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Earthquake effect on the Niayesh tunnel, north of Tehran megacity

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Abstract

This research investigates the effect of earthquakes on the Niayesh tunnel in Tehran Megacity. First, the amount of stress in the tunnel's up, wall, and bottom was calculated by analyzing the area's soil properties. Then, using the acceleration data from large earthquakes occurring in different directions of the tunnel construction, displacement and potential risk were assessed using PLAXIS software in three modes, static, quasi-static, and dynamic. These methods are used to calculate the deformation and displacement of the Niayesh tunnel. To determine the maximum displacement in three cases, the largest earthquake in the region should be considered. On average, this value was 45.6 mm at the earth's surface. The values obtained in the dynamic state show that surface ground movement in the tunnel restrains the area. The natural frequency of the Niayesh, calculated using Fourier spectrum analysis, is 5.94 Hz for the structure, which decreases to 5 Hz during an earthquake, with a corresponding period of 0.16 seconds and 2 seconds during an earthquake. In the static state, initial subsidence was obtained after the tunnel's construction. In dynamic mode, subsidence was calculated for three soil types modeled in Tehran Megacity by modeling the waveform of the Manjil earthquake. Results show that increasing the amount of soil elasticity during an earthquake enhances the acceleration created. Consequently, with the duration of the earthquake vibration and the increase in the earthquake's magnitude, the energy entering the tunnel increases with the release of seismic waves. The acceleration contour for the static and quasi-static methods was not plotted as it is time-independent, and the acceleration value is considered zero. However, in dynamic mode, the acceleration is time-dependent, and modeled accelerations applied to the structure over the considered period. If the acceleration ranges between 0.2 g and 0.5 g, mild and repairable injuries are expected, and from acceleration of more than 0.5 g, more severe injuries will be expected. According to the vertical displacement obtained using the static method in the Niayesh tunnel, the vertical displacement obtained was 24.5 mm, which was analyzed in three-dimensional mode. However, this study calculated the two-dimensional displacement value obtained as 22.48 mm. As a result, the tension created around the tunnel increases. A compressive state is created more than a tensile state. These results are inapplicable agreement with other results obtained in other underground spaces.

Keywords: Earthquake effect, Niayesh tunnel, PLAXIS software, Tehran megacity

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1 Introduction

In recent decades, urban depth tunnels in Iran have been designed considering recorded earthquakes, which typically occur at depths between 30 and 40 meters. Significant historical earthquakes in Iran, such as Tabas (16 September 1978, Mw=7.4), Manjil (21 June 1990, Mw=7.4), Bam (26 December 2003, Mw=6.6), Kojour (28 May 2004, Mw=6.3) and Ezgeleh (12 November 2017, Mw=7.3) (Iranian Seismological Center, http://irsc.ut.ac.ir/2024) , have focal depths ranging from 8 to 10 km and are among the country's most powerful seismic events.. In this study, the effect of earthquakes has been investigated with different magnitudes behaving differently in underground spaces, which can be used to measure earthquakes focusing on the dynamic analysis of underground structures based on the peak ground acceleration (PGA), which is calculated according to the magnitude of the earthquake (Afkar et al., 2012). Changes in the underground water level in the area of Tehran's Niayesh tunnel and its possible effects on the stability of the tunnel have always been considered (Khosroshahi et al., 2012). Quasi-static analysis of the earthquake effect on underground spaces is consistently important in determining stability, and it is modeled based on different programming (Amel Sakhi, 2013). Ashuri et al. (2014) performed the stability of the Niayesh tunnel using PLAXIS software. The non-linear characteristics of soil layers were considered by the one-dimensional equivalent linear analysis in the equivalent-linear earthquake site response analyses (Hu et al., 2020). Similar trends for all drift-PGA curves at different surcharges and soil densities indicate that all models experienced the same phenomena at similar time intervals and exhibited different performance levels (Mohammadi Haji and Ardakani, 2020). Investigating the effects of soil overburden compression and depth on the seismic response of the soil and tunnel system using numerical analysis (Majidian, 2021) shows promising results. Also, in managing an underground space during an earthquake, all arrangements and suggestions should be modeled for the vehicles and drivers traveling through the tunnel (Ilkhani et al., 2023).

