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ORIGINAL ARTICLE

Evaluation of local site effect from microtremor measurements in Babol City, Iran

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Abstract Every year, numerous casualties and a large deal of financial losses are incurred due to earthquake events. The losses incurred by an earthquake vary depending on local site effect. Therefore, in order to conquer drastic effects of an earthquake, one should evaluate urban districts in terms of the local site effect. One of the methods for evaluating the local site effect is microtremor measurement and analysis. Aiming at evaluation of local site effect across the city of Babol, the study area was gridded and microtremor measurements were performed with an appropriate distribution. The acquired data was analyzed through the horizontal-to-vertical noise ratio (HVNR) method, and fundamental frequency and associated amplitude of the H/V peak were obtained. The results indicate that fundamental frequency of the study area is generally lower than 1.25 Hz, which is acceptably in agreement with the findings of previous studies. Also, in order to constrain and validate the seismostratigraphic model obtained with this method, the results were compared with geotechnical, geological, and seismic data. Comparing the results of different methods, it was observed that the presented geophysical method can successfully determine the values of fundamental frequency across the study area as well as local site effect. Using the data obtained from the analysis of microtremor, a microzonation map of fundamental frequency across the city of Babol was prepared. This map has numerous applications in designing high-rise building and urban development plans.

Keywords Earthquake · Local site effect · Micotremor · Fundamental frequency · Microzonation

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1 Introduction

It is well accepted that, besides the earthquake magnitude and fault distance, local geologic conditions, known as site effects, can influence and amplify the earthquake ground motion (Yanger Walling et al. 2009; Tezcan et al. 2002). Numerous observations in earthquake-affected areas have shown that the local intensity of the earthquake and the amount of structural damage due to seismic impact are in some way influenced by the local subsoil. In particular, waves of certain frequencies can be amplified considerably by near-surface, unconsolidated deposits and in general soft soil layers amplify the ground motion. This fact increases the importance of assessing the site effects, in order to introduce suitable solutions for minimizing of earthquake damage and loss of life. The problem is studied with different methods. Nowadays, one of the most common one is based on the analysis of sets of microtremor measurements as this is a fast, non-invasive, and cost-effective method (Rezaei et al. 2015; Singh 2015).

Babol City is located in Mazandaran Province north of Iran. The subsoil of this city consists of soft deposits.

In the last three decades, the population of Babol City has increased and it resulted in very rapid growth of settlements. Many of Iran's cities, including Babol, are located in regions with high seismic hazard. One of the most important methods to evaluate the local effects for anti-seismic planning is the seismic microzonation, which consists in the subdivision of a region into zones with similar seismic response (Rezaei and Choobbasti 2014).

With the TC4 manual, the technical committee for earthquake geotechnical engineering has introduced three levels of microzonation (TC4 1999). According to TC4 manual specifications, level II maps are based on the microtremor records and simplified geological studies (Mahajan et al. 2007; Büyüksaraç et al. 2013; Matassoni et al. 2015). For this reason, in Babol City, microtremor measurements have been performed at 60 stations and the obtained data were analyzed with Nakamura's method (horizontal-to-vertical noise ratio (HVNR)) (Nakamura 1989). The results were compared with local geological and geotechnical data to confirm their reliability for a seismostratigraphic model definition.

2 Seismicity and geology of Babol City

Babol is located at latitude 650077.00 of north and latitude 4045008.00 of east. The city is located approximately 20 km south of the Caspian Sea on the east bank of Babolrood River and in front of the Alborz Mountain which is a tectonically active region. Babol City is very young from a geological point of view and hence unstable. In the last three decades the, population of Babol has increased; therefore, an accurate natural hazard risk assessment is now necessary (Choobbasti et al. 2013; Choobbasti et al. 2014). The area around Babol has repeatedly experienced earthquakes. In Table 1, the magnitudes, Mercalli–Cancani–Sieberg (MCS) intensities in epicenter, year of occurrence, and location of these earthquakes are reported. There are historical references to this area being prone to earthquake. The first historically reported major earthquake in this city occurred in 1809 having an MCS intensity of IX. The Amol earthquake killed many people in Amol and Babol. It was felt in a very large area. The 1935 Talarrood earthquake produced moderate shaking and was felt almost 190 km away. The 1935 Chahardange earthquake caused the collapse of wooden houses in Sari, Babol, and Amol. The 1957 Bandpey earthquake produced violent shaking in Babol. The Bandpey earthquake killed 1500 people in Babol and damaged several places. The 1971 Babol earthquake produced moderate shaking and killed one person in Babol. The 2004 Kojoor earthquake killed 35 people in Mazandaran Province, and finally, the 2012 Marzikola earthquake killed one person in Babol. Figure 1 shows the faults, the location and magnitude of earthquakes, and the focal mechanism near Babol (Rezaei 2014).

Table 1 List of recorded damaging earthquakes in and around Babol City (Choobbasti et al. 2014)

Location	Year	Source	Intensity	Magnitude
Amol	1809	20 km W Babol	IX	6.5
Talarrood	1935	35 km SE Babol	VII	5.7
Chahardange	1935	60 km ES Babol	VIII	6.3
Bandpey	1957	10 km W Babol	IX	6.8
Babol	1971	Babol	VI	5.2
Kojoor	2004	60 km NW Babol	VIII	6.3
Marzikola	2012	Babol	VI	5

Depending on the lithological variations through 36 boring logs in the study area, the subsurface geological model at Babol City can be classified and is composed of the following five types (Fig. 2). The geotechnical boreholes have been drilled for the Babol City microzonation project, and their depths are between 30 to 40 m so that none of them reached the bedrock (Microzonation of Babol City 2012).

3 Methodology

Microtremors are ground vibrations with displacement amplitude of about 1–10 μm and velocity amplitude of around 0.001–0.01 cm/s that can be detected by seismographs with high magnification (Dikmen and Mirzaoglu 2005). One of the possible sources of microtremors can be human activity, such as traffic, industrial noises, and natural phenomena, such as wind and ocean waves.

The analysis of microtremor was initially proposed by Kanai and Takana (1961). Since then, many researchers have used microtremor measurements for site effect evaluation (e.g., Nakamura 1989; Lermo and Chavez-Garcia 1994; Bour et al. 1998; Yanger Walling et al. 2009; Purnachandra Rao et al. 2011; Guo et al. 2014; Rezaei and Choobbasti 2017).

