Magazine of Civil Engineering. 2022. 110(2). Article No. 11008

Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

DOI: 10.34910/MCE.110.8

The site effect investigation using nonlinear and Iranian seismic code methods in Babol city

S. Rezaei*, A. Hasanzadeh

Babol Noshirvani University of Technology, Babol, Mazandaran, Iran

**E-mail: S_Rezaei1366@yahoo.com*

Keywords: earthquake, site effect, nonlinear method, seismic code, design spectrum, response spectra

Abstract. Site effect is known as one of the important issues in geotechnical earthquake engineering. The site effect can change the characteristics of seismic waves and amplify the vibrations which results in the casualties and financial damages. Nonlinear method is an appropriate numerical method for site effect analysis due to its accuracy and its close results compared to the actual soil behavior. Thus, in this research, nonlinear analysis was applied for evaluation of site effect and for achievement of a suitable design spectrum in Babol city located in the north of Iran. For this purpose, first, seismic, geophysical and geotechnical data of Babol city were provided. Then, by modeling the subsurface conditions, the tripartite response spectra were found for different areas of Babol. According to the obtained results, the behaviors of tripartite response spectra are fundamentally different in some frequency ranges. In addition, the shape factors obtained from site analysis for different parts of Babol city were compared with the shape factor of the design spectrum presented by Iranian seismic code. This comparison indicated that the response spectrum obtained through analysis differs from the Iranian seismic code design spectrum. Finally, it can be concluded that the structures designed according to Iranian seismic code are neither safe nor economic in some areas. This issue shows the necessity for more serious consideration of site effect phenomenon in Iranian seismic code.

1. *Introduction*

One of the most important issues in seismic study of an area is evaluation of the site effect on the characteristics of seismic waves. The occurrence of catastrophic earthquakes such as Caracas 1967, San Fernando 1971, Mexico City 1985, Loma Prieta 1989, Manjil–Rudbar 1990, Izmit 1999, Bam 2003, Sichuan 2008, Tohoku 2011 and Chiapas 2017 revealed the significant effect of geotechnical conditions on the earthquake characteristics [1–3]. By studying the influence of soil on the earthquake-induced damage, it was found that soil behavior can be an important factor in causing damage in different ways. When the natural period of the site is the same as the natural period of the structure, the resonance phenomenon occurs. In this case, the ground motions caused by the earthquake are amplified and will be applied to the structure with a greater acceleration. Besides, site effect can increase vibration duration and change its frequency content. Another factor that impacts the amount of earthquake-induced damage is the dominant period and amplification factor of site. The dominant period of site is the period associated with the highest peak on the acceleration spectrum. Physically, the main factor causing the amplification of ground motions in soft deposits is the trapping of the seismic waves between deposits and the bedrock [4–7].

Nowadays, all the developed countries have incorporated the site effect phenomenon into their seismic codes. There are different soil classifications in codes considering the mechanical and dynamic properties, liquefaction and collapse potential of soils [8–10].

In Iranian seismic code (standard No. 2800), site effect has been considered using the design spectrum shape factor (B_1). This parameter is dependent on the period of structure, soil type and seismic

Rezaei, S., Hasanzadeh, A. The site effect investigation using nonlinear and Iranian seismic code methods in Babol city. Magazine of Civil Engineering. 2022. 110(2). Article No. 11008. DOI: 10.34910/MCE.110.8

hazard level of the region [11]. The results of previous investigations showed that the shape factor presented in standard No. 2800 has some shortcomings and does not well represent the site effect on a given structure. Some of the problems in this standard are as follows:

1. The design spectrum shape factor does not take into account the amplification effect for short-period earthquakes.
2. The design spectrum shape factor does not consider the nonlinear response of the site, particularly in soft clayey soils.
3. Different parts of standard No. 2800 has been directly derived from the Uniform Building Code (UBC) which has undergone major changes itself and in its new edition the effects of the site are taken into account more seriously.
4. The effects of near-field earthquakes were not considered in standard No. 2800.
5. Standard No. 2800 does not address earthquake directivity effects.
6. The major geotechnical features such as soil layering, profile thickness and shear strength of soft soil were not accurately addressed in standard No. 2800 [12–18].

Since Iran is located in a seismic zone with the possibility of occurrence of destructive earthquakes, serious attention to the earthquake effect in the design and construction of structures seems necessary. Overall revision of United States building code induced other seismic countries to take a new look at the effect of site on the base shear [11, 17–19]. By studying various codes, it can be found that in addition to the Vs_{30} parameter (the average seismic shear wave velocity from the surface to a depth of 30 meters), other parameters such as the depth of the seismic bedrock, material type, vibration intensity, site period and deposit depth have been used to consider the site effect [17–19].

In the new edition of standard No. 2800, application of site-specific design spectrum has been recommended. This spectrum depends on several factors such as seismic, geological and tectonic characteristics of the site. Since application of site-specific design spectrum is only necessary for the design of particular structures, engineers do not take it into account for the design of common buildings [11]. Thus, it is essential to conduct a comprehensive study to reveal the importance of site-specific design spectrum. In other words, using site analyses, the effective factors on the structures can be found and different approaches to confront the destructive effects of earthquakes in the design of structures can be suggested.

Generally, there are two approaches for evaluation of site effect including field and numerical methods. Field methods include all geotechnical, seismic, geophysical and geological activities that are carried out in the field. Numerical methods mainly use the information of field methods (earthquake record, borehole log, shear wave velocity, etc.) as primary data for the detailed analyses [20, 21].Numerical methods of site effect analysis are divided into several methods based on different factors such as model and domain of analysis, pore water pressure, problem dimensions and characteristics of materials [22].

The application of an elastic model is appropriate when behavior of soil is anticipated to remain within the small strain range ($<10^{-5}$). For the medium strain range (10^{-3}), the behavior of soil gets elasto-plastic and shear modulus reduces with the increase of the shear strain. The damping ratio and shear modulus do not alter with the progression of cycles in this strain level (non-degraded hysteresis). In the case of shear strain level greater than 10^{-2}, the characteristics of soil tend to alter significantly not only with shear strain but also with the progression of cycles. This behavior is called as the degraded hysteresis [16, 22]. During destructive earthquakes, large strains occur in the soil. Under these conditions, nonlinear analysis can accurately present the actual soil behavior as well as irreversible deformations.

Thus, in this study, nonlinear analysis is performed for evaluation of site effect considering site-specific design spectrum. For this purpose, in the city of Babol, geophysical data by performing down-hole tests and geotechnical data using 90 boreholes were provided and employed. The results of analyses are presented as tripartite response spectra. At the next step, the shape factors of design spectra obtained by numerical analyses are compared with the one presented in standard No. 2800. Finally, using standard No. 2800 and the results of this investigation, structures with different stories are modeled and their structural design characteristics (base shear and drift) are compared to reveal the importance of considering site effect on structures.

