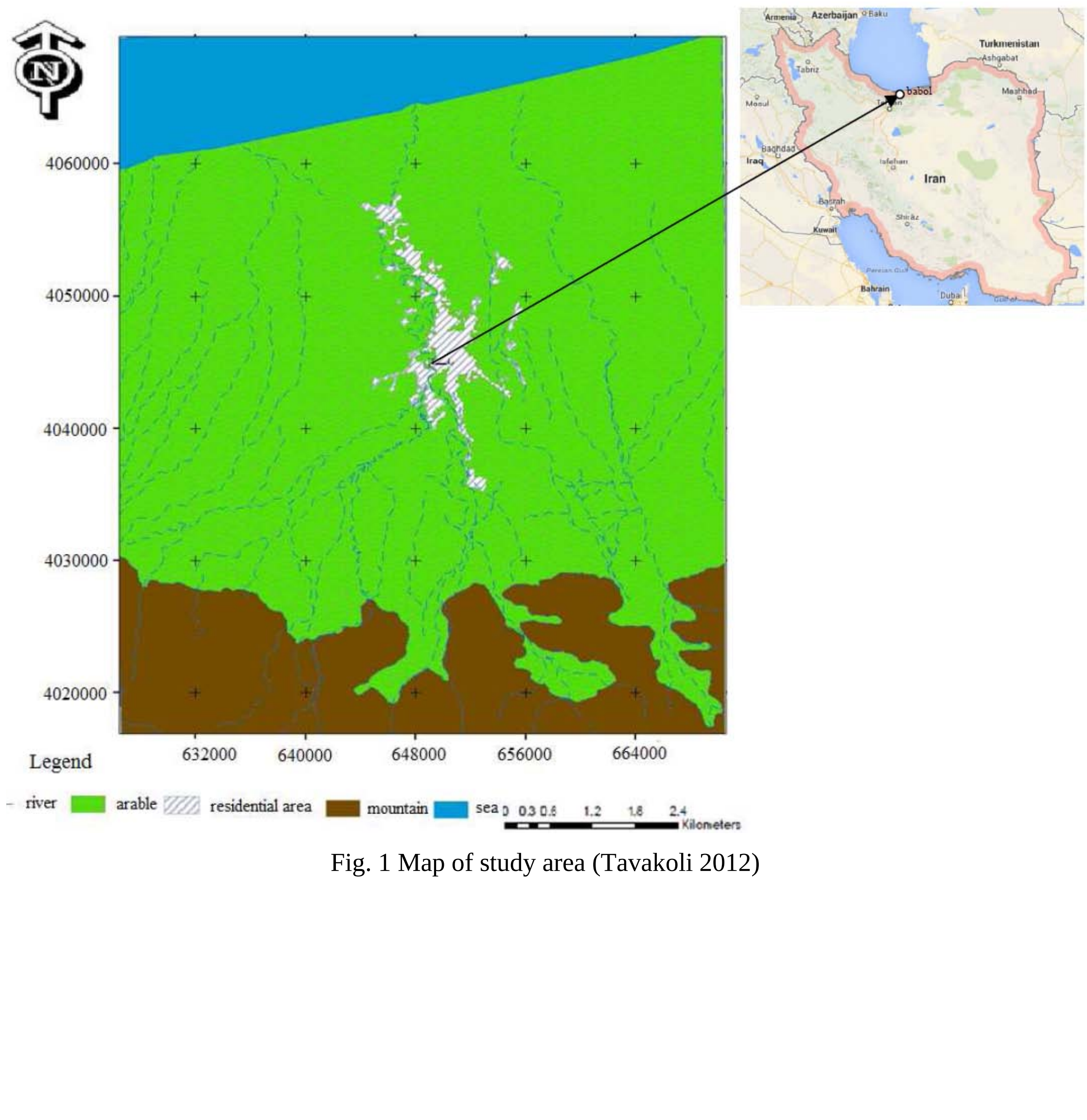


Fig. 1 Map of study area (Tavakoli 2012)

reviewed. Lozano *et al*. (2009) found negligible dependence between site effects and the source location and type Koçkar and Akgün (2012) identified three key factors that affected site response including the age of the local geological formation, the depth of the soil thickness and soil characteristics in the younger sediments, and non-uniform subsurface configurations. Di Giulio *et al*. (2008) compared H/V spectral ratios of ambient noise obtained from borehole data to those obtained from theoretical transfer functions of 1D models along five well-constrained profiles. For this purpose, the near-surface geology parameters were regarded. In a similar study, Kamalian *et al*. (2008) used microtremor measurements and one-dimensional non-linear site response analyses of the geotechnical profiles representing the Qom city's geotechnical model.

2. Seismic hazard analysis

The national seismic hazard maps are generated using a method called probabilistic seismic hazard analysis, or PSHA, which estimates the probability of exceedance of different levels of ground motion intensity at a given location. PSHA has been employed by many researchers, including Bommer *et al*. (2013), Bindi *et al*. (2012), Han and Davidson (2012) and Sokolov *et al*. (2004), to characterize the potential ground shaking levels subsequent to future earthquakes in the region. This is approximately valid for earthquake catalogs that have been "declustered", i.e., catalogs in which all dependent earthquakes, aftershocks and foreshocks, have been deleted. Probabilistically speaking, magnitude and likelihood of different earthquake sources near the study site must be evaluated using attenuation laws and considering the random nature of variables involved. Accelerations, velocities and displacements as well as the frequency content of the strong motion are resulted, finally, as a single curve that integrates effects of all earthquakes of different sizes, occurring at different sources and at different probabilities of occurrence. This curve shows the probability of exceeding different levels of ground motion, during a specified period of time. Following the PSHA approach, analyses were carried out using the earthquake catalogue available over a radius of 150 km around Babol city. For seismic studies, a complete and homogeneous catalog of earthquakes is required. The seismotectonic conditions of Babol are influenced by the condition of the Iranian tectonic plate in the Middle East. The most significant and primary faults in the vicinity of Babol City include: Khazar, North Alborz, Kandevan, Mosha, North Tehran, Astaneh, Atari and some other faults (Fig. 2). The seismicity parameters, including the Gutenberg–Richter parameter (β), maximum possible earthquake (M_{max}) and mean activity rate (λ) of each seismic zone used for the PSHA are given in Table (1). Both, the seismicity and the attenuation of strong ground motion are needed to be known for a reliable assessment of seismic hazard in a region. The uncertainties associated with the seismic wave attenuation form some of the important uncertainties in earthquake hazard analysis. Obtaining attenuation relationships of peak ground accelerations has been the subject of several studies carried out for different regions of the world. These studies, however, have led to widely varying peak ground acceleration results due to use of different databases and published empirical attenuation relations. Therefore, selecting a relationship that can be considered appropriate for a specific application has become difficult. Additionally, differences between geological and tectonic features of the area a particular relationship has been proposed for the target area may lead to inaccurate values. Therefore, two proper attenuation relationships proposed by Campbell and Bozorgnia (2006) and Ambraseys and Douglas (2005) have been considered. The calculated bedrock horizontal and vertical peak ground acceleration (PGA) for different years return period of the study area are presented in Figs. 3 and 4.