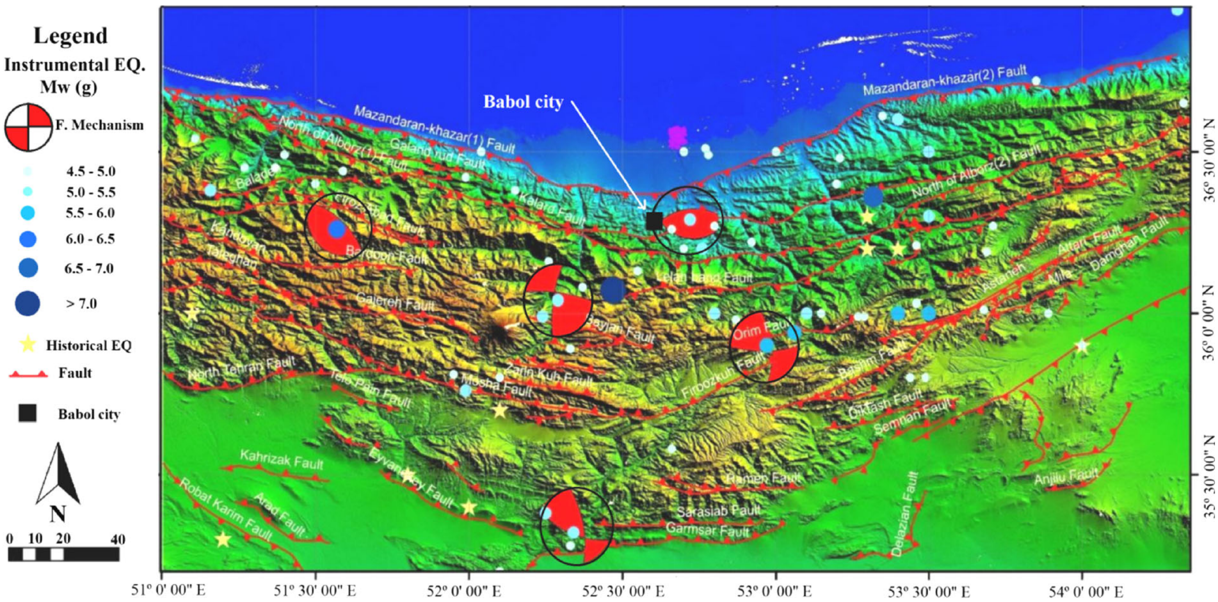


Fig. 1 Location and magnitude of earthquakes, faults, and their mechanism near Babol City

As mentioned above, one of the most popular techniques for site effect estimation in regions with low seismicity is the analysis of microtremor measurement with Nakamura's method (HVNR) (Nakamura 1989), a method that has become popular and is now used worldwide (Ullah and Prado 2017).

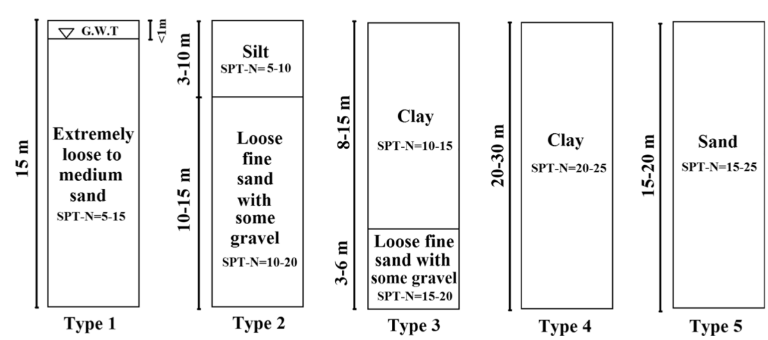
Nakamura has introduced the method, but his interpretation of the source of ambient noise and the nature of the H/V peaks is different compared to most authors. Nakamura assumes that ambient noise is composed of body waves and interprets the H/V curve as the S-wave transfer function, ignoring surface waves. Instead, it is now commonly assumed that microtremor is predominantly composed of surface waves (Rayleigh waves) and that the H/V amplitude is only a qualitative measure of the impedance contrast causing seismic amplification (Lachet and Bard 1994; Konno and Ohmachi 1998; Fäh et al. 2001).

As mentioned above, Nakamura presumes that microtremors consist predominantly of body waves. Observation of tremor data showed that the ratio between horizontal and vertical motion is related to soil conditions and is almost equal to 1 for firm soil and bedrock. The horizontal component of the shear wave is amplified by the layer of soft soil due to the multiple-reflection phenomena of the waves. However, Nakamura assumed that the soft soil layer does not amplify the vertical component, i.e., P wave. The transfer function (S_T) of surface layers is defined as the ratio between the horizontal tremor spectrum on the surface (H_S) and the horizontal tremor spectrum on the substratum (H_B).

$$S_T = H_S/H_B \tag{1}$$

In this interpretation, it was assumed that the horizontal tremor spectrum on the surface is affected by the

Fig. 2 Classification of the subsurface conditions in the Babol City



Rayleigh waves, which are considered as noise for microtremor measurements. And also, the Rayleigh waves affect the vertical spectrum at the surface but do not affect the vertical spectrum at the bedrock. Moreover, it was assumed that soft sediments do not amplify the vertical waves; hence, the effect of the Rayleigh waves (E_{RW}) can be evaluated by taking the ratio of the vertical component at the surface (V_S) and at the bedrock (V_B).

$$E_{RW} = V_S/V_B \quad (2)$$

Hence, incorporating the effects of Rayleigh waves, new transfer function (S_M) can be written as

$$S_M = S_T/E_{RW} = (H_S/H_B)/(V_S/V_B) \quad (3)$$

Where,

$$H_B/V_B = 1 \quad (4)$$

Thus, an estimate of the transfer function is given by the spectral ratio between the horizontal and the vertical components of the motion at the surface:

$$S_M = H_S/V_S \quad (5)$$

Many theoretical and experimental studies show that this method has the capability of estimation of two important parameters (amplitude of the peak and fundamental frequency) (Nakamura 1989; Bour et al. 1998; Milana et al. 2011; Yalcinkaya et al. 2013; Galgaro et al. 2014).

4 Data collection and analysis procedures

The microtremor measurement for Babol City was carried out in 2011 and 2012 at 60 stations. The study area was divided in the form of 700 × 700 m squares and one station was specified for measurement in each square. In Fig. 3, the red circles are representative of the microtremor stations, the blue circles are for the geotechnical boreholes, the red star is for the location of the accelerograph, and the lines are the cross sections.

All the experimental conditions for the current work were controlled mainly by the European SESAME research project. To reduce the effect of local noise sources, such as industrial facilities, almost all recordings were done between 10 pm and 3 am.

The measurement system used (Sara-SL07) consists of power supply, GPS, amplifiers, 32-bit A/D converters, and a laptop, with a three-component velocity sensor unit (two in two orthogonal horizontal directions and one in vertical directions). At each site, microtremors were measured for 15 min. The time series were divided into 44 windows each of 20.48-s duration. For each site, we discarded windows by close noise sources. Each window was baseline corrected for anomalous trends, tapered with a Hanning window and bandpass filtered between 0.2 and 20 Hz. These appropriate windows were used for the calculation. After obtaining the H/V spectra for each window, the average of all windows was obtained as the H/V spectrum for a particular site. The peak frequency of the H/V spectrum plot shows the fundamental frequency of the site (Ullah and Prado 2017; Macau et al. 2015).

In order to assess the accuracy of the measurements, reliability and clarity of the peak in the H/V curve have been checked. For this purpose, we used the SESAME guidelines. The SESAME guidelines on the H/V spectral ratio technique are the result of comprehensive and detailed analyses performed by the SESAME participants during the three years, 2001–2004 (SESAME 2004; Chatelain et al. 2008).

5 Microtremor measurement results

By the aid of the method described in Section 3, the microtremor data of Babol City were analyzed. Figure 4 shows the H/V curves for all microtremor stations. The values of fundamental frequency (f_0) and the associated amplitude (A_0) for the measurement stations are presented in Table 2. In all stations, the criteria including clarity of the peak and reliability of H/V curve are checked and verified by the SESAME group criteria. Some stations were discarded when no clear or unique peak was identifiable.