2. Methods

Evaluation of previous earthquakes has shown that geotechnical conditions can significantly affect the damage distribution in residential areas. The results found by different researchers have proved that soft deposits are problematic for high structures and far-field earthquakes. In addition, stiff deposits are dangerous for short structures and near-field earthquakes due to the amplification of ground motion. In other words, it can be stated that soil acts like a filter and changes the characteristics of ground motion during earthquake [22–25]. Density, age, thickness and other geotechnical properties of soil can alter the characteristics of seismic waves so that site effect can increase intensity up to 3 degrees in Mercalli scale [26–32]. Thus, the importance of site effect evaluation and its application in building codes becomes more pronounced.

The study area in the present research is Babol city in Iran. This city is situated in a high seismic area due to its location in front of Alborz Mountain, which is tectonically an active region. The tectonic of Alborz Mountain is controlled by boundary conditions due to convergent motion between Arabia and Eurasia, which probably started in the Cretaceous [16, 24]. The texture and thickness of deposits in Babol city are mainly affected by the sedimentation of Babolrood River and the coastal deposits of Caspian Sea. Fig. 1 shows the study area and location of boreholes. In this study, 57 geotechnical boreholes with variable depths (5 to 40 m) were collected from different sources. Moreover, 33 boreholes were drilled for better evaluation of subsurface conditions.

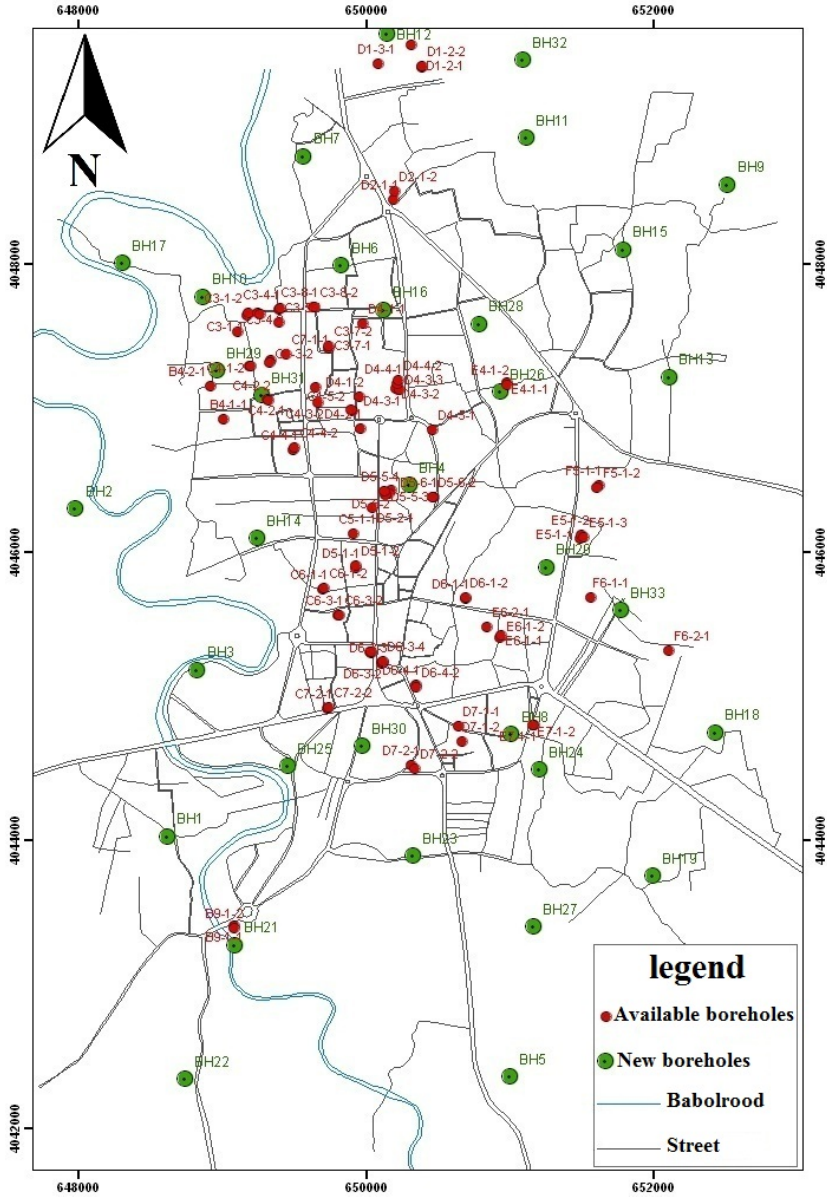

Figure 1. The study area and location of boreholes.

Using geotechnical data and Rockworks software, soil layering in the study area was obtained for various depths. For example, Fig. 2 shows the distribution of soil texture at the ground level.

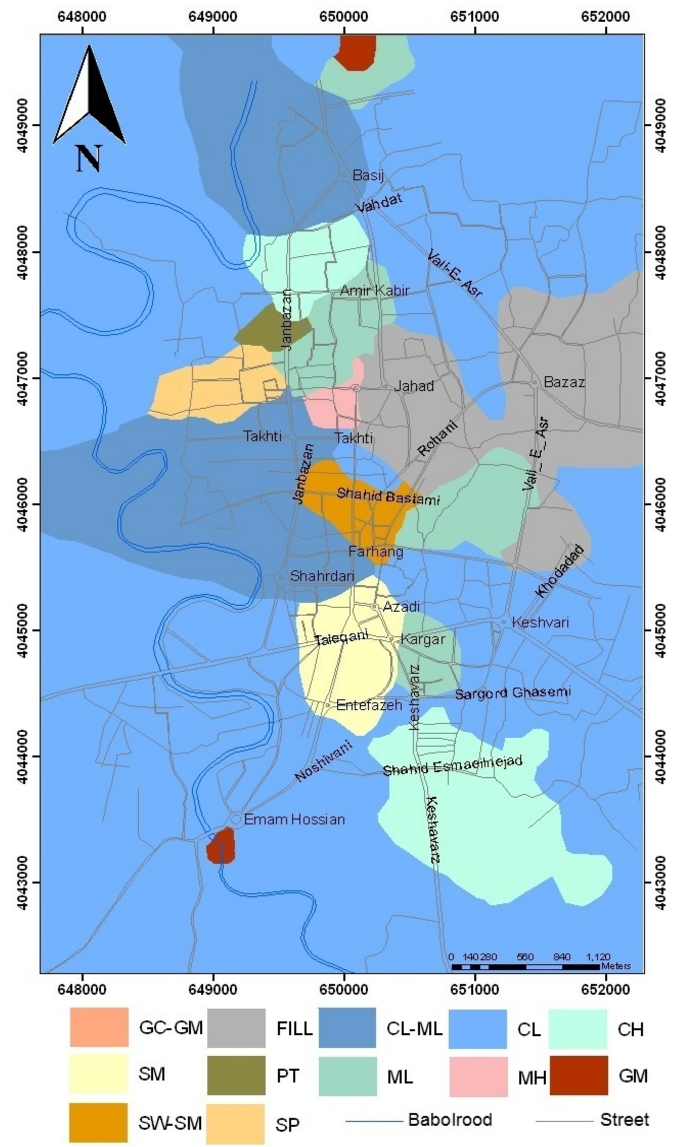

Figure 2. Distribution of soil texture at the ground level in Babol city.