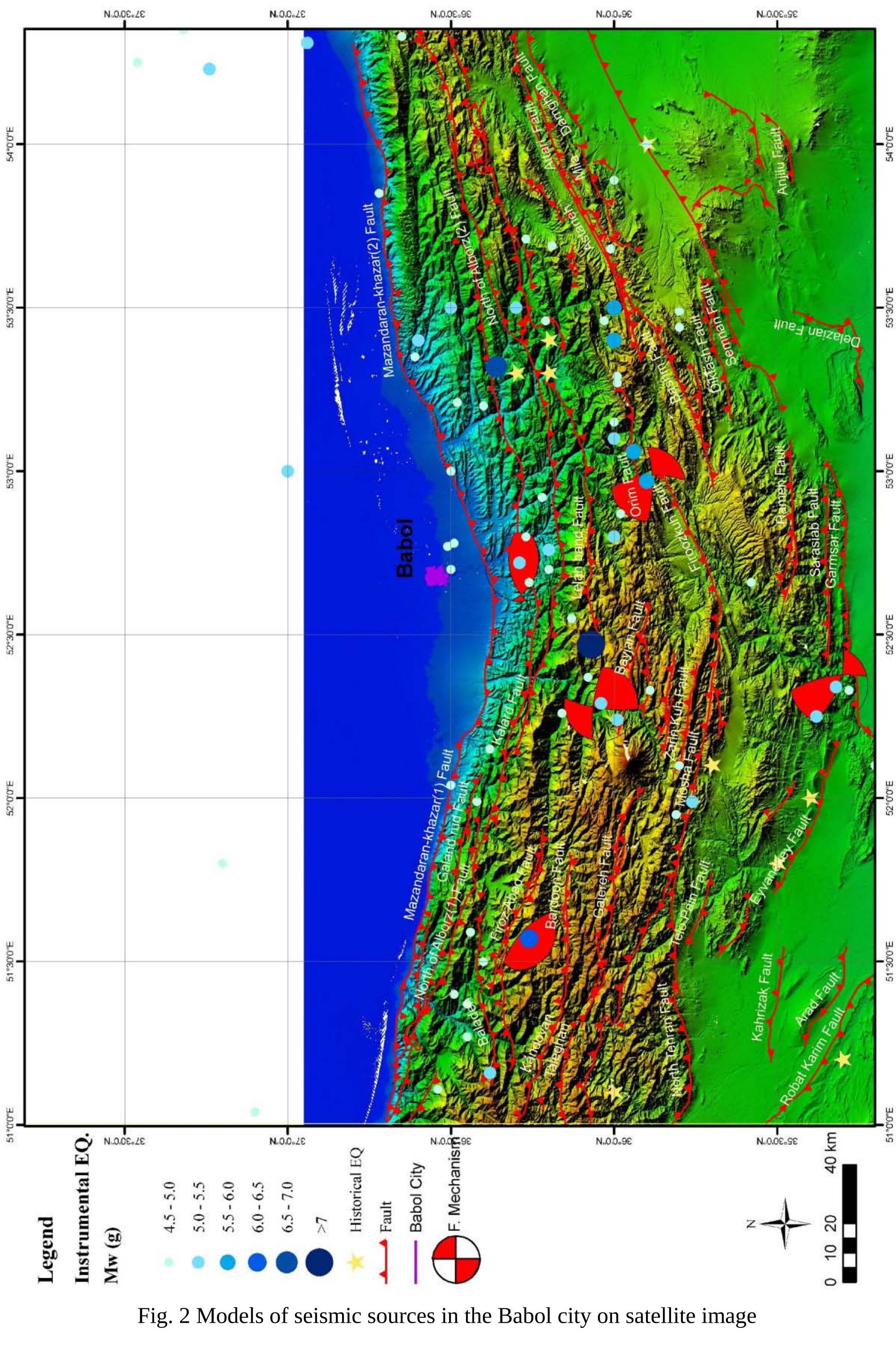


Fig. 2 Models of seismic sources in the Babol city on satellite image

Table 1 Parameters of seismic zones used for the PSHA

Zone	β	λ	M_{max}
1		7.3	7.1
2		8.7	7.7
3		8	6.5
4		8.2	6.5
5	2.23	8.2	7.2
6		7.8	6.5
7		7.6	7
8		8	7
9		9.9	6.2

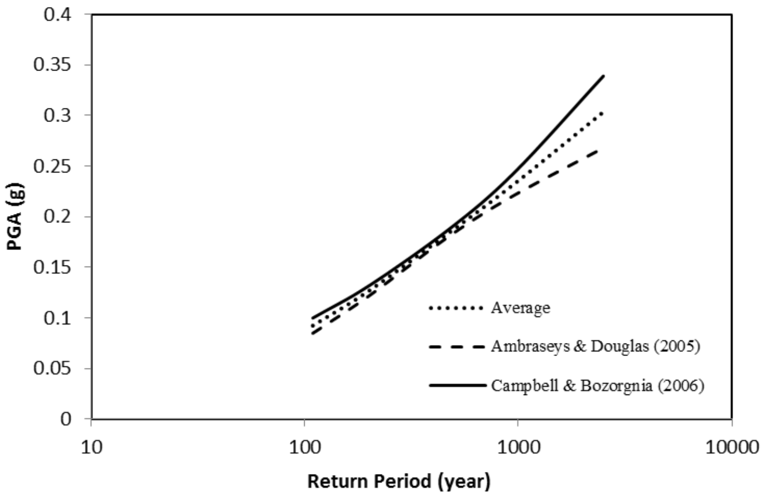


Fig. 3 Bedrock horizontal peak ground acceleration

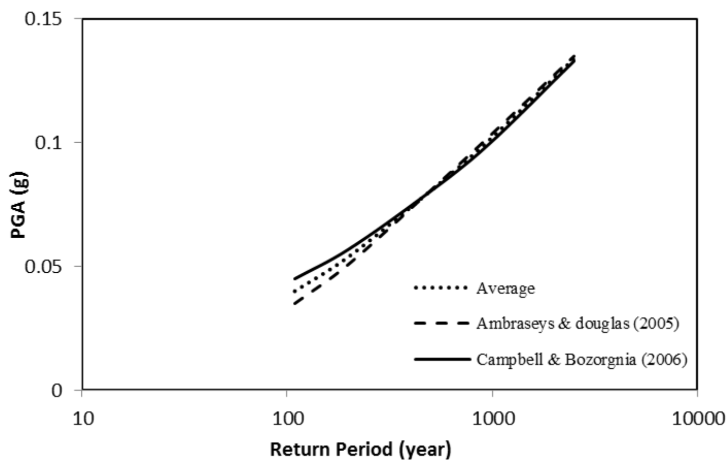


Fig. 4 Bedrock vertical peak ground acceleration

3. Site effect estimate

The parameters of a ground motion in any region are influenced by the soil type in that region. Roullé and Bernardie (2010) and Lombardo *et al*. (2006) have shown the importance of very shallow soft layers as peat or saturated mud in low frequency site effects simulations. Also, Altun *et al*. (2012) showed that the geological factors play very important role in distribution of ground motion parameters in Izmir, Turkey. Locally speaking, amplification of the ground motion is commonly dominated by the soft surface layer due to the trapping of the seismic energy trapped in this layer as a result of the impedance contrast between the soft surface soils and the underlying bedrock. Resonance patterns are determined by the interference between these trapped waves. Geometrical and physical characteristics of the structure determine the amplitude and frequency of these resonance patterns that are very simple in horizontally layered media but become very complex for 2D and 3D structures.

Joyner and Chen (1975) investigated the effects of site parameters such as secant shear modulus, low-strain damping ratio, types of sand and clay, location of water table, and depth of bedrock. The parametric studies have shown that the secant shear modulus, depth of bedrock, and types of sand and clay have a significant effect on the results of site response analysis.

Moreover, the studies of ground motion amplification related to: (a) surface topography; (b) to sedimentary sites; and (c) to strong lateral discontinuities, are highly revealing. The direct effect of site peculiarities was seen in wave propagation phenomena. Due to the flatness of Babol's topology, topography was not considered, in this study, and the city's geotechnical properties of soil layering was regarded as the most determining factor in Babol's site effect.

As a part of the microzonation study in this research, investigated region was divided into cells of 1×1 km size in order to be able to analyze and evaluate the available geotechnical information. For obtaining these information, the microzonation studies were regarded and the site data obtained through soil borings were used for extracting soil profiles down to the bedrock level for each cell (Fig. 5). Wherever one or more borehole data were available, representative (hypothetical) soil profiles of the grids were reevaluated by considering those borings. Nevertheless, for the grids with no borehole information, available hypothetical soil profiles were constructed by utilizing the available data from the neighboring grids using interpolation and extrapolation methods considering the topographical conditions and geology. In this study, the sub-surface condition and the soil structure have been determined with reference to the NEHRP code and using the information obtained from drilled boreholes, aerial photos, visited man-drilled and natural trenchings and observed sedimentation rate at the plains (Fig. 5). As it can be seen in this figure, major deposits in the north and south of the town are fine-grained clay-silt sediments with low plasticity. In central part of the city, a small area of silty sand can be seen. Areas in the eastern regions are covered with made ground to a depth of 2 meters. Also, western area as well as parts of the northern side is covered with silty clay sediments. A small area starting from the center and extending towards the south east and north directions is formed by silty soils.