Considering Table 2, the maximum and minimum values of fundamental frequency of the present research are 11.4 and 0.65 Hz, respectively. Also, the maximum and minimum values of amplitude of H/V peaks have been calculated as 3.71 and 1.19, respectively. The most significant point is that the fundamental frequency of the major part of Babol City's soil is smaller than 1.25 Hz in agreement with the previous knowledge of the city's geological setting (Choobbasti et al. 2014). The most important point to note in this table is that a large portion of the soil covering the city of Babol has a fundamental frequency less than 1.25 Hz, which is in good agreement

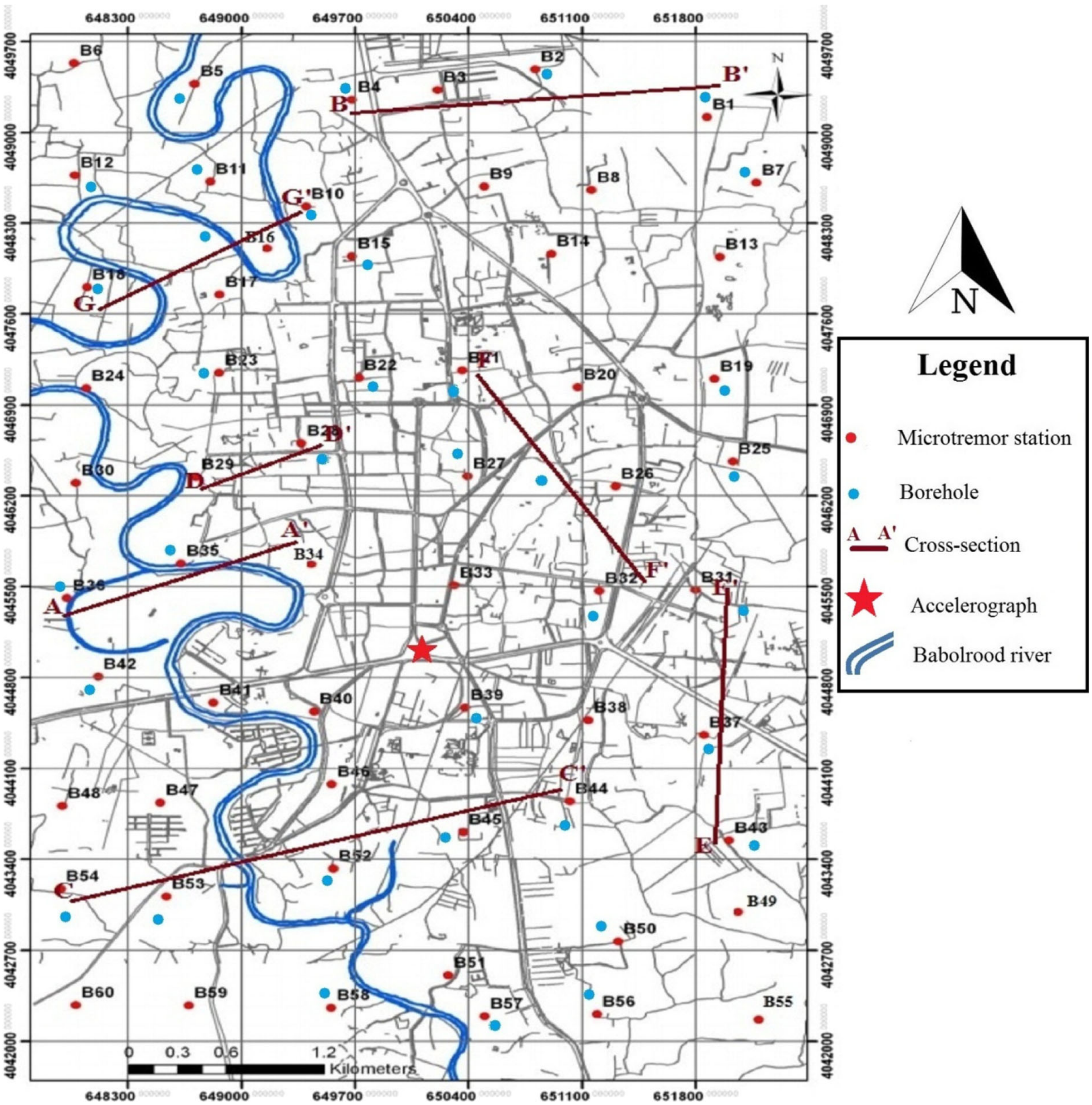


Fig. 3 Location of microtremor recording stations, geotechnical boreholes, accelerograph, and cross sections

with previous research. Choobbasti et al. (2014) used a non-linear dynamic analysis to evaluate site effect in Babol City; their results showed that the frequency is less than 1.25 Hz in a large area of the city.

Meanwhile, some stations (e.g., B5, B30, B40) show H/V spectral ratio with two peaks probably attributed to the fundamental frequency of the entire soil deposit at the lowest frequency and the shallower soil layers at higher frequencies (Macau et al. 2015; Pastén et al. 2016).

Another relevant point is the presence of some stations with very high (> 5 Hz) fundamental frequencies. In these cases, microtremor recording and data analysis were repeated, but similar results were obtained. By reviewing the location of these stations, it can be observed that all of them are located near Baboolrood River. Considering the lack of sufficient geotechnical information (in some stations), the above phenomena need to be integrated with other methods. For this purpose, the data of electrical resistivity tomography (ERT)