Using these data, the geological model of the study area was provided which is used for numerical analysis. In addition, the results of the laboratory (direct shear, unconfined compression and Atterberg tests) and field (Standard Penetration Test) tests showed that the study area is consisted mainly of fine-grained soil with low relative density (Standard Penetration Test number <10, unconfined compressive strength <60 kPa). The study area and its surroundings up to 150 km radius are located in two seismic zones of Rasht-Gorgan and Central Alborz. Table 1 presents the major faults within the 150 km radius of the study area.

Table 1. Characteristics of faults around the study area [24].

Fault name	Distance to study area (km)	Fault length (km)	Fault mechanism
Firooz Abad	85	112	thrust fault
Alborz	44	300	thrust fault
Khazar	16	550	thrust fault
Attari	91	85	thrust fault
Astane	93	75	thrust fault
Garmsar	136	70	thrust fault
Kandovan	100	64	thrust fault
Masha	91	400	thrust fault
North of Tehran	115	108	thrust fault
Ivanaki	143	75	thrust fault
Firoozkooh	84	40	thrust fault
Basham	96	71	thrust fault
Ourim	72	44	thrust fault
Damghan	136	100	thrust fault
Robat Karim	184	90	thrust fault
Bayjan	60	45	thrust fault

The study area has repeatedly experienced earthquakes such as Qumis (22 December 856), Rey-Taleghan (23 February 958), Damavand-Shemiranat (27 March 1830), Ah-Mubarakabad (2 October 1930), Kusut (11 April 1935), Bandpay (2 July 1957), Babol Kenar (2 August 1971), Kojoor (28 May 2004), Marzi Kola (16 January 2012), Kiasar (21 March 2013), Surak (20 March 2017) and Juybar (23 September 2018).

Fig. 3, which was provided using GeoMap software, depicts the epicenter of the earthquakes with magnitudes greater than 5 Richter occurred around the study area within the last 50 years. Table 1 and Fig. 3 show the high seismic potential of the study area which highlights the need for site effect evaluation.

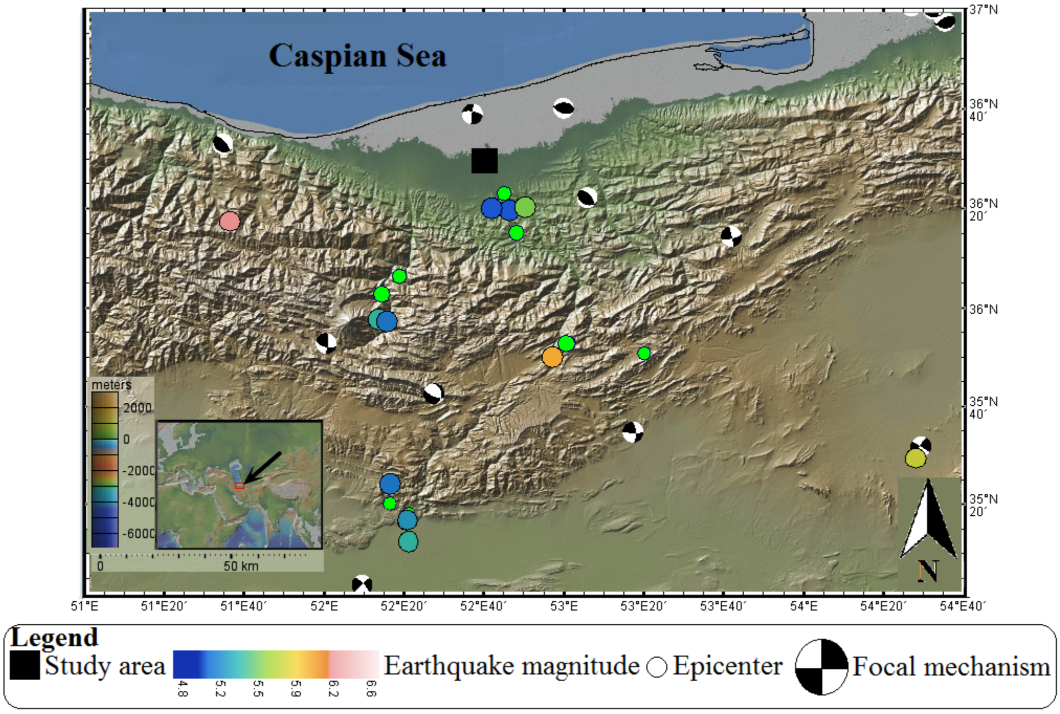

Figure 3. Earthquakes with magnitudes of more than 5 Richter occurred around the study area.

In order to analyze site effect, nonlinear method using PLAXIS software was applied in this study. Nonlinear analysis is in fact, the analysis of real nonlinear response of soil mass using direct numerical integration in the time domain. By integrating the equation of motion in short- time steps, any linear or nonlinear stress- strain model or even complex behavioral model can be solved [22]. Nonlinear dynamic analysis in PLAXIS software is divided into three general sections. The first part is modeling geometry, selecting materials and appropriate constitutive model, introducing boundary conditions, static and dynamic loading, and generating finite element mesh. The second part is introducing the first conditions of the model and finally, the third part is receiving results from the software [33]. In this study, 6-node triangular elements were used. To analyze the propagation of waves and the impact of alluvium on earthquake, some characteristics such as soil type, number and thickness of soil layers, soil density, moisture content, groundwater level and shear wave velocity should be determined. This data set is called the dynamic site profile. The shear wave velocities are obtained by down-hole tests and other data are found through borehole logs and laboratory tests. The results of down-hole tests showed that Babol soil type is generally type IV according to soil classification in standard No. 2800. Fig. 4 indicates the results of down-hole tests for one of the boreholes (BH1).