3.1 Site classification

Shear wave velocity is a critical factor to identify the stiffness of the sediment in determination of the amplitude of ground motion and might be a useful parameter to characterize local sediment conditions quantitatively for calculating site response (Holzer *et al*. 2005, Park and Elrick 1998). In this study, to determine the shear wave velocity, a downhole testing is used. Thus, the shear

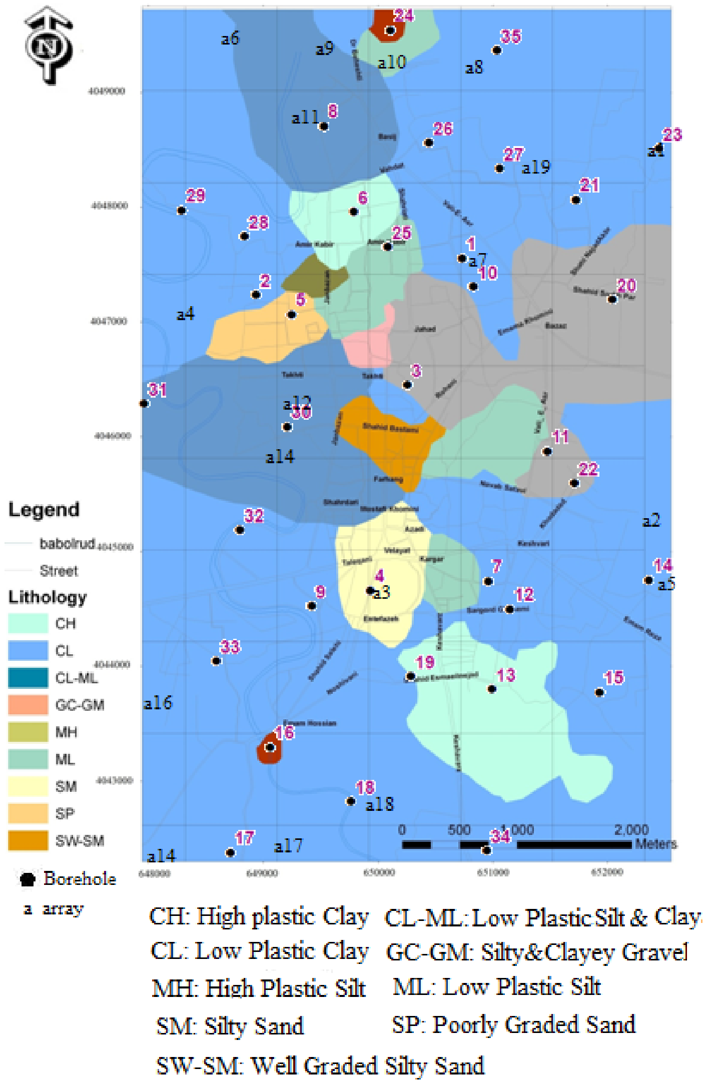


Fig. 5 Distribution map of sub-surface soils and positions of the borings and microtremor array (Tavakoli 2012)

waves are generated by the impact of a hammer on two sides of a wooden beam. The beam has been in a perpendicular position in a distance of 3 meters of speculation. Generating these seismic waves at the surface and acquiring data in three dimensions, the shear wave velocity is measured at different depths and intervals sampled at 1.5 and 2 m in the borehole. Accordingly, the shear wave velocity to a depth of 30 meters is obtained at 35 equivalent site models across the city of Babol. In order to extract the shear wave velocity to a depth of 130 meters, a microtremor array was used (Fig. 5). In this regard, extended spatial autocorrelation method and refraction microtremors have been used, in this study. In Fig. 6, variation of the shear wave velocities to a depth of 130 meters of several profiles was presented. The variation of the average shear wave velocities in the upper 30 m of the region as well as the soil classes among National Earthquake Hazard Reduction Program

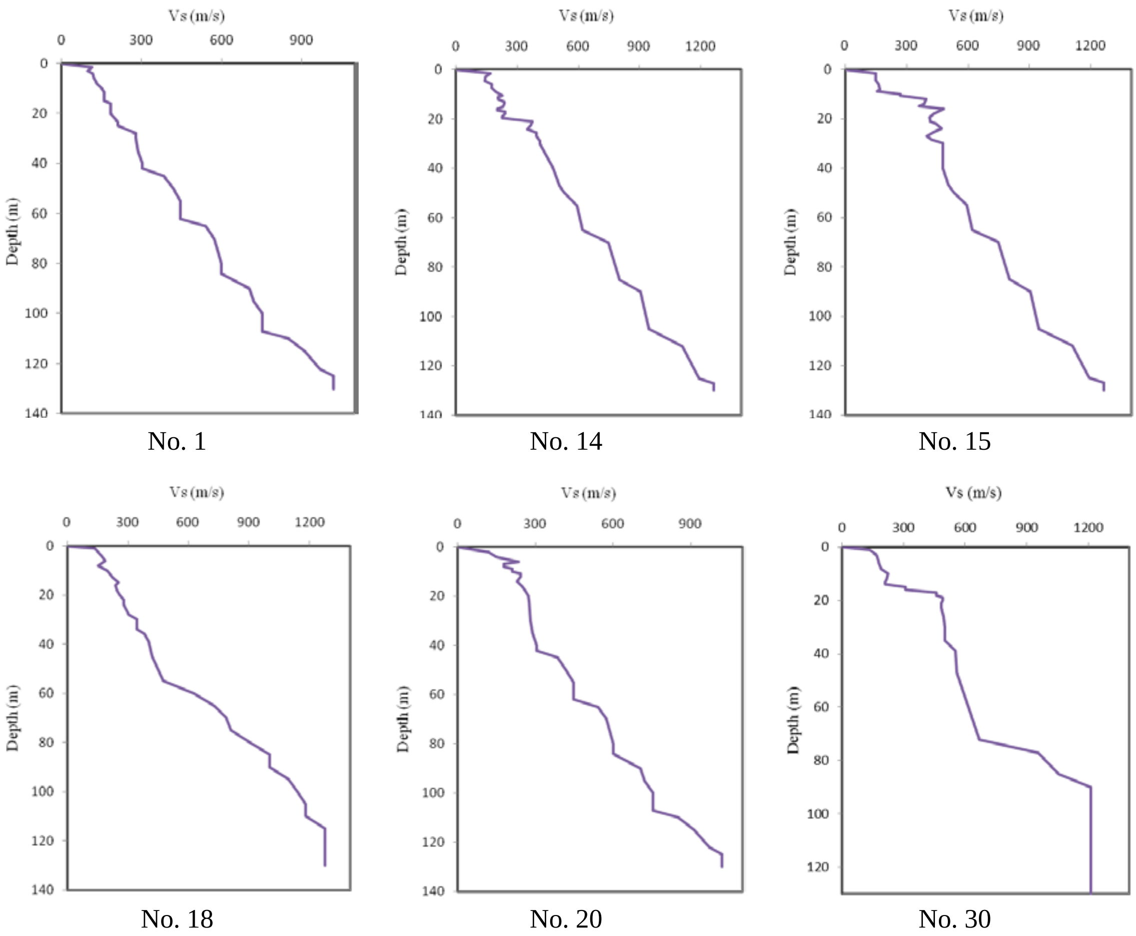


Fig. 6 Shear wave velocity changes to a depth of 130 meters of some profiles

(NEHRP 2000) are thematically investigated to determine the variation of soil properties in the region. The average shear wave velocity measurements of 30 m [V_{s30}] for soil classes provided by NEHRP provision were listed in Table 2. $V_{s(30)}$ have been calculated in accordance with Eq. (1) below, and then used to develop categories for local site conditions.

$$V_{s\,(30)} = \frac{30}{\sum_{i=1}^{30} \frac{h_i}{v_{si}}} \tag{1}$$

Where h_i and V_{si} denote the thickness (in metres) and the shear-wave velocity of the i^{th} layer, in a total of N, existing in the top 30 m.

The obtained results were mapped using GIS techniques by applying linear interpolation among the site equivalent models. According to the Eq. (1), average shear wave velocity at the 30 m depth varied between 150 and 300 m/s in various profiles with the majority of the areas having a value between 180 and 300 m/s. Regarding these data, the classification of the different profiles was performed. Thus, the NEHRP site classification based on average shear wave velocities indicated

Table 2 Site classification scheme in terms of V_{s30}, according to NEHRP provisions and geological sketches

Classification	Definition of V_{s30} (m/s)	Geological sketch
A	$V_{s30} > 1500$	Hard rock
B	$1500 \geq V_{s30} > 760$	Firm to hard rock
C	$760 \geq V_{s30} > 360$	Dense soil and soft rock
D	$360 \geq V_{s30} \geq 180$	Stiff soil
E	$180 > V_{s30}$	Soft soil