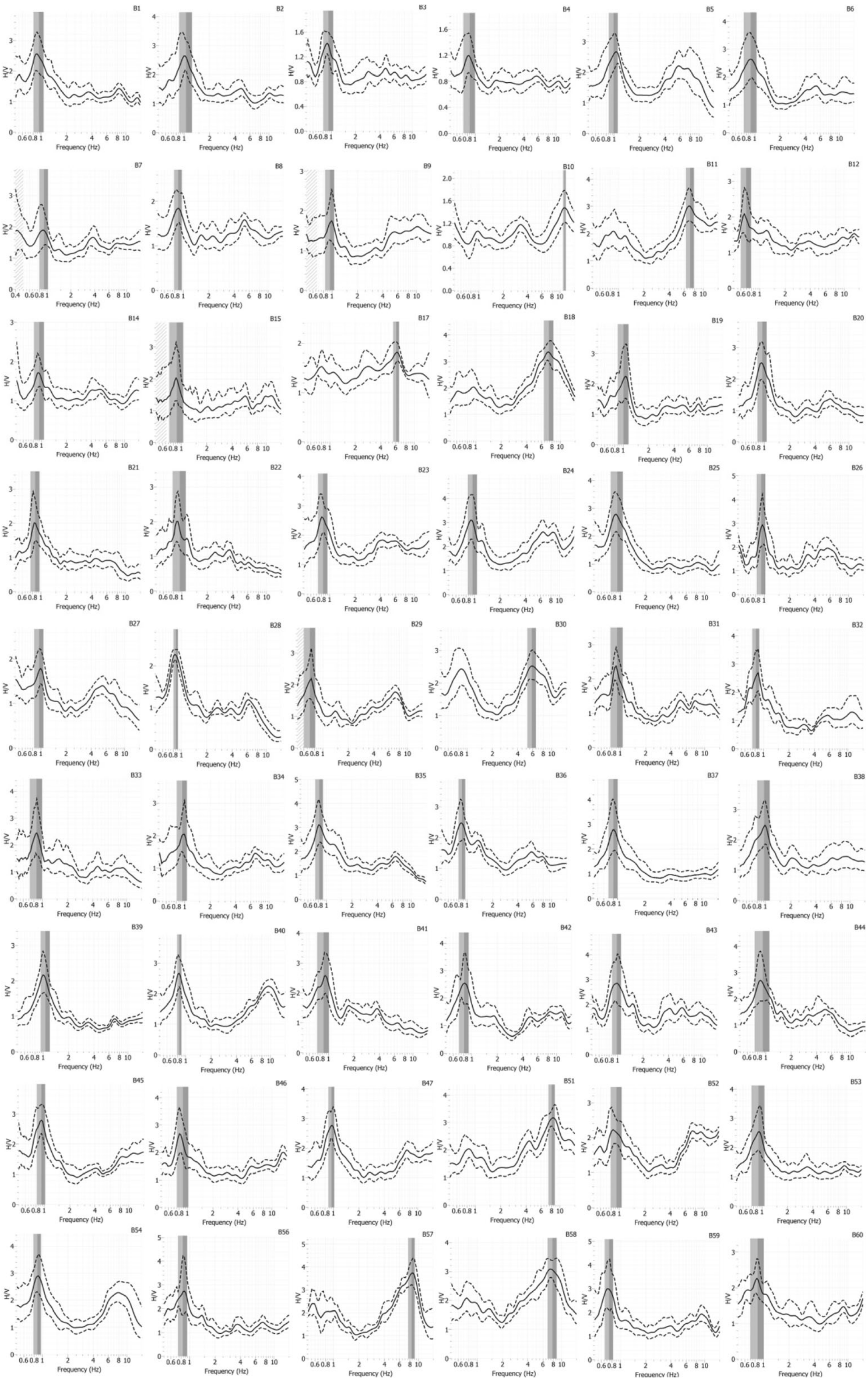


Fig. 4 H/V spectral ratio

Table 2 The analysis results for all microtremor stations

Station	B01	B02	B03	B04	B05	B06	B07	B08	B09	B10	B11	B12	B13	B14	B15
A_0	2.47	2.58	1.39	1.19	2.57	2.64	1.88	1.84	1.70	1.48	3.01	2.10	–	1.70	2.02
f_0	0.94	1.05	0.93	0.86	0.98	0.89	0.91	0.87	0.95	11.40	7.05	0.65	–	0.94	0.88
Station	B16	B17	B18	B19	B20	B21	B22	B23	B24	B25	B26	B27	B28	B29	B30
A_0	–	1.81	3.36	2.15	2.50	2.00	2.01	2.58	3.04	2.73	2.85	1.74	2.25	2.13	2.52
f_0	–	6.13	7.35	1.01	0.94	0.86	0.90	0.83	0.94	0.92	0.93	0.95	0.86	0.71	5.86
Station	B31	B32	B33	B34	B35	B36	B37	B38	B39	B40	B41	B42	B43	B44	B45
A_0	2.23	2.56	2.44	2.00	3.10	2.46	2.77	2.44	2.07	2.65	2.46	2.53	2.85	2.60	2.78
f_0>	0.92	0.82	0.96	0.93	0.82	0.86	0.85	0.96	1.06	0.85	0.87	0.81	0.98	0.91	0.92
Station	B46	B47	B48	B49	B50	B51	B52	B53	B54	B55	B56	B57	B58	B59	B60
A_0	2.33	2.76	–	–	–	3.14	2.14	2.53	2.88	–	2.69	3.71	2.75	2.96	2.23
f_0	0.89	0.95	–	–	–	8.02	0.93	0.91	0.87	–	0.83	8.33	7.78	0.74	0.85

were used. This is an ERT survey related to the Babol City microzonation project. Its investigation depth is reported to be about 100 m. In this paper, the results of this survey are used, but it is avoided to be mentioned in detail. The ERT showed that small regions of the northwest, west, and south areas have high resistance values probably related with the presence of hard deposits in the shallow subsoil. Babolrood River diversion in the west part and its return to the previous direction in the northern section is possibly due to the existence of these relatively hard deposits (Fig. 3) (Microzonation of Babol City 2012). By comparing these two tests, we observed that the ERT results correlate with the microtremor data analysis. So, we can conclude that the high-frequency peaks measured are reliable, but we need direct investigation to associate them to a specific shallow geological layer.

In this research, we used the microtremor analysis results to draw fundamental frequency map for the microzonation study of Babol City, by using H/V spectral ratio obtained for all microtremor stations. In order to represent the spatial distribution of the fundamental frequency over Babol City, interpolation between the stations was carried out by utilizing the Kriging method. For this purpose and to prepare the desired map, Surfer13 was used.

Figure 5 shows the microzonation map based on the fundamental frequency. As observed from the figure, a large part of Babol City has a frequency value less than 1.25 Hz, except for the parts in the northwest, west, and south of the city that have fundamental frequencies of more than 5 Hz.

6 Comparison of microtremor measurement results with the geotechnical and geological data

The results of microtremor data analysis can be compared with those of other methods, such as the available geotechnical and geological data, spectral ratios of strong ground motion, and numerical modeling of the seismic site response. In our opinion, one of the best methods would be to record the strong ground motion caused by a large enough local earthquake (Bour et al. 1998; Ojeda and Oscallon 2000; Birgören et al. 2009; Sivaram et al. 2012; Navarro et al. 2014; Galea et al., 2014; Natarajan and Rajendran 2016; Yamanaka et al. 2016). However, such events are not frequent in Babol City; hence, for site response analysis, this method is not applicable. Although, there is an accelerograph at the provincial office of Babol City, which can be used to assess the results of the microtremor station located nearby.

Hence, considering the present conditions, the best thing to do is to compare the H/V results with the available geotechnical and geological data and try to correlate peaks with interfaces producing the resonance (i.e., characterized by an impedance contrast). This method has been used by many researches (Gosar 2007; Mahajan et al. 2007; Mundepi et al. 2010; Kockar and Akgun 2012; Kolat et al. 2012; Vella et al. 2013; Paolucci et al. 2015; Macau et al. 2015).

In order to assess the geological framework of the study area, the Rockworks software has been used. Rockworks software is used for an easy archive and management of any kind of geological, geophysical,

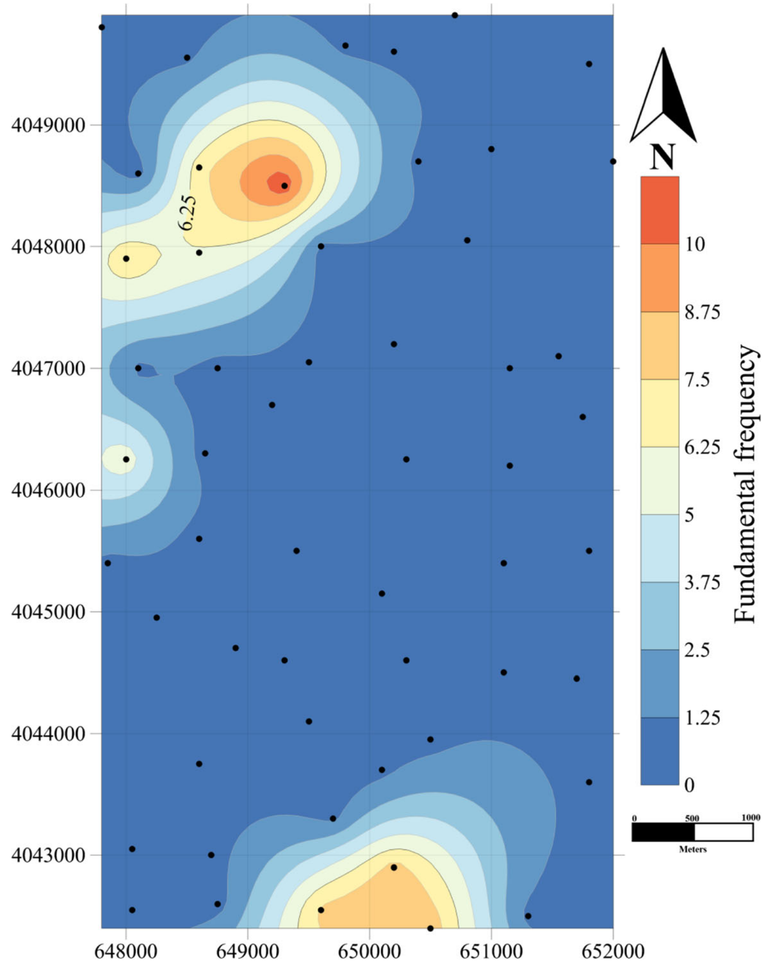


Fig. 5 Microzonation map based on the fundamental frequency

and geotechnical data (Haque et al. 2016). The data of 36 geotechnical boreholes, up to 30–40 m deep, performed for the Babol's microzonation project (Fig. 3), were entered in the Rockworks database. These data include soil type, soil layering, groundwater table, coefficient of permeability, shear strength parameter, Atterberg limits, and SPT-N.