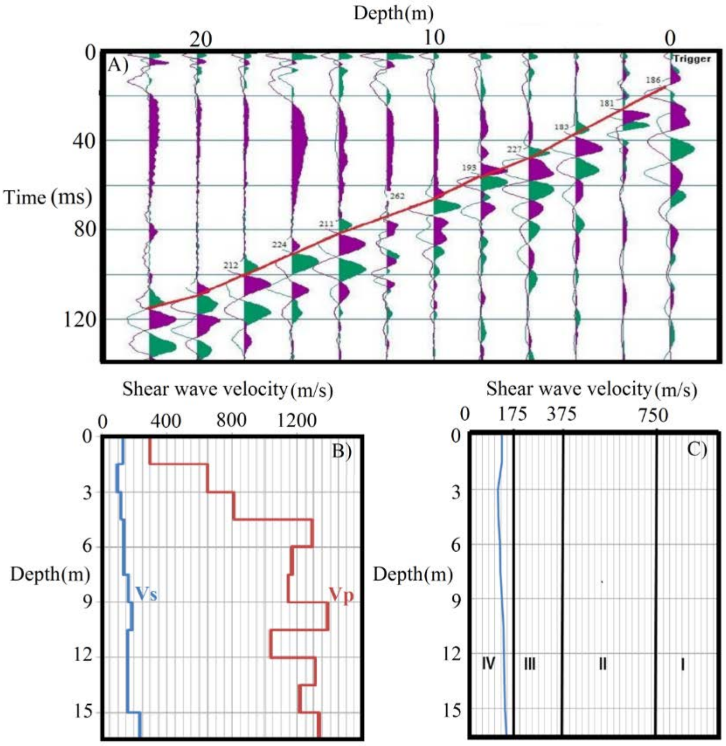

Figure 4. Down-hole test for BH1 borehole (a) Shear wave mapping (b) Shear and compressional wave velocity profiles (c) Variation of mean shear wave velocity with depth and its classification according to standard No. 2800.

The Mohr-Coulomb elasto-plastic model was selected as the appropriate behavioral model in this study. The side boundaries are restricted in the horizontal direction and the bottom boundary is restricted in both horizontal and vertical directions. Since soil is a semi-infinite space, special boundary conditions have to be defined for dynamic problems such as earthquakes. Without these boundary conditions, the waves reflect on the boundaries due to the disturbance. To avoid this wrong reflection, absorbent boundaries are applied using the damping spring at the boundary. In PLAXIS software, the conditions of absorbing reflection waves from the boundaries are provided using dampers. Moreover, the earthquake is simulated by a predefined inductive displacement at the bottom boundary. Another important issue in dynamic analysis is the numerical instability of wave propagation that can be occurred due to inappropriate modeling. To provide accurate wave propagation in a model, maximum element size (Δl) should be less than one-tenth of the longest wavelength (λ):

$$\Delta l \le \frac{\lambda}{10}. \quad (1)$$

For most of the earthquakes, frequency range of Fourier spectrum is between 0 and 10 Hz. In order to avoid numerical instability, Eq. (2) was applied in the numerical modeling:

$$\lambda \le \frac{c}{f}, \quad (2)$$

where c is wave propagation velocity and f is frequency. Since the lowest shear wave velocity in this research is 110 m/s and the highest earthquake frequency is 10 Hz, it can be expressed that:

$$\Delta l \le \frac{110}{10 \times 10} = 1.1 \text{ m}. \quad (3)$$

To improve the accuracy, Δl was considered 1 m in this study. In order to analyze site response, selection of appropriate accelerogram is very important [25, 34–35].

In order to estimate the earthquake hazard within a radius of 150 km from Babol city, first, all tectonic activities are identified and mapped using satellite imagery and aerial photographs. Then, the seismic features of faults and the seismic history of the study area are investigated. At the next step, the seismic model of the study area is proposed and important seismic sources are identified. The seismic characteristics of each region are determined using the data of earthquakes as well as the empirical relationships. Then, seismic parameters are predicted based on probabilistic statistics method. Finally, appropriate accelerograms are introduced and scaled. In this study, accelerograms of Bam, Naghan, Tabas, Baladeh, San Fernando and Northridge earthquakes were used. It should be mentioned that at least 3 stations were evaluated for each earthquake. Several factors such as spiky behavior, near or far field and vibration duration of earthquakes were considered for selection of stations and accelerograms. In fact, considering different parameters and accelerograms causes most of the possible earthquake scenarios to be investigated. The process of scaling accelerograms should be in such a way that response spectrum of accelerograms at the end of the computation is similar to the target response spectrum for each design level. For this purpose, first, applying the main accelerogram in the frequency domain, the response spectrum of the considered accelerogram is calculated and then, by considering the values of the original accelerogram response spectrum and the target response spectrum, the scaling process is performed. This process is repeated several times until scaled accelerogram response spectrum matches target response spectrum as much as possible. Finally, using inverse Fourier transform in time domain, the scaled accelerogram is obtained.

Fig. 5 shows one of the modified earthquakes for Babol in which green and red accelerograms are related to original and modified earthquakes, respectively. After modeling and application of seismic loading, the results of site analysis for different zones (90 boreholes) are obtained.

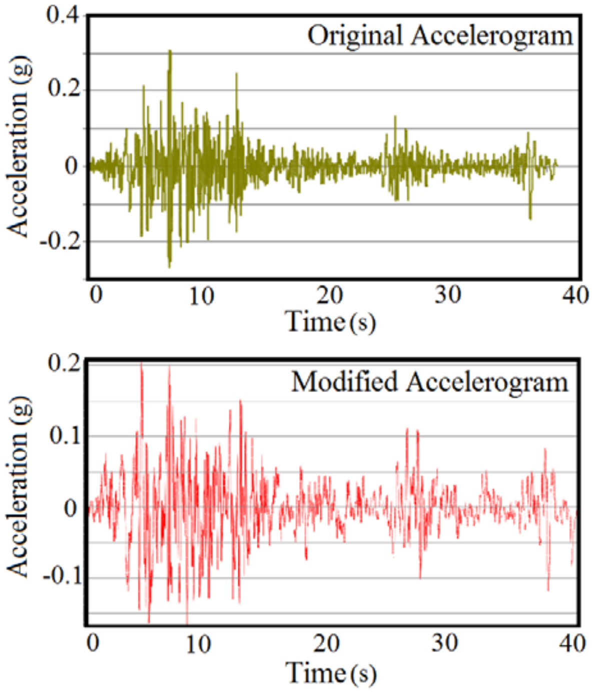

Figure 5. One of the scaled earthquakes for Babol site (Tabas earthquake-Deyhook station, horizontal component).