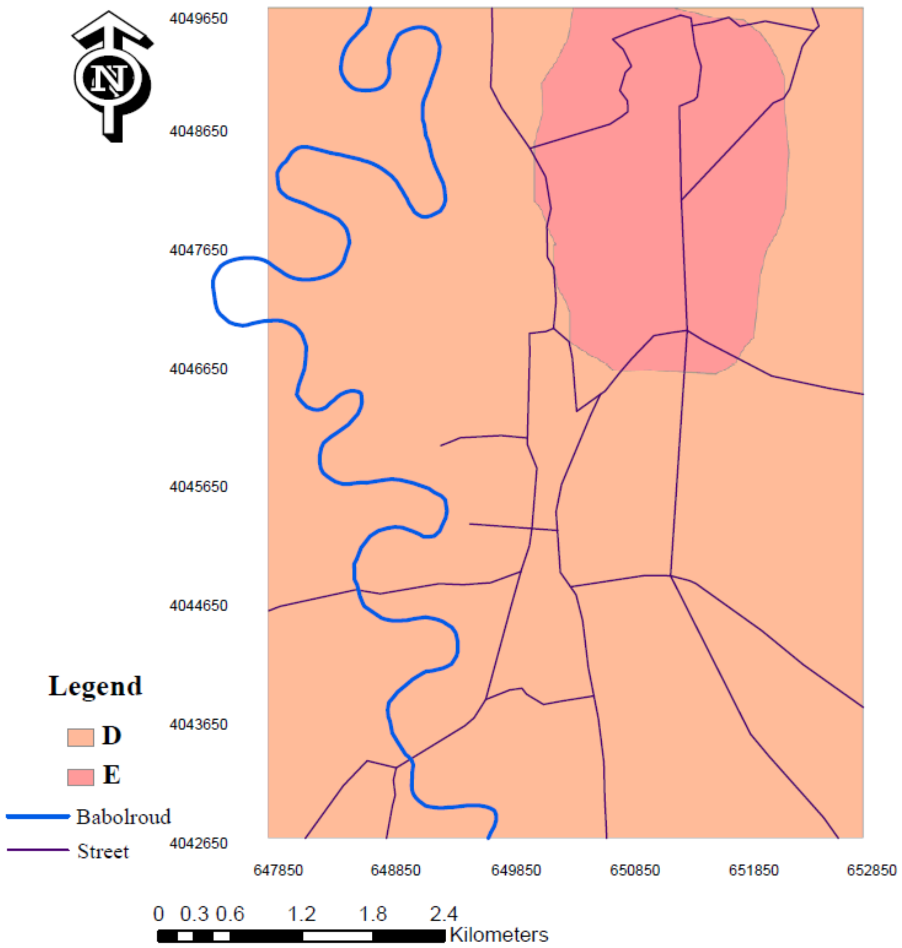


Fig. 7 Site classification according NEHRP (2000) site classification

that most of the investigated region could be designated as class D and a small portion as class E (Fig. 7). According to the NEHRP classification, the soil type categories of the area make it prone to large magnitudes during a potential earthquake occurrence. Thus, to reduce the life and monetary losses consequent to future earthquakes, the expected magnitudes must be evaluated with especial care.

3.2 Depth to bedrock

The site study shows only a partial underground layer which can leave a strengthening or weakening effect on the seismic motions. This part of underground layer is located on a layer with high stiffness that is expected not to amplify earthquake waves. The last layer which can be called bedrock is not necessarily geological bedrock and is an alluvial layer with high elasticity stiffness. For the purpose of the study, seismic bedrock has been defined as rock-like media with shear wave velocities of over 750 m/s (Ishihara and Ansal 1982) which is suitable for ordinary low to medium-rise buildings (TC4 1999). Depth distribution map of the seismic bedrock is shown in Fig. 8. Although the 30 m depth is recommended for conducting sub-surface studies by many of the earthquake guidelines such as the NEHRP code, the seismic bedrock of the Babol city is located at a 70 m depth and, therefore, neglecting the dynamic characteristics of the earth between the 30 and 70 depths will yield in a considerable loss of accuracy in the dynamic analysis of the structures. Thus, the v_{s30} is recommended to be replaced by the accurate depth of the seismic bedrock in design of tall and especial buildings.

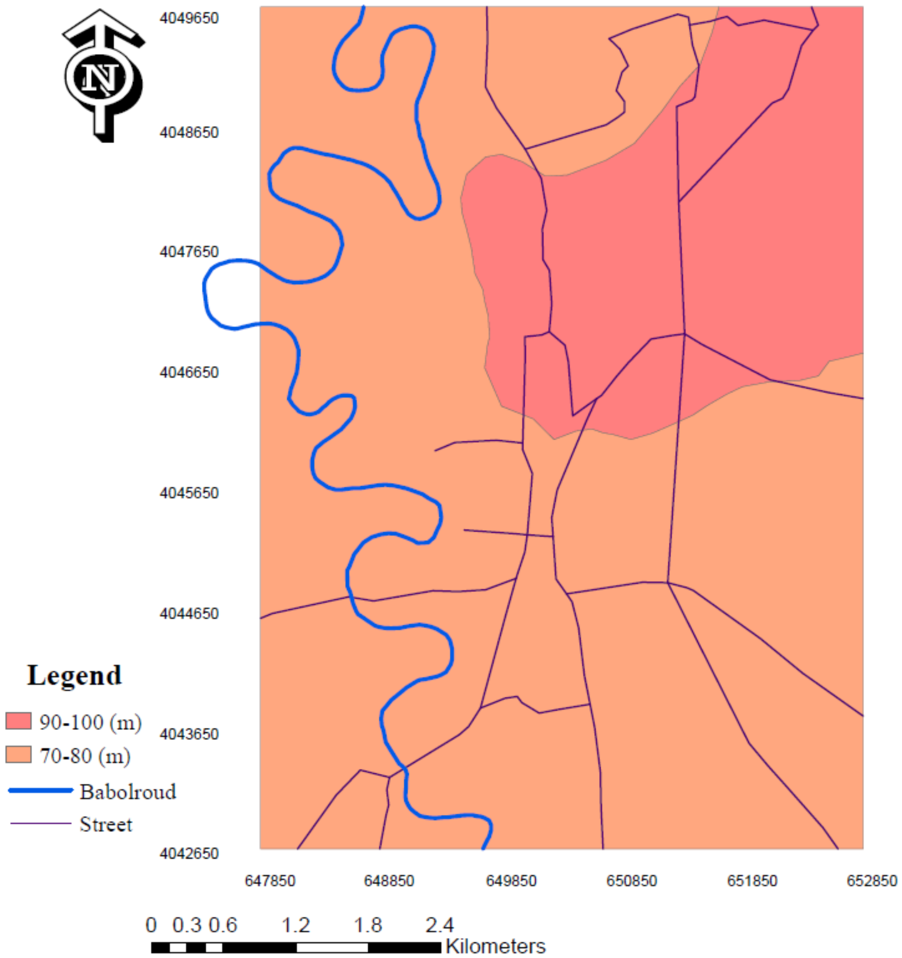


Fig. 8 Variation of bedrock depths in the region

3.3 Natural period

Surface layers can greatly influence the amplification of the seismic waves by causing resonance between the natural period (s) of the ground layers and the frequency content of the earthquake waves. The extent of such influence depends on the soil properties and thicknesses of soil layers. The soil's fundamental period which is called the characteristic site period is only a function of the thickness and shear wave velocity of soil layers and indicates the vibration period at which amplification is expected to be most pronounced.

$$Ts = 4h/Vs \quad (2)$$

Where V_s is the shear wave velocity (m/s) in the surface layer and h is its thickness (m). The natural period is found to range between 5 second for very thick deposits, such as in Los Angles or Tokyo or for extremely soft materials such as in Mexico City and 0.1 second or more for very thin layers such as alluvial deposits or weathered rocks (Hashash and Park 2001). After determining

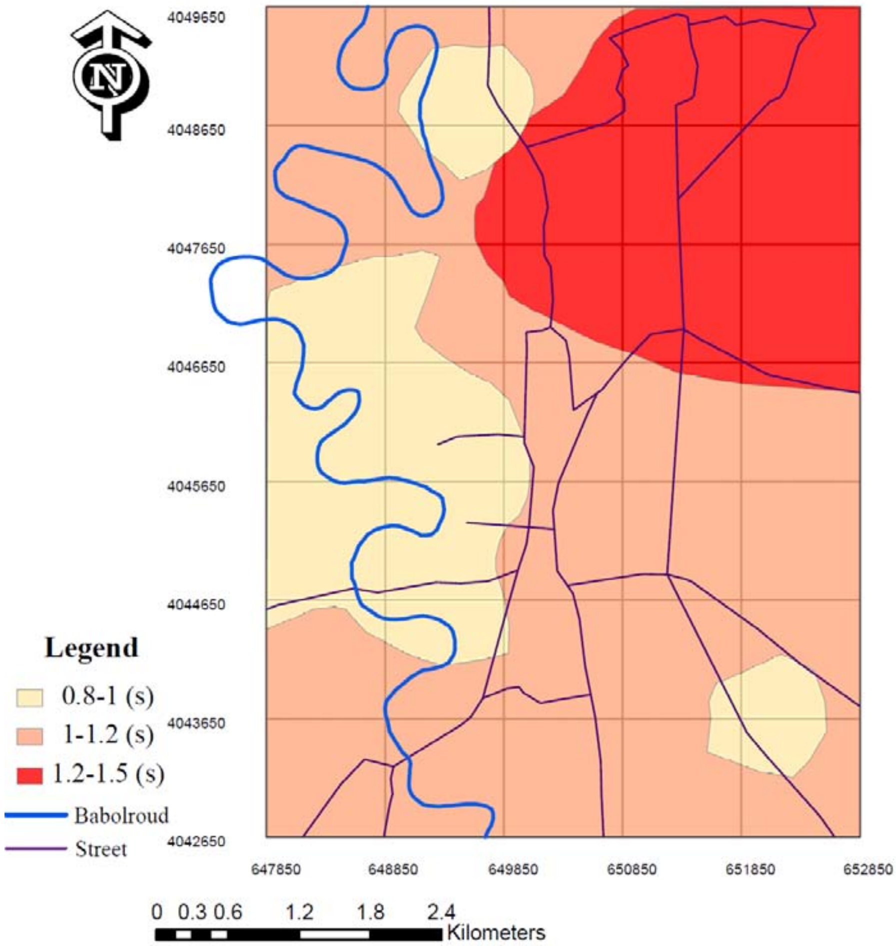


Fig. 9 Distribution map of natural period

soil layers at the 35 boreholes, geotechnical model is obtained for each profile. In this study, natural period of alluvium is divided into three areas as following