In order to estimate which depth we need to investigate to explain a specific peak in the H/V function, we can apply the simple law:

$$f = V_S/4H \tag{6}$$

Where f is the fundamental frequency, V_S is the shear wave velocity, and H is the depth up to the basement. We have V_S from downhole tests and we estimated f with microtremor H/V. We can therefore infer the thickness of the layer (H) generating resonance at that frequency. This is the simplest and most effective way to compare H/V data and geological data (Mundepi et al. 2010; Sivaram et al. 2012). As previously mentioned, the depths of the boreholes are less than 40 m and do not reach the bedrock. Therefore, the depth of boreholes in some stations (stations with resonance frequencies down to 0.6–0.7 Hz) may not be enough to detect an effective layer—that is, the layer generating resonance frequency.

A comparison of the results of microtremor measurements with geological and geotechnical data requires investigating the changes in shear wave velocity. In this study, V_{s30} values are calculated for the study area using the results of downhole seismic testing and correlation between V_s and SPT-N. Figure 6 shows the map of changes in V_{s30} in the study area.

In order to evaluate the geotechnical and geological conditions in Babol City, cross sections are to be prepared. Considering changes in soil layers in the study area, a total of seven cross sections, the locations of

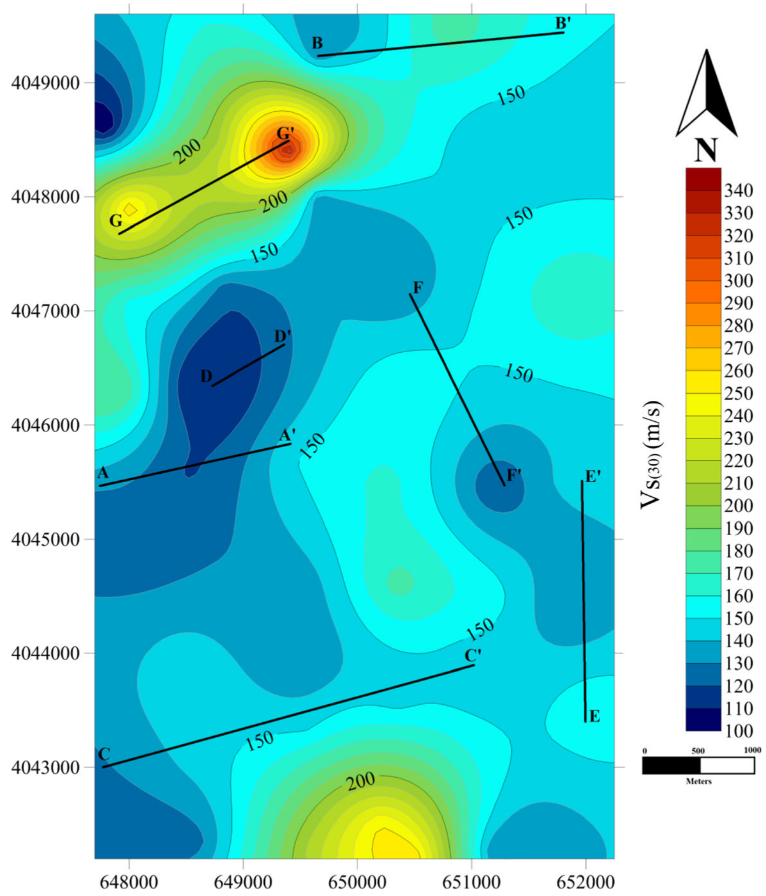


Fig. 6 V_{s30} in the study area

which are shown in Fig. 3, are supposed. Because of small depth-to-length ratio for the cross sections, Figs. 7, 8, 9, 10, 11, 12, and 13 are shown in an unscaled manner.

6.1 Cross section A-A`

This cross section with a length of 1600 m located in the western part of the study area is oriented along the west–east direction. Figure 7 illustrates that this cross section mainly contains clay and silt, both with low plasticity index and in some cases silty gravel and silty sand found at the beginning and end of the cross section. In this figure, warm colors (red, yellow, orange, etc.) demonstrate coarse-grained soils, while cool colors (deep blue, light blue, etc.) are indicative of fine-grained soils. As shown in Fig. 6, the values of shear wave velocity are high at the beginning of the cross section. However, the more you move to the middle of cross section, the more its value decreases. From the middle to the end, its value increases. According to the changes in soil layers, SPT-N and V_{s30}, fundamental frequency from the beginning to the middle of the cross section is to be decreased, continuing to the end, the frequency is to be increased. This cross section passes through the three stations 36, 35, and 34. These stations have fundamental frequencies 0.86, 0.82, and 0.93 Hz, respectively. It is shown that geotechnical and geological data are compatible with the changes in the fundamental frequency.

6.2 Cross section B-B`

This cross section with a length of 2300 m located in the northern part of the study area is oriented along the west–east direction. Figure 8 shows that this cross section mainly contains clay and silt, both with low plasticity index and in some cases silty gravel and silty sand are found at the middle of the cross section. Assessments show a low V_{s30} for the beginning of the cross section, an increasing V_{s30} for the middle part, and a

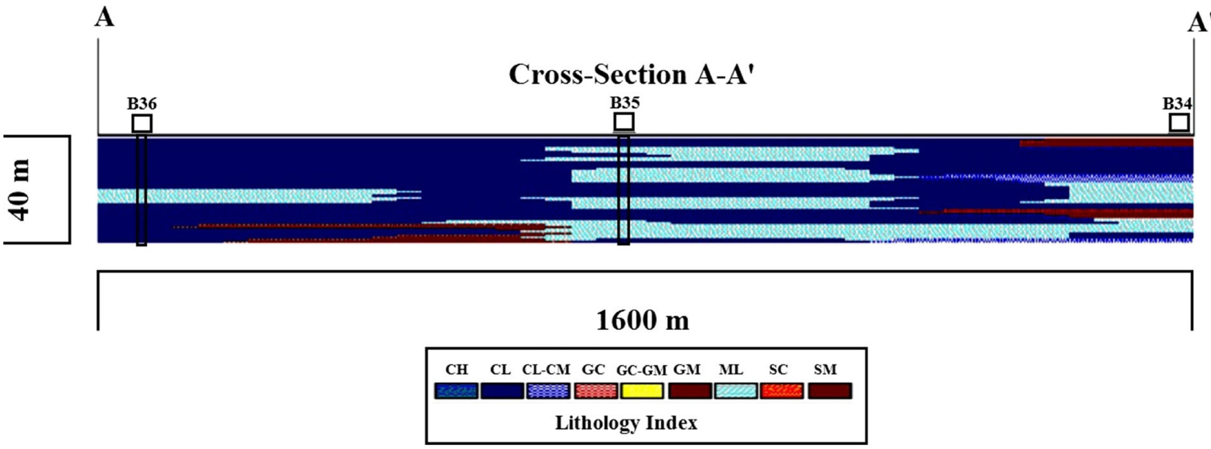


Fig. 7 Cross section A-A`

roughly decreasing V_{s30} for the rest, to the end, of the cross section (Fig. 6). The fundamental frequency is expected to have the lowest value at the beginning, to increase up to the middle, and to gradually decrease at the end of the cross section with regard to the reduced V_{s30}. This cross section also passes through the four stations 4, 3, 2, and 1, with the fundamental frequencies 0.86, 0.91, 1.05, and 0.94 Hz, respectively. It is shown that geotechnical and geological data correspond to the changes in the fundamental frequency.