The arc section of the tunnel is more sensitive to earthquakes than other parts of the tunnel structure. One of the factors contributing to an increase in the tunnel's cross-section is at intersections and subway stations. Also, the presence of two or more tunnels together usually causes the concentration of static stress between the tunnels. The choice of design method depends on the importance of that structure. Therefore, in most cases, it is not economical or feasible to design tunnels in such a way that they can resist all damaging factors. However, these damages can be minimized by taking precautions. Therefore, modeling was done in three static, quasi-static, and dynamic modes.

Geotechnical studies have been carried out to identify the subsurface layers and determine and evaluate the underground water level and the conditions of the subsurface layers. **A** total of 20 boreholes of 25 to 45 meters and 24 wells with a depth of 10 to 30 meters have been drilled. Results of geotechnical tests show that the area soil consists of dense sand and sand, both of which contain some silt and clay (table 1). These soils contain different amounts (5 to 50%) of granule; siltware is also observed between the layers. The location of boreholes and tunnel are shown in Figure (1). According to regulation 2800, soil classification is of the fourth type. The recent century earthquake activity in the Tehran area are shown in Figure 2. Historical earthquakes in Tehran due to the lack of accelerometers and recent earthquakes in Tehran due to small earthquakes (M<6) cannot be used in dynamic analysis. The data on large earthquakes in Iran that occurred in different azimuths of the Niayesh tunnel were used.

In order to identify the effect of an earthquake on the Niayesh tunnel, it is necessary to identify the soil of the study area and calculate the stress and strain in the wall and floor of the tunnel, using maps of earthquakes that have occurred in the area of Iran in the area under study to check the displacement and or the possible risks caused by an earthquake.

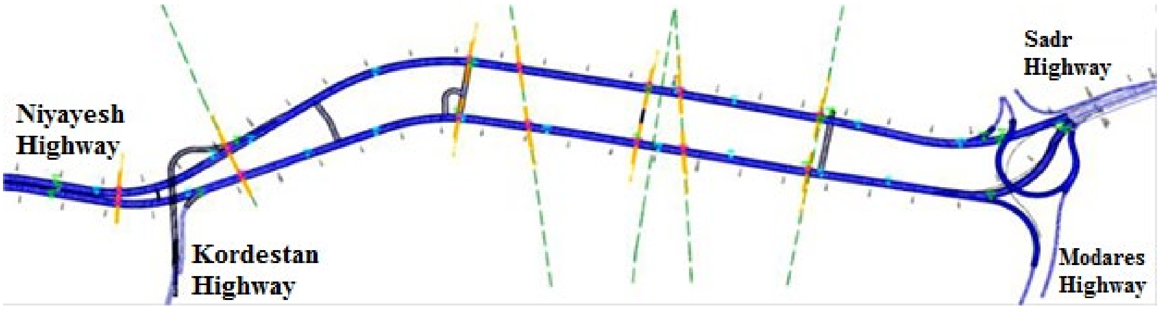


Figure 1. The cross-section of the drilled boreholes (Edit, Tehran Municipality Engineering and Civil Engineering Organization, 2012).