$$1-0.8 \leq T_s \leq 1$$

$$2-1 \leq T_s \leq 1.2$$

$$3-1.2 \leq T_s \leq 1.5$$

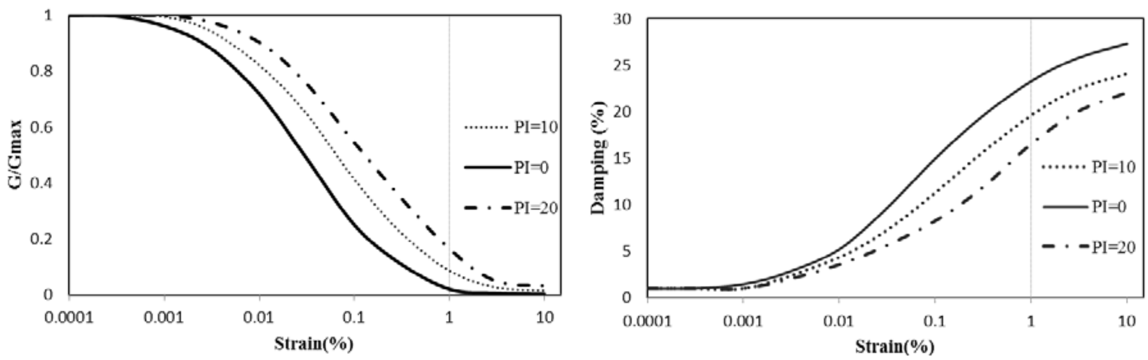
As shown in Fig. 9, an increase in the natural alluvium period is observed when moving from west side of Babol to other regions. Using the site classification suggested by the natural period of alluvia and regarding the natural period of the soil falling between 0.8 and 1.5 in the majority of the areas, the site class D is determined, again, following the NEHRP recommendations.

4. Numerical site response analyses

Many parameters contribute to site response analyses carried out by analytical methods. The outcomes of analysis of earthquake ground motions and corresponding response spectra are affected by these parameters. Therefore, investigating the effect of these parameters on site response analyses is necessary for making confident evaluations of earthquake ground motions at site. Generally, ground response during earthquakes can be numerically analyzed by two approaches, i.e. equivalent linear methods performed in the frequency domain by the complex response method (e.g., Schnabel *et al*. 1972) and nonlinear methods solved in the time domain through direct integration (e.g., Lee and Finn 1978). Equivalent linear model is one of the most widely used approaches to model soil nonlinearity. To approximate the actual nonlinear, inelastic response of soil, an equivalent linear approach was proposed by Schnabel *et al*. (1972). In the equivalent linear approach, soil properties (G and ξ of each layer corresponding to a uniform strain distribution) are, initially, assigned small values. These values are repeatedly modified according to the effective shear strain estimated using time history analysis of the shear strain in various layers. The analyses are repeated until an effective consistency is obtained between shear strains induced in the soil and that resulting from soil properties.

The effect of nonlinearity is largely a function of soil type (plasticity index in Vucetic and Dobry 1991). Factors such as cementation and geologic age may also affect the nonlinear behavior of soils. To account partially for these factors, a site classification scheme should include the nonlinear behavior of soil and measuring the dynamic stiffness of the site and depth of the deposit (Rodríguez-Marek *et al*. 2000). Yoshida (1994), Huang *et al*. (2001), Yoshida and Iai (1998) showed that equivalent linear analyses lead to larger peak acceleration because the method calculates acceleration in a highly wide range frequency. Analytical method employed in this research is based on one-dimensional equivalent-linear modeling of the soil layers. One-dimensional ground response analyses are based on the assumption that all boundaries are horizontal and that the response of a soil deposit is predominantly caused by SH-waves propagating vertically from the underlying bedrock. For one-dimensional ground response analysis, the soil and bedrock surface are assumed to extend infinitely in the horizontal direction. Procedures based on this assumption have been shown to predict ground response that is in reasonable agreement with measured response in many cases.

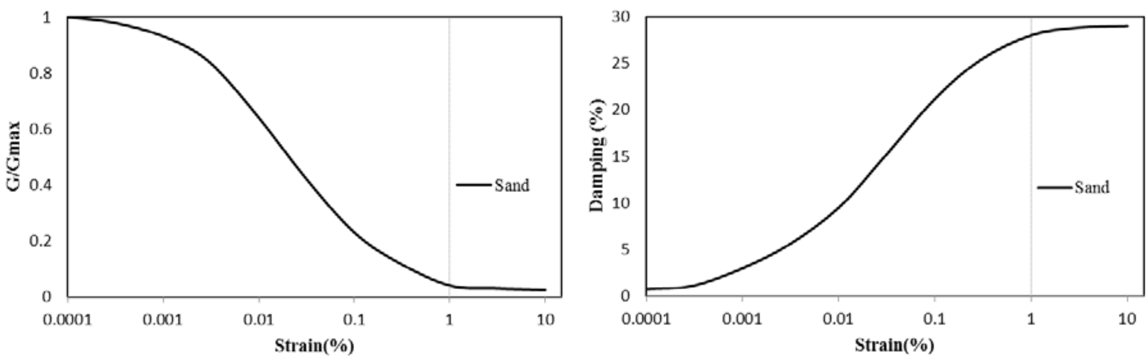
In order to conduct one-dimensional site response analysis, DEEPSOIL software is used. DEEPSOIL is a one-dimensional site response analysis program that can perform both: (a) 1-D nonlinear; and (b) 1-D equivalent linear analyses and features an intuitive graphical user interface. DEEPSOIL was developed under the direction of Prof. Youssef M.A. Hashash in collaboration with several graduate and undergraduate students at the University of Illinois at Urbana-Champaign (Hashash and Park 2011). The shear modulus and damping ratio soil properties can be defined by discrete points. The option of defining the soil curves using discrete points is only applicable for the Equivalent Linear analysis. For this option, the G/G_{max} and Damping ratio (%) are defined as functions of shear strain (%). Hence, for each soil layer in the soil profiles, total unit weight, thickness, shear wave velocity, and G/G_{max} and damping relationships are provided as inputs. In the study for clay type soils the G/G_{max} and damping curves proposed by Vucetic and Dobry (1991) and for alluvial sites the curves of Seed and Idriss (1991) are used Figs. 10 and 11. Since there are no recorded bedrock strong motion time histories for Babol city, 23 proper earthquake time histories were selected from available national and international databases (Table 3). In Fig. 12, target and scaled response spectra of Bam earthquake recorded at Bam station is



(a) Modulus reduction using Vucetic and Dobry (1991) curves

(b) Damping curves using Vucetic and Dobry (1991) curves

Fig. 10 Evaluation of proposed damping reduction factor



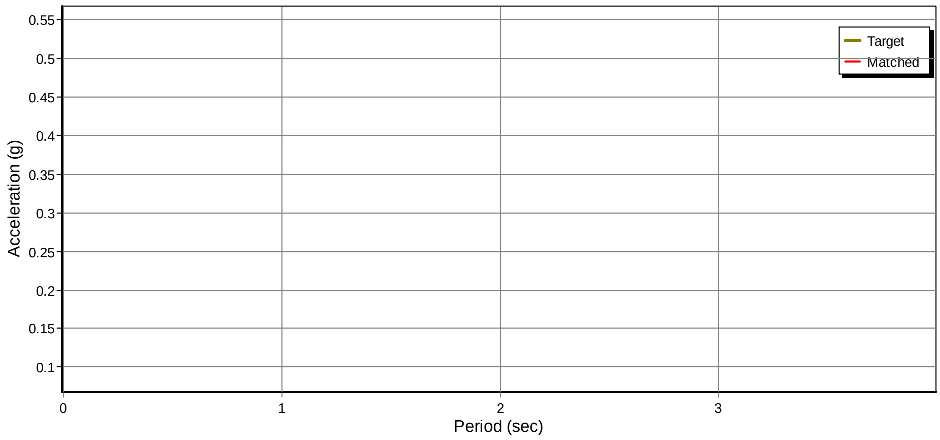
(a) Modulus reduction using Vucetic and Dobry (1991) curves