6.3 Cross section C-C`

This cross section with a length of 3100 m located in the southwestern part of the study area is oriented along the west–east direction. Figure 9 shows that this cross section contains clay and silt, both with low plasticity index, silty gravel and silty sand, and clayey gravel. Evaluations reveal a low value for V_{s30} at the beginning and slight changes for the rest of the path, but more than its value at the beginning. At the end of cross section, the V_{s30} value relatively increases (Fig. 6). The SPT-N value resulting from geotechnical borehole also shows a similar trend for the changing V_{s30}. According to the soil layers, SPT-N values, and V_{s30}, the lowest fundamental frequency at the beginning and increasing ones for the rest of the path are expected. This cross section passes through the five stations 54, 53, 52, 45, and 44, with the fundamental frequencies 0.87, 0.91, 0.92, 0.91, and 0.91 Hz, respectively. As demonstrated, the lowest fundamental frequency is related to the beginning. Then, for the rest of cross section, soil layers and V_{s30} change in an unnoticeable way—that is, a sign for the roughly permanent fundamental frequency. It is shown that

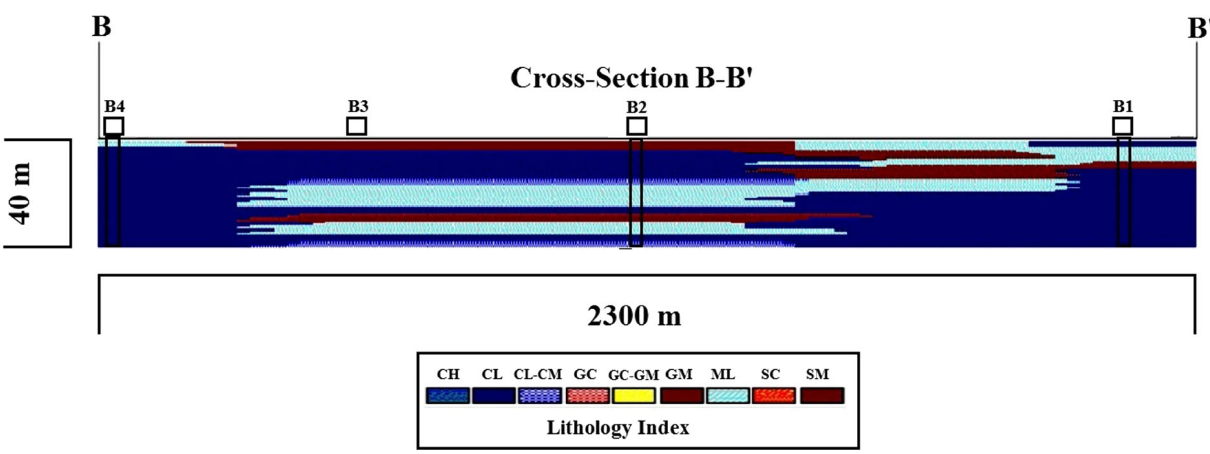


Fig. 8 Cross section B-B`

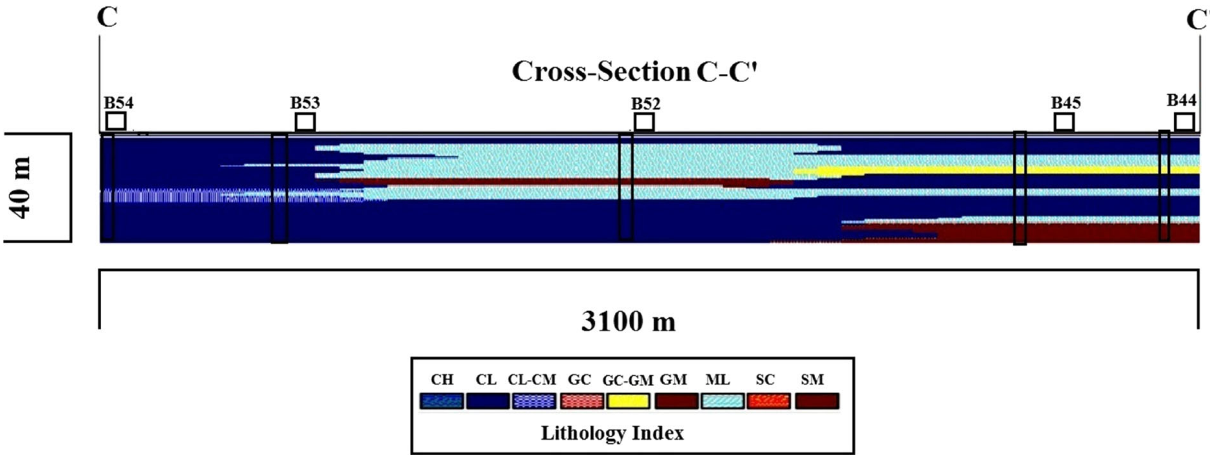


Fig. 9 Cross section C-C`

geotechnical and geological data correspond to the changes in the fundamental frequency.

6.4 Cross section D-D`

This cross section with a length of 950 m located in the middle part of the study area is oriented along the west–east direction. Figure 10 shows that almost all the cross section consists of clay with low plasticity index except for its end which contains silt with low plasticity index and silty sand. Regarding the soil layers, SPT-N values, and V_{s30} (Fig. 6), it is expected to see a low fundamental frequency for the whole cross section, especially at its beginning. This cross section passes through the two stations 29 and 28, with the fundamental frequencies 0.71 and 0.86 Hz, respectively. It is shown that geotechnical and geological data correspond to the changes in the fundamental frequency.