3. Results and Discussion

In this section, after modeling dynamic profiles at different zones, results of their nonlinear analyses are compared with each other. Utilization of response spectrum is one of the common methods for description of ground motion. Although the response spectrum cannot accurately describe the actual ground motion, it contains valuable information about the impact of ground motion on structures [22, 36–37]. The tripartite response spectra were used in this study because they contain information about displacement, pseudo-velocity and pseudo-acceleration response spectra [22]. Since it is not possible to present the results of 90 analyses individually, the similar results were collected in one group. Overall, the tripartite response spectra were classified into 5 types. Several parameters such as natural site period, acceleration time-history and velocity time- history were considered in this classification. Fig. 6 shows five different types of tripartite response spectra in Babol city which should not be mistaken with soil types in standard No. 2800. As observed, for acceleration sensitive range (period < 0.5 s), response spectra are close to each other. For velocity sensitive range (0.5 < period < 3 s), response spectra have the maximum difference with each other. For displacement sensitive range (period > 3 s), response spectra are also different from each other. The location of each response spectrum type in Babol city is presented in Table 2 which can be used for providing Babol zonation map.

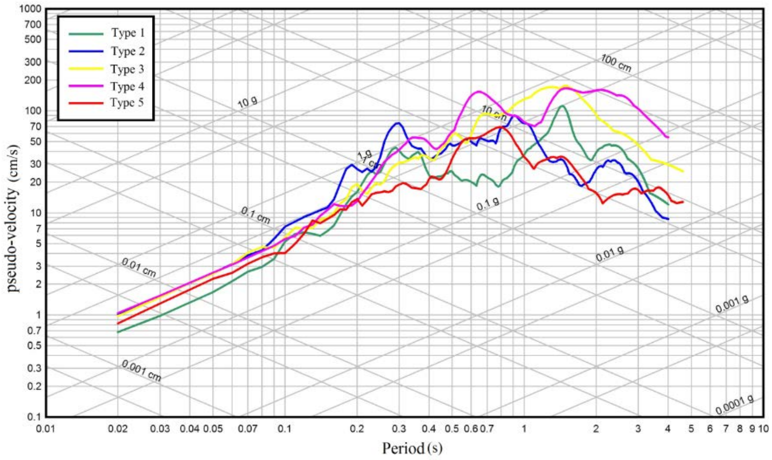

Figure 6. Five different types of tripartite response spectra.

Table 2. Location of response spectra in Babol city.

Response spectrum type No.	Location
Type 1	The central and northern parts of the city
Type 2	The west and northwest parts of the city
Type 3	The eastern and southeastern parts of the city
Type 4	The southern and southwest parts of the city
Type 5	The northeast part of the city

Fig. 7 indicates comparison of the shape factors obtained by nonlinear analyses and the design spectrum shape factor presented in standard No. 2800 for soil type IV. The obtained shape factors through nonlinear analysis shows soil amplification for different periods during seismic loading. The outputs of PLAXIS are imported into Seismosignal software and shape factors for different types are determined. The soil type IV in standard No. 2800 is a non-cohesive soil with low to medium density or soft to stiff cohesive soil. The average shear wave velocity in different soil layers up to 30 m depth from the base level, corrected standard penetration number and undrained shear strength up to 30 m depth from the base level are 175 m/s, 15 and 70 kPa, respectively [11]. Thus, the dominant soil in the study area is type IV. Several points are evident from Fig. 7:

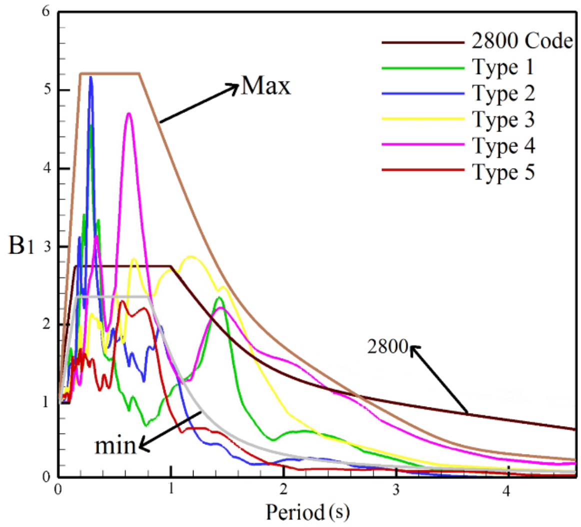

Figure 7. Shape factors obtained by nonlinear analyses and standard No. 2800 for soil type IV.

1. In various zones of Babol city, soil layers have different natural periods. When the period of site matches the structure period, resonance phenomenon occurs. This issue should be considered in urban development planning.

2. The obtained response spectra by nonlinear analyses, except for natural site periods (0 < period <
< 1 s), are in the range of the standard No. 2800 design spectrum or very close to this range. Hence, it can

be stated that unless when the natural periods of structures are within the range of 0 to 1 second, the design of the structures based on standard No. 2800 is almost safe and reliable. It should be noted that type 5 is out of this rule and the design provided by standard No. 2800 is safe in all frequency bands.

3. More than one peak is observed for some spectra (type 1 and 4) in which the first and second peaks show the period of the higher modes of site and the natural site period, respectively.

4. The design spectrum of standard No. 2800 for long periods (more than 2.5 seconds) is greater than the obtained response spectra from the nonlinear analyses.

5. For natural site periods, the shape factor presented by standard No. 2800 (except type 5) is not appropriate.

6. The difference between results of nonlinear analyses with design spectrum of standard No. 2800 becomes more obvious with increasing earthquake magnitude. This clarifies the necessity to consider the nonlinear analysis of site, particularly for the design of important structures.

7. When soil behavior is in the range of elastic or elasto-plastic, standard No. 2800 can be applied. Otherwise, nonlinear analysis method is recommended.

8. The declining part of the design spectrum presented by standard No. 2800 (period > 2.5 s) should be modified and the shape factor needs to be reduced. On the other hand, for shorter periods (period < 1s), the shape factor presented by standard No. 2800 should be increased.

In order to reveal the differences between the results found by nonlinear analysis and standard No. 2800, base shear and drift for one to six-story structures (common structures in Babol) are calculated using three different design approaches which are design spectrum of standard No. 2800 and the maximum and minimum spectra found by the site analysis. The maximum site spectrum is the spectrum that other spectra are below it (Fig. 7) and the minimum site spectrum is the spectrum that only type 5 spectrum (the lowest spectrum) is below it (Fig. 7). For modeling of the structures, ETABS software was used. In order to avoid over-resistance in the members and also to increase the accuracy of the results, the columns and beams are selected so that the stress ratio is close to 1.