(b) Damping curve using Vucetic and Dobry (1991) curves

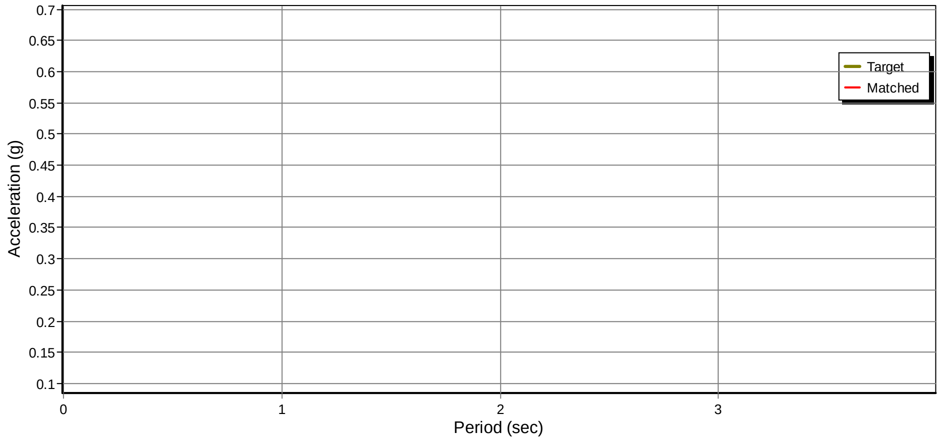
Fig. 11 Evaluation of proposed damping reduction factor presented for different return periods. The seismic waves that move throughout the alluvium towards thesubstrate and reach to the surface make the frequency and amplitude characteristics of the soil to change and, thus, cause different accelerograms and Fourier spectra to be shown by the seismic ground motions. Horizontal acceleration amplitude Fourier spectrum of bedrock is combined with the dynamic characteristics of alluvium or geometric properties of the surface to form the newly obtained Fourier spectrum. The amplification function is, finally, obtained by dividing the Fourier spectrum of the surface over the Fourier spectrum of the bedrock. The accelerograms corresponding to multiple return periods are averaged and used in the alluvium profile analysis. Fig. 13 depicts the amplifying microzonation scheme for the scope of alluvium mapping using the data obtained from analysis. As was expected and is shown in figure, amplification ratio is greater than one in all areas. Moreover, in all return periods, by moving from

Table 3 Specification of selected accelerograms for site response analysis

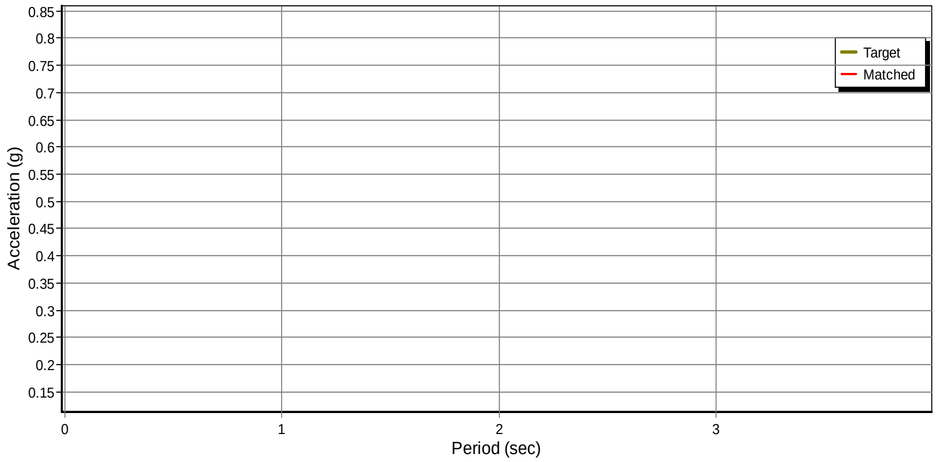
No.	Earthquake station	Distance (km)	Magnitude
	Return period of 109 years		
1	Koloor	14	5.6
2	Maymand	17	5.6
3	Khan zinu	8	5
4	Qaen	10	6.4
	Return period of 475 years		
5	Baladeh	24	6.3
6	Suza	17	6.1
7	Bam	0	6.5
8	Qaen	10	6.4
9	Talesh	14	6.2
	Return period of 950 years		
10	Deyhok	10	7.4
11	Abbar	10	7.3
12	Bam	0	6.5
13	Poul	25	6.2
14	Avaj	23	6.5
15	Northridge	19	6.6
16	San Fernando	17	6.6
	Return period of 2500 years		
17	Deyhok	10	7.4
18	Abbar	10	7.3
19	Bam	0	6.5
20	Poul	25	6.2
21	Avaj	23	6.5
22	Northridge	19	6.6
23	San Fernando	17	6.6



(a) In return period of 475 years

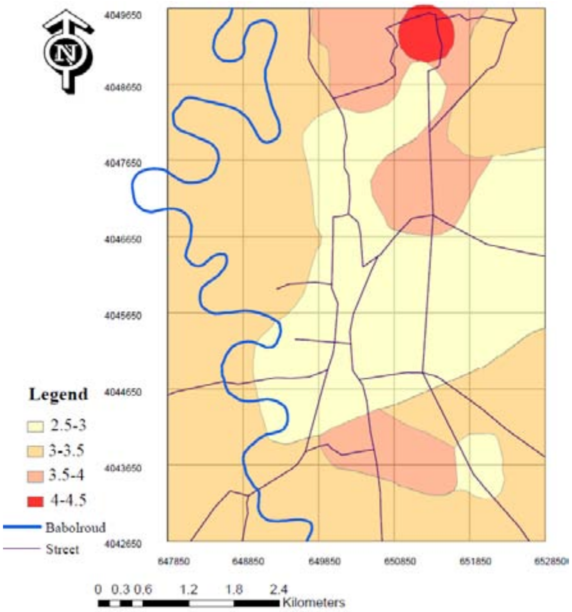


(b) In return period of 950 years

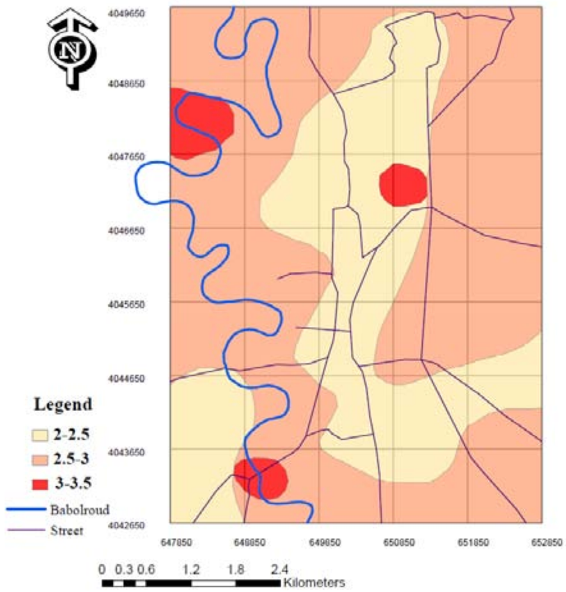


(c) In return period of 2500 years

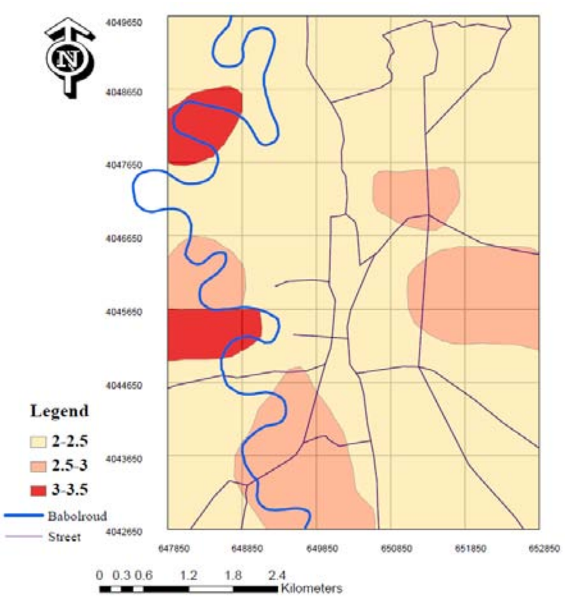
Fig. 12 Target and scaled response spectra computed for Bam earthquake recorded at the Bam station