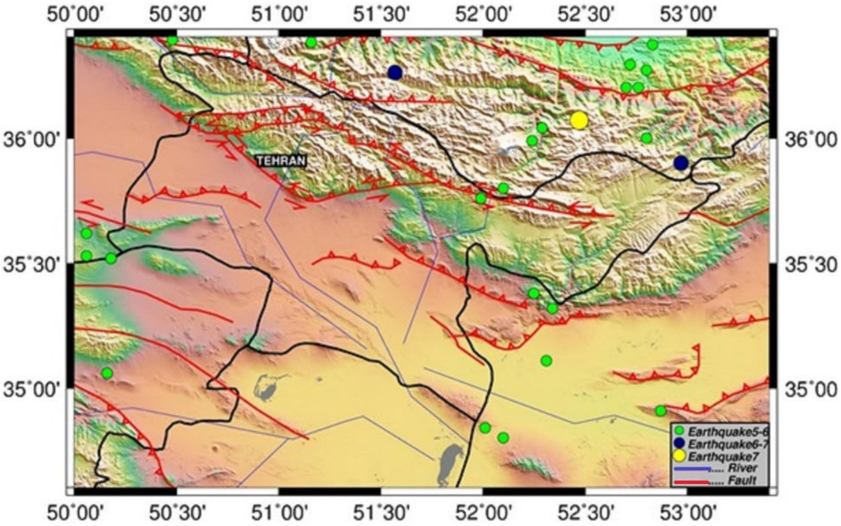


Figure 2. Tehran earthquakes (M>5).

This research has been done in three ways: static, quasi-static, and dynamic. The first and most straightforward method of seismic design is experimental design. In this method, predictions are made based on the results of previous research about the desired project. This method can be useful for starting the design and entering the discussion. The model's design obtained the static analysis of vertical displacement during tunnel excavation. In the quasi-static method, the total amount of acceleration applied during the calculation, which is the result of the input values of the acceleration component, was applied. For this design, the acceleration of 0.35 gal was considered and verified. In the higher stage, mathematical solutions are suggested, which are an introduction to numerical modeling and control of modeling accuracy. Finally, using numerical modeling, it is possible to analyze and accurately design complex underground structures against seismic waves using 2D Plexis software; in this method, the interaction changes by directly entering the acceleration in terms of time (acceleration history). The irregular lining of the tunnel and the surrounding rock under the action of acceleration at any time was considered, and this was investigated numerically in three earthquakes with different magnitudes. It was verified, and finally, the construction and dominant periods were calculated.

2 Methodology

This research used geotechnical studies to identify subsurface layers and determine the geotechnical parameters. Geotechnical studies were done to evaluate the underground water level and the conditions of the subsurface layers. According to the results of these tests and geotechnical specifications, the area's soil consists of sand and dense sand, both containing some silit and clay. In the soil classification, these soils contain different amounts of materials that are small in dimension. In this test, the geotechnical parameters of the soil layers presented in Table (1) (Kolivand et al., 2019).

Table 1. Geotechnical characteristics of the soil layers used for the structure model (Kolivand et al., 2019).

Depth	Specific weight unsaturated (γ_{sat})	Specific weight Saturation (γ_{sat})	Modulus of elasticity of loading (E_{ur}^{ref})	Momentary elasticity model (E_{50}^{ref})	Odometer elasticity model (E_{oed}^{ref})	cohesion (C)	Poisson's Ration (ν_{ur})	Angle of internal friction (φ)	K_0^{nc}
m	KN/m^2	KN/m^2	KN/m^2	KN/m^2	KN/m^2			Degree	
0-15	16	17	2.423×10^5	8.077×10^4	8.077×10^4	30	0.2	34	0.44
			2.827×10^5	9.423×10^4	9.423×10^4	40	0.2	36	0.41

Table 2. Tunnel displacement of static, quasi-static and dynamic method.

Tunnel displacement (m) **Method**	**Earth surface**	**Crown**	**button**	**wall**
Static	0.022	0.028	0.025	0.006
Quasi-static	0.24	0.213	0.165	0.228
Dynamic	0.10	0.195	0.38	0.290

Acceleration and velocity were evaluated through detailed geophysical, tectonic, and soil mechanics investigations. In the 2800 law (Road, Housing and Urban Development Research Centerhttps://www.bhrc.ac.ir/), base accelerations on the design compared to the acceleration of gravity (g) are divided into four categories for different regions of the country. According to the fourth edition of Iran's 2800 Law, Tehran is located in an area with a high relative risk of seismicity, and the acceleration based on the design in such a region is recommended to be a=0.35 *g* (Road, Housing and Urban Development Research Center, https://www.bhrc.ac.ir/,2023). Also, the land where the Niayesh tunnel is constructed is of the fourth-floor soil type; the calculated velocity is Vs=147.2 (*m/s*), and according to the selection of the land type according to the regulations, the natural vibration period of the soil is to=0.15 s, Ts=0.1 s. The wave Vp in a limited one-dimensional body depends on the hardness E_{oed} and the density ρ of the medium, relationships (1) to (5):