Fig. 8 shows the 5-story structure model in this study. Fig. 9 shows variation of base shear values obtained using three different shape factors against the number of structure stories. The base shear values for all of the structures designed using the minimum spectrum were lower than the ones designed by standard No. 2800. In other words, in the areas of the city where the minimum spectrum is dominated, design of the structures using standard No. 2800 seems safe and uneconomic. For the areas of the city where the maximum spectrum is dominated, design of the structures using standard No. 2800 is unsafe.

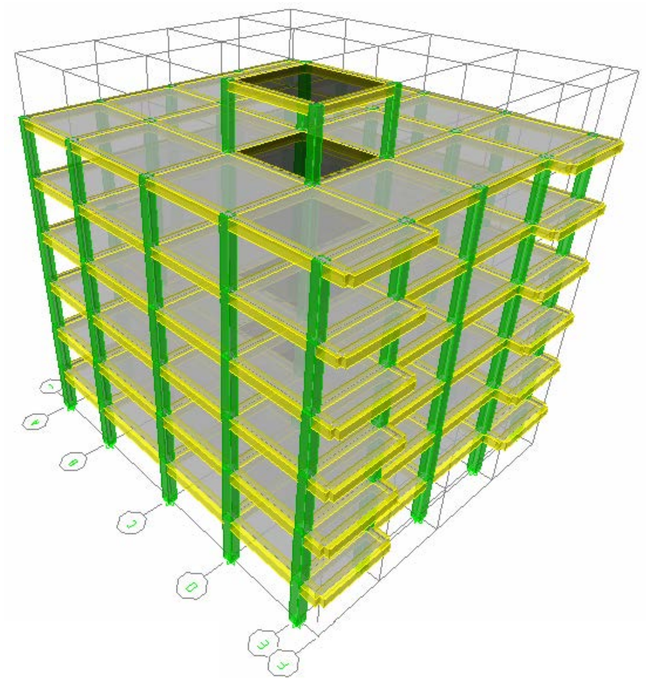

Figure 8. The 5-story structure model.

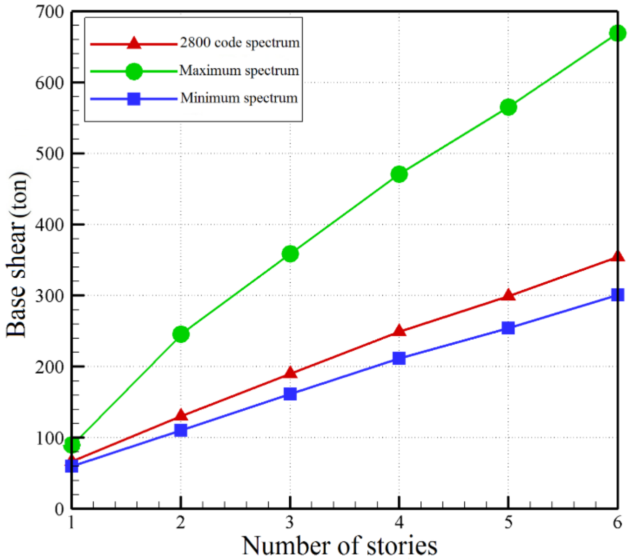

Figure 9. Variation of base shear values with the number of stories.

The results presented so far are related to the structures with the common number of stories in Babol city (one to six-story structures). At this stage, for a more detailed study of the site and structure effects, the base shear values are calculated for buildings with different frequencies. Since the tallest building in Babol city has less than 20 stories, the frequencies between 0.5 and 10 Hz were evaluated. Fig. 10 indicates variation of base shear with structure frequency. It is observed that the greatest base shear occurs at a frequency of about 1 Hz. This issue should be considered in the future design of structures in this city.

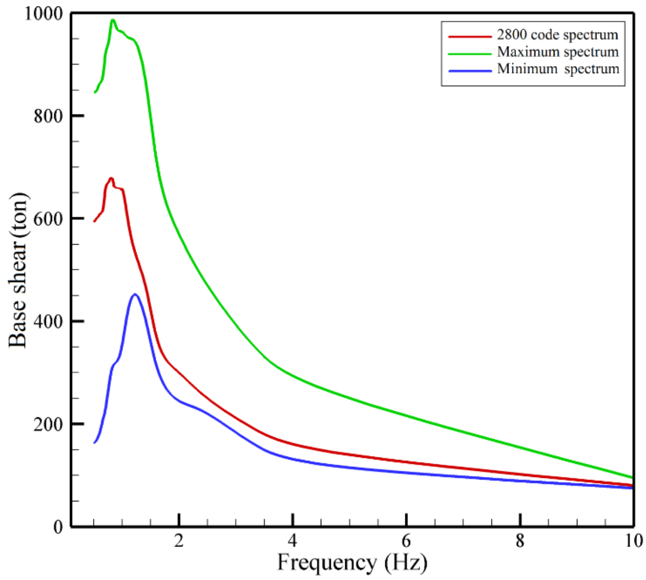

Figure 10. Variation of base shear with structure frequency.

Figs. 11 and 12 indicate variation of the number of stories with drift for a 6- and 4-story structure designed with the three mentioned spectra, respectively. For both of these Figs., the values of drifts achieved by the minimum spectrum are less than the ones presented by standard No. 2800. Therefore, in the areas of the city where this spectrum is dominated, design of the structures using standard No. 2800 is safe. Furthermore, the values of drifts obtained by the maximum spectrum are more than the ones presented by standard No. 2800. This can cause the structure to collapse during an earthquake.

The results of the modeling depict that design of structures based on standard No. 2800 is unsafe and uneconomic in some areas. Thus, consideration of site effect, particularly site-specific design spectrum, is necessary for design of structures. It should be remarked that the periods of the considered structures (common structures in Babol) were less than 1 s. Therefore, the difference between the results obtained by the minimum spectrum and standard No. 2800 is not considerable.

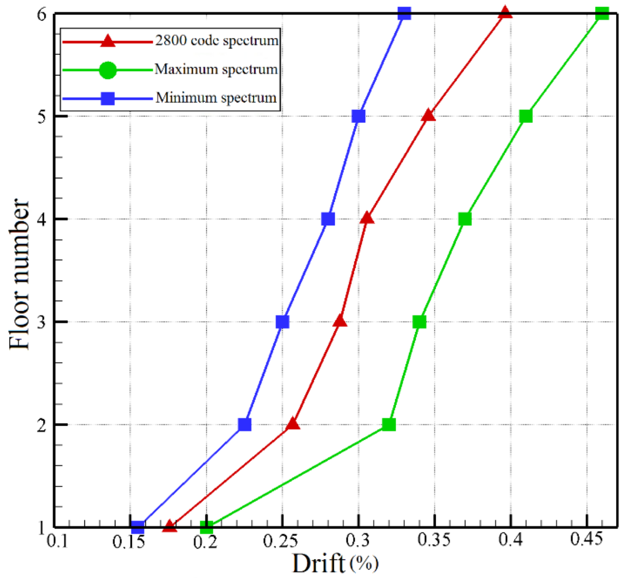

Figure 11. Variation of the floor number with drift for a 6-story structure.