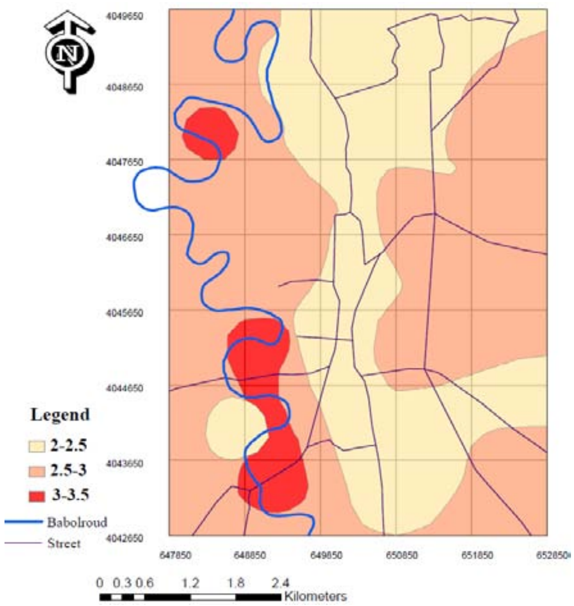
(a) In return period of 109 years



(b) In return period of 475 years



(c) In return period of 950 years



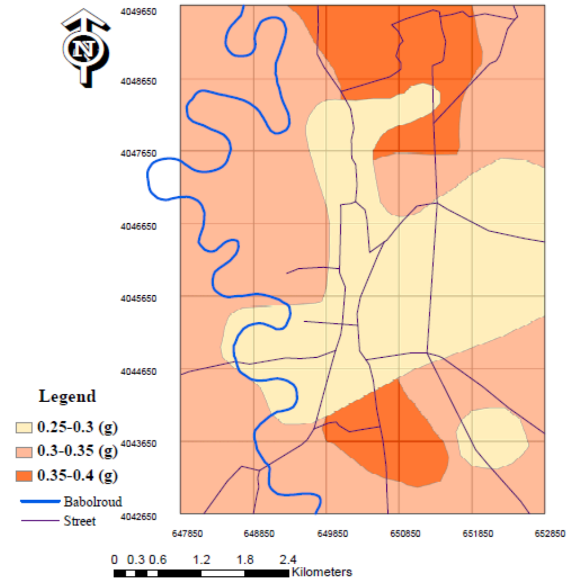
(d) In return period of 2500 years

Fig. 13 The map of alluvial amplification ratio

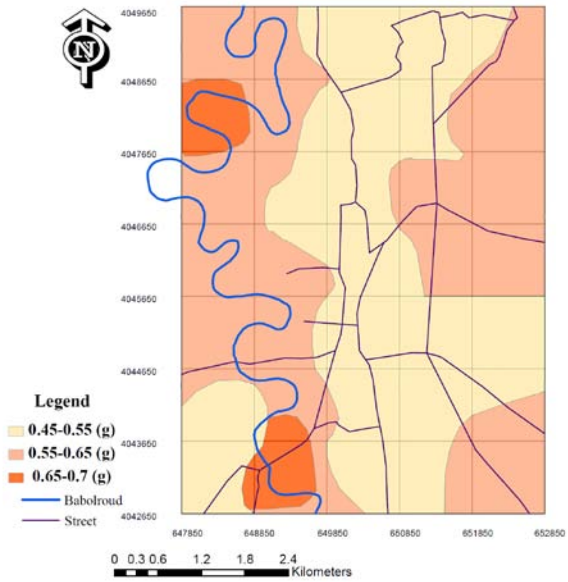
center of city in all directions, amplification ratios are increased with a rate that is decreased by increase of the return period. According to the alluvial magnification ratios, the peak ground acceleration values can be computed for various return periods by multiplying the average alluvial amplification ratio by the dispersion values and the bedrock accelerations related to different return periods. Example details regarding this calculation are reported in Table 4 for profile No. 1 by including the bedrock acceleration values and the resulting alluvial amplification ratios used in the computation process. In production of these maps, the peak ground acceleration values obtained for different return periods have been divided into 3 ranges. As illustrated in Fig. 14, the lowest value of the peak ground acceleration is related to the 109 year return period with a 0.25 g value while its largest value (1.1 g) is related to the 2500 year return period. For the 109 year return period earthquake, the probability of resonance has led to peak ground acceleration much higher than the value of the bedrock. Moreover, in all return periods, by moving from center of city in all directions, peak ground accelerations are increased with a rate that is decreased by increase of the return period. Therefore, especial cares must be taken to reduce the monetary and casualty losses probable in future earthquakes.

Table 4 Profile No. 1 by including the bedrock acceleration values and the resulting alluvial amplification ratios and peak ground acceleration used in the computation process

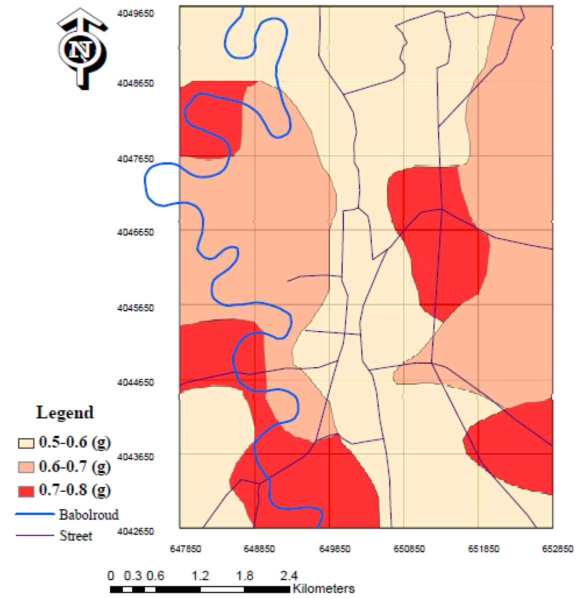
Return period	Earthquake station	Bedrock acceleration (g)	Amp. ratio (surface/input)	Average alluvial amplification ratio	Peak ground acceleration (g)	Average peak ground acceleration (g)
2500 years	Bam	0.373	2.42	2.28	0.85	0.72
	San Fernando	0.364	2.28		0.83	
	Poul	0.337	2.46		0.77	
	Abbar	0.307	2.1		0.70	
	Deyhok	0.269	2.3		0.61	
	Northridge	0.276	2.29		0.63	
	Avaj	0.299	2.09		0.68	
950 years	Bam	0.284	2.47	2.36	0.67	0.58
	San Fernando	0.278	2.5		0.66	
	Poul	0.262	2.48		0.62	
	Abbar	0.235	2.11		0.55	
	Deyhok	0.205	2.2		0.48	
	Northridge	0.21	2.57		0.50	
	Avaj	0.231	2.2		0.55	
475 years	Baladeh	0.24	2.5	2.52	0.60	0.54
	Bam	0.227	2.5		0.57	
	Talesh	0.223	2.48		0.56	
	Qaen	0.196	2.53		0.49	
	Suza	0.186	2.57		0.47	
109 years	Khan zinu	0.108	3.77	3.69	0.40	0.36
	Maymand	0.094	3.66		0.35	
	Koloor	0.087	3.61		0.32	
	Qaen	0.102	3.71		0.38	



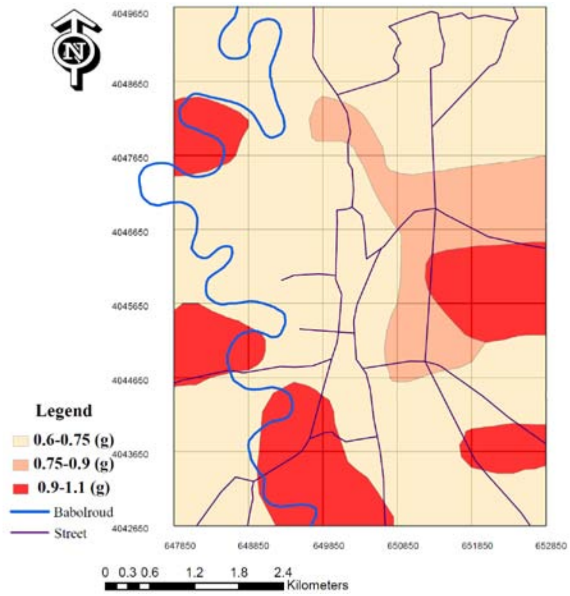
(a) In return period of 109 years



(b) In return period of 475 years



(c) In return period of 950 years



(d) In return period of 2500 years

Fig. 14 The map of alluvial peak ground acceleration

5. Experimental site response estimates

The use of microtremor measurements in estimation of site response was proposed in the 1950s. Although there is ongoing discussion about the applicability of this method in various site conditions and ground shaking levels, it has been widely used to estimate the fundamental period of soil deposits (Lermo and Chavez-Garcia 1994) and is recommended as one the approaches in Grade-2 methods in zoning for ground motions (TC4 1999). This method is also used in this study. Microtremor measurements were performed at 60 sites in the Babol area using a broadband sensor (SL07) with a natural period of 0.5 s, a 24-bit digitizer, a duration between 15 and 20 min and a sampling frequency of 100 Hz. To limit the noise resulting from the passage of numerous site visitors, most of the measurements were performed overnight. Each measurement was acquired with a N–S instrumental axis orientation according to the longitudinal axis of the Babol (real E–W) and E–W according to the transversal axis (real N–S). For each measuring point, the following