6.5 Cross section E-E`

This cross section with a length of 2000 m located in the Eastern part of the study area is oriented along the south–north direction. A close look at Fig. 11 reveals that this cross section contains clay and silt both with low plasticity index and silty gravel and silty sand. There is a high value of V_{s30} at the beginning of the cross section. To the middle, its value is reduced. And, from the middle to the end, the value is increased; however, it remains less than that of the beginning (Fig. 6). The SPT-N values show a trend similar to that of the changing V_{s30}. With regard to the soil layers, SPT-N values, and V_{s30}, it is expected to see a high fundamental frequency at the beginning, a decreasing one for midway points, and an increasing one, again, at the end of cross section. This cross section passes through the three stations 43, 37, and 31. These stations have

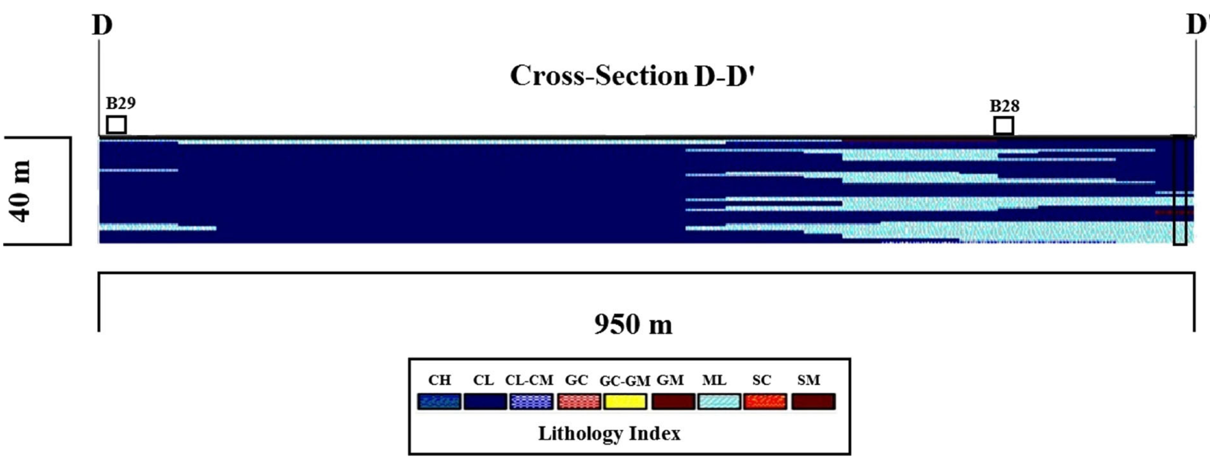


Fig. 10 Cross section D-D`

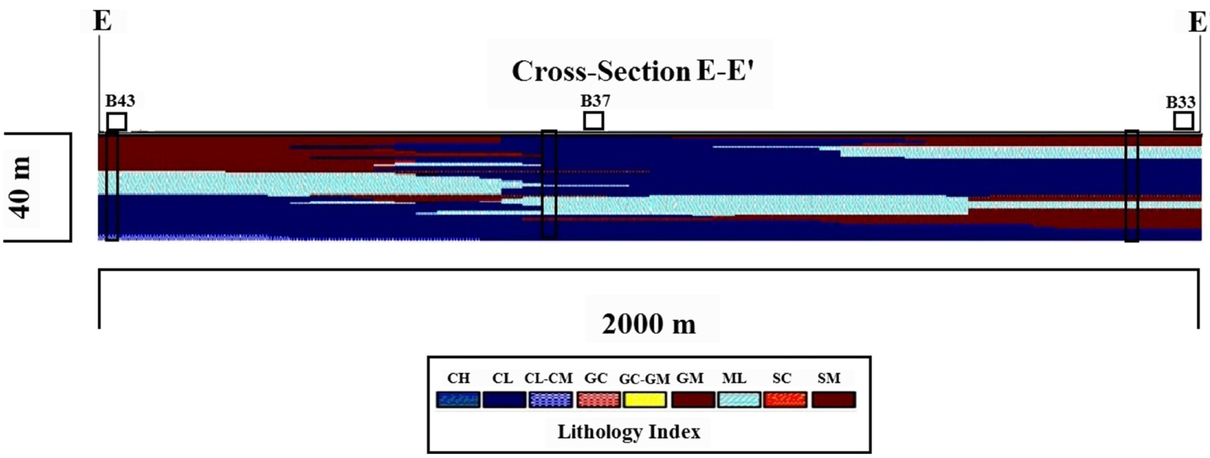


Fig. 11 Cross section E-E`

fundamental frequencies 0.98, 0.85, and 0.92 Hz, respectively. It is shown that geotechnical and geological data are compatible with the changes in the fundamental frequency.

6.6 Cross section F-F`

This cross section with a length of 1900 m located in the middle part of the study area is oriented along the northwestern–southeastern direction. Figure 12 shows that this cross section almost consists of clay and silt both with low plasticity index apart from some area with silty sand. Assessment demonstrates that there is an increasing trend for V_{s30} from the beginning to the middle of the cross section. Then, with the move to the end, V_{s30} shows a considerable reduction (Fig. 6). SPT-N values resulted from a geotechnical borehole shows a compatible trend, as well. Taking the soil layers, SPT-N values, and V_{s30} into account, fundamental frequency is expected to increase from the beginning to the middle and to decrease from the middle to the end of cross section. This cross section passes through the three stations 21, 26, and 32, the fundamental frequencies of which are 0.86, 0.93, and 0.82 Hz, respectively. It is shown that geotechnical and geological data are compatible with the changes in the fundamental frequency.

6.7 Cross section G-G`

This cross section with a length of 1550 m located in the northwestern part of the study area is oriented along the southwestern–northeastern direction. A close look at Fig. 13 illustrates that this cross section mostly consists of coarse particles (silty sand, clayey gravel, clayey sand, and silty gravel). With regard to the soil layers and high values for V_{s30} (Fig. 6), the fundamental