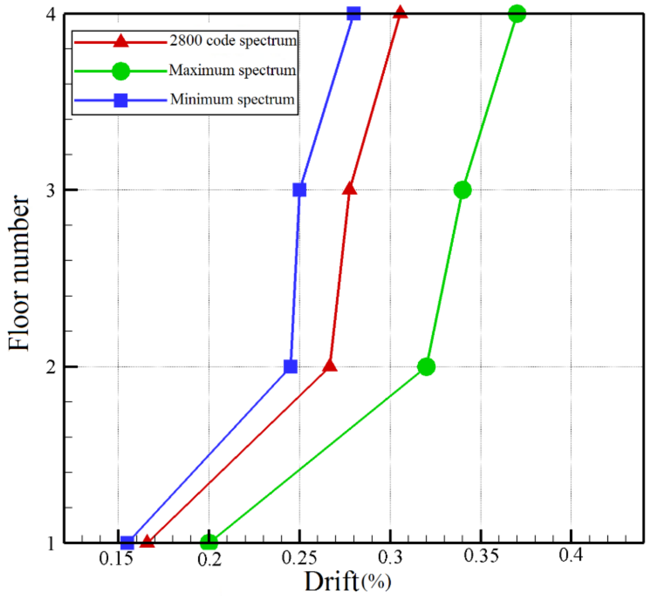

Figure 12. Variation of the floor number with drift for a 4-story structure.

4. Conclusions

In this study, nonlinear analysis method was used for evaluation of site effect and achievement of appropriate design spectrum in Babol city. Regarding to the nonlinear site response analysis, the following conclusions achieved:

1. Using seismic, geotechnical and geophysical data, dynamic profiles of 90 regions in Babol were modeled and 5 types of response spectra were introduced. Evaluation of the tripartite response spectra of these 5 types indicates that their behavior differ substantially from one another in some parts of the frequency range. This issue illustrates the importance of site effect consideration.

2. In order to compare the results obtained by nonlinear analysis with standard No. 2800, the shape factors of different types were compared with the design spectrum of soil type IV of standard No. 2800. This comparison indicated that the response spectrum obtained through analysis is different from the Iranian seismic code design spectrum.

3. The standard No. 2800 design spectrum is conservative for long periods. For natural site periods, except for type 5, the shape factor presented by the standard No. 2800 is not appropriate. It can be stated that application of standard No. 2800 is only recommended for elastic or elasto-plastic ranges. Otherwise, nonlinear analysis method should be employed.

4. To further investigate the differences in the results of site analysis with standard No. 2800, base shear and drift of 1 to 6-story structures (common structures in Babol) were calculated using the standard No. 2800 design spectrum and the maximum and minimum spectra obtained from the site analyses. The results showed that base shear and drift values for all structures designed using the minimum response spectrum were lower than the ones designed by standard No. 2800. It can be expressed that in areas of the city where this spectrum is dominant, design of the structures using standard No. 2800 is safe.

5. Base shear and drift values for structures that were designed using the maximum response spectrum were higher the ones designed by standard No. 2800. In other words, in areas of the city where this spectrum is dominated, the design using standard No. 2800 is unsafe and structures are seriously damaged during earthquakes. In addition, the greatest base shear occurs at a frequency of about 1 Hz. This issue should be considered in the future design of structures in this city. Finally, it can be concluded that consideration of site effect phenomenon in standard No. 2800 is very necessary.

References

1. Kockar, M.K., Akgun, H. Evaluation of the site effects of the Ankara basin, Turkey. Journal of Applied Geophysics. 2012. 83. Pp. 120–134. DOI: 10.1016/j.jappgeo.2012.05.007
2. Rezaei, S., Choobbasti, A.J., Kutanaei, S.S. Site effect assessment using microtremor measurement, equivalent linear method, and artificial neural network (case study: Babol, Iran). Arabian Journal of Geosciences. 2015. 8. Pp.1453–1466. DOI: 10.1007/s12517-013-1201-1
3. Rezaei, S., Choobbasti, A.J. Evaluation of local site effect from microtremor measurements in Babol City, Iran. Journal of Seismology. 2018. 22. Pp. 471–486. DOI: 10.1007/s10950-017-9718-5
4. Pamuk, E., Ozer, C. The site effect investigation with using horizontal-to-vertical spectral ratio method on earthquake data, South of Turkey. Geotectonics. 2020. 54. 4. Pp. 563–576. DOI: 10.1134/S001685212004010X
5. Asakereh, A., Tajabadipour, M. Analysis of local site effects on seismic ground response under various earthquakes. AUT Journal of Civil Engineering. 2018. 2. Pp. 227–240. DOI: 10.22060/AJCE.2018.13696.5253
6. Kohrangi, M., Bazzurro, P., Vamvatsikos, D. Seismic risk and loss estimation for the building stock in Isfahan: part II–hazard analysis and risk assessment. Bulletin of Earthquake Engineering. 2021. 1. Pp. 1–25. DOI: 10.1007/s10518-020-01036-2
7. Zafarani, H., Jafarian, Y., Eskandarinejad, A., Lashgari, A., Soghrat, M.R., Sharafi, H., Afraz-e Haji-Saraei, M. Seismic hazard analysis and local site effect of the 2017 Mw 7.3 Sarpol-e Zahab, Iran, earthquake. Natural Hazards. 2020. 103. Pp. 1783–1805. DOI: 10.1007/s11069-020-04054-0
8. Vedugo, R., Ochoa-Cornejo, F., Gonzalez, J., Valladares, G. Site effect and site classification in areas with large earthquakes. Soil Dynamics and Earthquake Engineering. 2019. 126. No. 105071. DOI: 10.1016/j.soildyn.2018.02.002
9. Bisch, P., Carvalho, E., Degee, H., Fajfar, P., Fardis, M., Franchin, P., Kreslin, M., Pecker, A., Pinto, P., Plumier, A. Somja, H. Eurocode 8: seismic design of buildings worked examples. 2011. Luxembourg.
10. New Zealand society for earthquake engineering. The seismic assessment of existing buildings. Technical Guidelines for Engineering Assessments. Part B – Initial Seismic Assessment. 2017. Wellington.
11. Permanent Committee for Revising the Iranian Code of Practice for Seismic Resistant Design of Buildings (Standard No. 2800), 4th Edition. Building and Housing Research Center. 2014 (in Persian).
12. Hoshmand, S., Fatemi Aghda, S.M., Hashemi Tabatabaei, S. Soil classification using standard No. 2800, UBC 1997, IBC 2006, Eurocode 8 2004 (case study: Piroozi Avenue, Tehran, Iran). Journal of Engineering Geology. 2011. 1. Pp. 1177–1192.
13. Nicknam, A., Yousefi Dadras, E. Modification of the design response spectra in Iranian standard 2800 (fourth version) taking into account the directivity effects. Amirkabir Journal of Science and Research. 2014. 46. Pp. 165–188.
14. Nicknam, A., Mazarei, A., Ganjvar, M. Assessment of Iran seismic design response spectra (standard No. 2800) regarding site-distance effects particularly at near fault sites. Amirkabir Journal of Civil Engineering. 2017. 49. Pp. 547–564. DOI: 10.22060/ceej.2016.862
15. Nicknam, A., Kazemi, M.T., Nicknam, A. Evaluation and comparison of near- and far-fault earthquakes using design spectrum of standard No. 2800. Journal of Civil Engineering Islamic Azad University. 2008. 1. Pp. 71–79.
16. Choobbasti, A.J., Rezaei, S., Farrokhzad, F., Heidarzadeh Azar, P. Evaluation of site response characteristics using nonlinear method (Case study: Babol, Iran). Frontiers of Structural and Civil Engineering. 2014. 8. Pp. 69–82. DOI: 10.1007/s11709-014-0231-4
17. Uniform Building Code. International conference of building officials. 1997.
18. International code council. 2018's International building code. 2018.
19. National earthquake hazards reduction program. NEHRP recommended seismic provisions for new buildings and other structures. 2009.
20. Trifunac, M.D. Site conditions and earthquake ground motion – A review. Soil Dynamics and Earthquake Engineering. 2016. 90. Pp. 88–100. DOI: 10.1016/j.soildyn.2016.08.003
21. Sánchez-Sesma, F.J., Palencia, V.J., Luzón, F. Estimation of local site effects during earthquakes: an overview. ISET Journal of Earthquake Technology. 2002. 39. Pp. 167–193.
22. Kramer, S.L. Geotechnical earthquake engineering. New Jersey, 1996. 653 p.
23. Adampira, M., Alielahi, H., Panji, M., Koohsari, H. Comparison of equivalent linear and nonlinear methods in seismic analysis of liquefiable site response due to near-fault incident waves: a case study. Arabian Journal of Geosciences. 2015. 8. Pp. 3103–3118. DOI: 10.1007/s12517-014-1399-6
24. Rezaei, S., Choobbasti, A.J. Liquefaction assessment using microtremor measurement, conventional method and artificial neural network (case study: Babol, Iran). Frontiers of Structural and Civil Engineering. 2014. 8. Pp. 292–307. DOI: 10.1007/s11709-014-0256-8