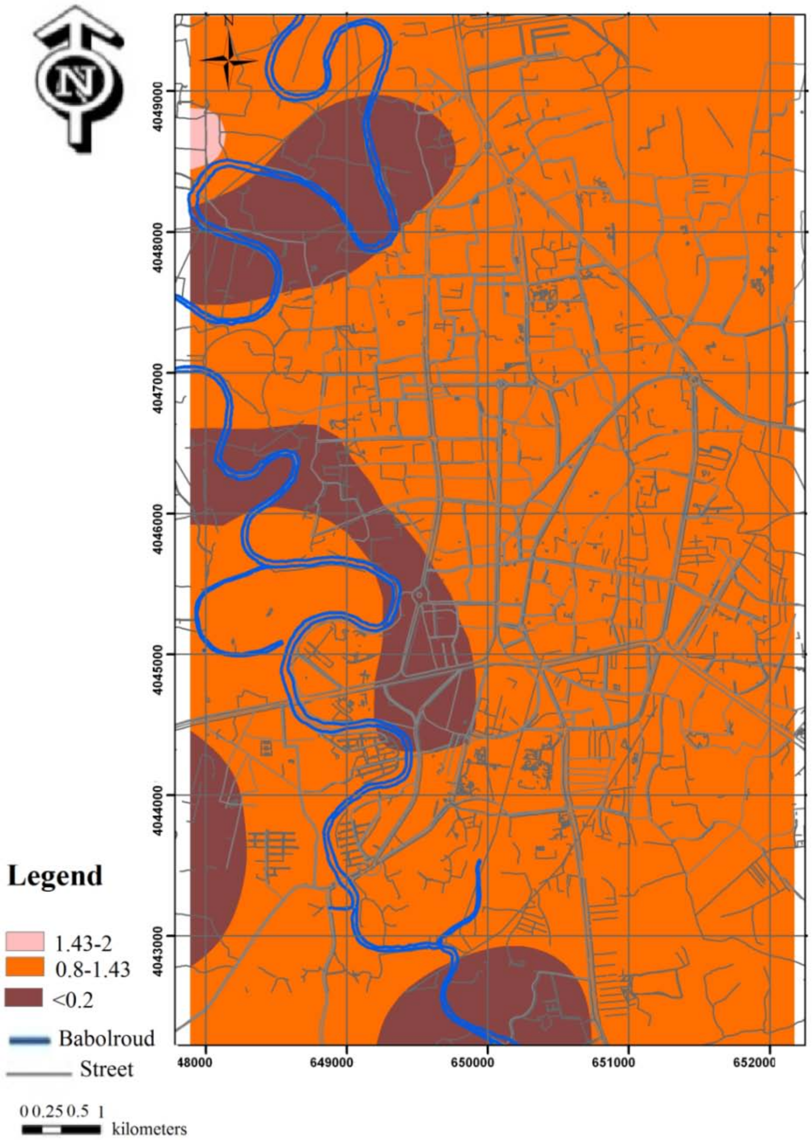


Fig. 15 The map of fundamental period of microtremor stations

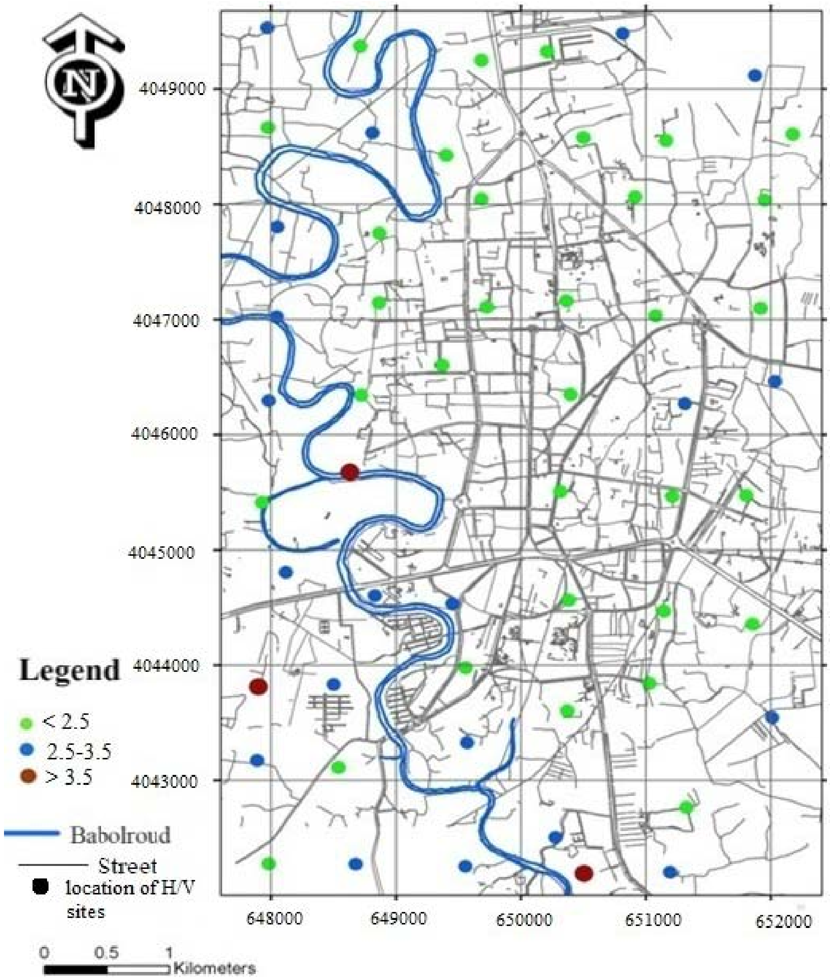


Fig. 16 Values of Microtremor stations amplification ratio

features were reconstructed: (1) amplification /frequency plots obtained by the spectral ratio between the geometric means of the horizontal and vertical components; (2) a directional graph showing the variability of amplification values as a function of frequency and direction highlighting the contribution to the average figure provided by each of the two horizontal components; (3) a stability chart of the HVSR measurement showing the variability of amplification values as a function of the frequency and duration of the measurement to detect any coherent signal associated with localized sources of noise and/ or characteristic frequencies that can adversely affect the measurement. Figs. 15 and 16 show the fundamental periods and the associated amplification ratios. Two site classes B and D can be identified throughout the city following the NEHRP code with the class D sites covering the majority of the city. A good agreement between the proposed ranges of natural periods and alluvial amplification ratios obtained through the one-dimensional response analysis method and the experimental microtremor studies verifies the analytical model to provide a good engineering reflection of the subterraneous alluviums conditions.

6. Conclusions

Babol is underlain by deep saturated soil deposits, which are expected to have a significant effect on the ground response. In order to perform Numerical site response analyses for the region, representative soil profiles were defined for each 1×1 km^2 grid. Estimation of strong ground motion characteristics uses one-dimensional site response analyses of the representative geotechnical profiles. The final site periods and amplification ratio maps of the study area were prepared in the Geographical Information System (GIS) media. Moreover, in this study the evaluation of the local site effects for Babol city was conducted according to the most popular and world-wide approach through the calculation of the horizontal to vertical spectral ratio (HVSR) for the recorded ambient vibrations. These spectral ratios show the fundamental period and the associated amplification ratio.

The results of investigation indicated that:

- According to the results of the numerical approach, the natural alluvium period is observed to increase by moving from west side of Babol to other regions.
- Although the 30 m depth is recommended for conducting sub-surface studies by many of the earthquake guidelines such as the NEHRP code, the seismic bedrock of the Babol city is located at a 70 m depth and, therefore, neglecting the dynamic characteristics of the earth between the 30 and 70 depths will yield in a considerable loss of accuracy in the dynamic analysis of the structures. Thus, the v_{s30} is recommended to be replaced by the accurate depth of the seismic bedrock in design of tall and especial buildings.
- The numerical and experimental results reveal that amplification ratio is greater than one in all areas. Therefore, special cares must be taken to reduce the monetary and casualty losses probable in future earthquakes.
- Regarding the numerical results, it was shown that by moving from center of city in all directions, amplification ratios and peak ground accelerations are increased with a rate that is decreased by increase of the return period.
- For the 109 year return period earthquake, the probability of resonance has led to peak ground acceleration much higher than the value of the bedrock.
- A good agreement between the proposed ranges of natural periods and alluvial amplification ratios obtained through the one-dimensional response analysis method and the experimental microtremor studies verifies the analytical model to provide a good engineering reflection of the subterraneous alluviums conditions.

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