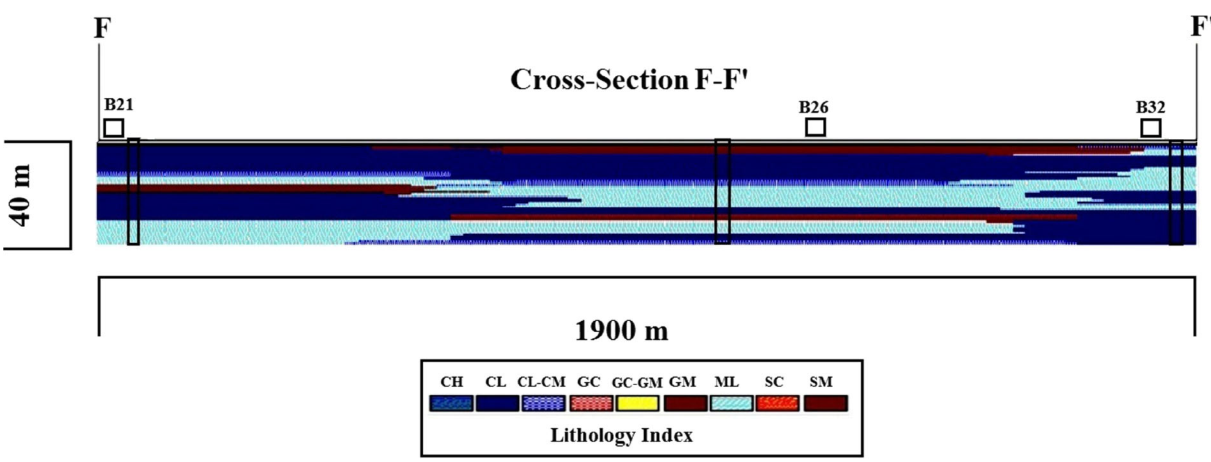


Fig. 12 Cross section F-F`

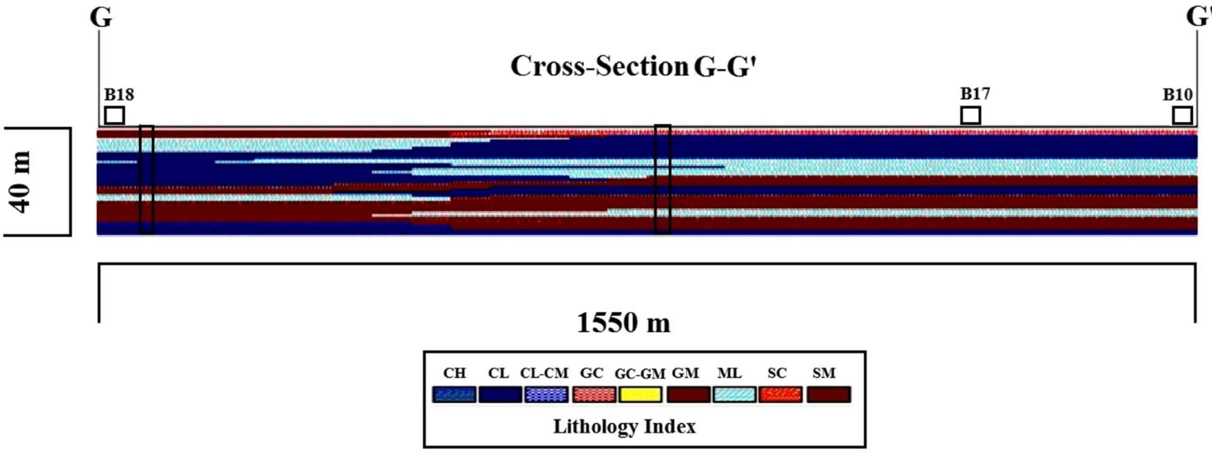


Fig. 13 Cross section G-G`

frequency is likely to be in a high range. This cross section passes through the three stations 18, 17, and 10, the fundamental frequencies of which are 7.35, 6.13, and 11.4 Hz, respectively. It is shown that geotechnical and geological conditions are responsible for the changes in the fundamental frequency.

7 Comparison of microtremor measurements results with the seismic data

As stated previously, one of the reliable methods for validation of results of a microtremor measurement is using seismic data (Bour et al. 1998; Ojeda and Escallon 2000; Sivaram et al. 2012; Navarro et al. 2014; Natarajan and Rajendran 2016; Yamanaka et al. 2016). To carry out such a comparison in the study area, the seismic data used has been available at the provincial office of Babol City. Figure 3 shows the location of the accelerograph. This station recorded two strong ground motions, the specification of which have been prepared in Table 3.

Calculating H/V spectral ratio (HVSR) for a strong ground motion is one of the most credible methods of using strong ground motion data. Lermo and Chavez-Garcia (1994) applied the H/V spectral ratio method for strong ground motion records at Mexico City. They could find similarities between the results of H/V spectral ratio and that of microtremor measurements in order to determine the fundamental frequency. Field et al. (1995) adopted the HVSR method and concluded that the shape of the spectral ratio is compatible with the geotechnical data.

In order to calculate the HVSR, the Fourier spectra in three directions for a strong ground motion record are obtained. The ratio of averaged two spectra in horizontal directions over a spectrum in vertical direction is known as the HVSR (Ojeda and Escallon 2000; Sivaram et al. 2012; Navarro et al. 2014). Figure 14 shows the HVSR for the strong ground motion records. As observed in Fig. 3, the accelerograph is located near the station B39. The fundamental frequency, at this station, is 1.06 Hz; however, it has the value 0.90 and 0.95 Hz using the seismic data. Thus, it is obvious that the value of fundamental frequency obtained by HVNR is very close to its value calculated by the HVSR method.

The microtremor measurements are related to the soil's linear behavior and during the occurrence of

Table 3 Specification of strong ground motion

Station	Longitude	Latitude	Date	Time	Focal depth (km)	Epicentral distance (km)	M
Babol	52.67	36.53	28/5/2004	12:38	16	100	6.4
Babol	52.67	36.53	11/1/2012	17:08	18	18	5.2

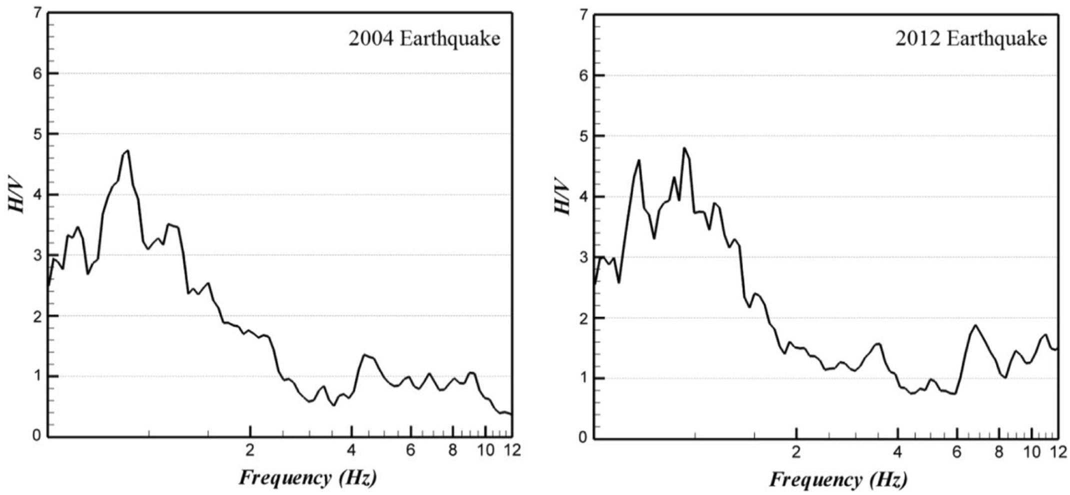


Fig. 14 HVSR of the strong ground motion

earthquake; soil loses its linear behavior and gains a non-linear one. Non-linear effects generally lead to a slight shift of the fundamental frequency towards the lower frequencies (Bour et al. 1998). Therefore, it is reasonable to obtain a lower fundamental frequency in Fig. 14 when it comes to comparing its value to that of a microtremor measurement. These two methods give different amplification ratios which is logical with respect to the earlier discussion (Section 3) (an amplification measured by HVNR, differs from an amplification factor).

8 Conclusion

In the present research, in order to evaluate site effects in Babol City, microtremor measurements have been conducted at 60 stations. Data have been analyzed using the Nakamura method (HVNR), then their fundamental frequencies have been extracted, and finally a microzonation map is presented. In addition, to assess the reliability of the method, the obtained results have been compared with geotechnical, geological, and seismic data. The results are summarized as follows:

1. The data has been analyzed by use of the Nakamura method (HVNR). The results show minimum and maximum fundamental frequencies 0.65 and 11.4 Hz, respectively. Assessment also reveals that the major parts of Babol City have the fundamental frequencies less than 1.25, which are in conformity with that of previous research.
2. When evaluating the results, a few stations with values of very high fundamental frequencies were observed near Babolrood River. ERT survey also shows a hard deposit in these areas.
3. The microzonation map has been prepared based on the fundamental frequency. This map shows that a large part of the city has a fundamental frequency less than 1.25 Hz, except for the parts in the north-west, west, and south of the city that have fundamental frequencies more than 5 Hz.
4. According to the results of seven cross sections, it can be concluded that fundamental frequency variations are in line with the geotechnical and geological data in the study area. It means that this method is the appropriate way to assess the local site effect in the city of Babol. It is also observed that besides the soil layers, the soil stiffness and its shear wave velocity are effective factors in changing the fundamental frequency.
5. Using seismic data, the HVSR of two strong ground motions have been calculated and the results have been compared with the nearest microtremor recording station. Analyzing the spectral ratios demonstrates that the value of the fundamental frequency obtained by the HVNR method (1.06 Hz) is very close to that of frequencies obtained by the HVSR method (0.95 and 0.90 Hz).

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