25. Shreyasvi, C., Venkataramana, K., Chopra, S. Local site effect incorporation in probabilistic seismic hazard analysis – A case study from southern peninsular India, an intraplate region. Soil Dynamics and Earthquake Engineering. 2019. 123. Pp. 381–398. DOI: 10.1016/j.soildyn.2019.04.035
26. Rezaei, S., Shooshpasha, I., Rezaei, H. Evaluation of ground dynamic characteristics using ambient noise measurements in a landslide area. Bulletin of Engineering Geology and the Environment. 2020. 79. Pp. 1749–1763. DOI: 10.1007/s10064-019-01637-5
27. Verdugo, R. Seismic site classification. Soil Dynamics and Earthquake Engineering. 2019. 124. Pp. 317–329. DOI: 10.1016/j.soildyn.2018.04.045
28. Rajabzadeh, H., Mehrnahad, H. Comparison of equivalent linear and nonlinear analyses in site response (case study: Tabas city). Journal of Engineering Geology. 2018. 1. Pp. 41–62.
29. Ehsani, N., Ghaemmaghamian, M.R., Fazlavi, M., Haghshenas, A. Investigation of site effects using numerical and experimental methods in Karaj. Journal of Engineering Geology. 2017. 1. Pp. 1–28.
30. Navarro, M., García-Jerez, A., Alcalá, F.J., Vidal, F., Enomoto, T. Local site effect microzonation of Lorca town (SE Spain). Bulletin of Earthquake Engineering. 2014. 12. Pp. 1933–1959. DOI: 10.1007/s10518-013-9491-y
31. Purnachandra Rao, N., Rabi Kumar, M., Seshunarayana, T., Shukla, A.K., Suresh, G., Pandey, Y., Dharma Raju, R., Pimprikar, S.D., Chandra, D., Kalpna, G., Mishra, P.S., Harsh G. Site amplification studies towards seismic microzonation in Jabalpur urban area, central India. Physics and Chemistry of the Earth. 2011. 36. Pp. 1247–1258. DOI: 10.1016/j.pce.2011.01.002
32. Belash, T.A., Ivanova, T.V. Earthquake resistance of buildings on thawing permafrost grounds. Magazine of Civil Engineering. 2020. 93. Pp. 50–59. DOI: 10.18720/MCE.93.5
33. Brinkgreve, R.B.J., Vermeer, P.A. Plaxis Manual (Version8). University of Stuttgart. Germany A.A. Balkema / Rotterdam / Brookfield-D. 2006.
34. Milana, G., Azzara, R.M., Bertrand, E., Bordoni, P., Cara, F., Cogliano, R.,Cultrera, G., Di Giulio, G., Duval, A.M., Fodarella, A., Marcucci, S., Puccilo, S., Regnier, J., Riccio, G. The contribution of seismic data in microzonation studies for downtown L'Aquila. Bulletin of Earthquake Engineering. 2011. 9. Pp. 741–759. DOI: 10.1007/s10518-011-9246-6
35. Sokolova, O.V. The selection of soil models parameters in Plaxis 2D. Magazine of Civil Engineering. 2014. 4. Pp. 10–15. DOI: 10.5862/MCE.48.2
36. Lu, T., Huo, J., Rong, M. Nonlinear response analysis of soil layers under severe earthquake. Procedia Environmental Sciences. 2012. 12. Pp. 940–948. DOI: 10.1016/j.proenv.2012.01.369
37. Takewaki, I. Critical excitation for elastic–plastic structures via statistical equivalent linearization. Probabilistic Engineering Mechanics. 2002. 17. Pp. 73–84. DOI: 10.1016/S0266-8920(01)00030-3

Contacts:

Sadegh Rezaei, S_Rezaei1366@yahoo.com
Hasanzadeh Ali, a_hasanzade64@yahoo.com

Received 10.09.2020. Approved after reviewing 29.03.2021. Accepted 31.03.2021.