$$\rho=\frac{\gamma}{g} \tag{1}$$

$$E_{oed}=\frac{(1-\upsilon)E}{(1+\upsilon)(1-2\upsilon)} \tag{2}$$

$$V_p=\sqrt{\frac{E_{oed}}{\rho}} \tag{3}$$

$$G=\frac{E}{2(1+\upsilon)} \quad (4)$$

$$V_s=\sqrt{\frac{G}{\rho}} \quad (5)$$

where ρ is density, γ total unit weight, g is gravitational acceleration (9/8 m/s^2), E is Young's module, υ is Poisson's ratio, Vp is compressional velocity, G is modulus of rigidity and Vs is shear velocity. The same expression can be found for shear wave Vs.

Crucial parameters that affect the seismic responses of the soil-structure system, such as (i) earthquake load condition, (ii) inertia of the structure, (iii) inertia of soil, (iv) soil-structure relative stiffness, and (v) soil-structure interface properties, are accounted (Xu et al., 2019).

The constitutive model of numerical analysis was designed based on defined elements. PLAXIS Software is used to analyze the stability and deformation of the Niayesh tunnel. According to the software instructions, the acceleration unit is simulated in cm/s^2. A two-dimensional finite element meshing model geometry is created to model the soil or rock's non-linear, time-dependent, and anisotropy behavior. The soil of the studied area has two types. It is modeled from the ground surface to a depth of 15 meters of dense sand and gravel from 15 to 50 meters. The geometry of the model is based on Pack's experimental relationship. The frame's dimensions are 70 meters wide and 50 meters high, 10 meters from the ground surface. The tunnel geometry is modeled as the mesh around the tunnel being 3 cm smaller and the mesh near the ground smaller due to more accurate calculations. The modeled ground structure is a strain analysis type of a 15-node element. Model boundaries are used according to the boundary conditions of the outgoing wave's attraction. Waveform modeling, total displacement amount for earthquakes, Mw= 6.3, Mw=6.6, and Mw=7.4, are calculated as movements and shocks in all directions. The earthquake is simulated by different locations of the prescribed displacements on the bottom boundary, according to Figure (3).

The Seismosignal software was used to analyze the Niayesh Tunnel dynamically. Based on the waveforms of the Manjil, Bam, and Kojour earthquakes, the peak ground acceleration (PGA) was calculated at 0.65 g, 0.49 g, and 0.078 g, respectively, as shown in Figure 4.

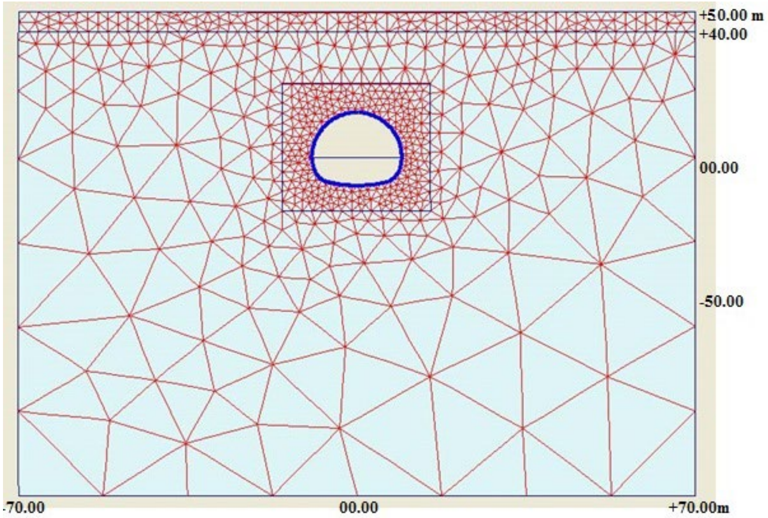
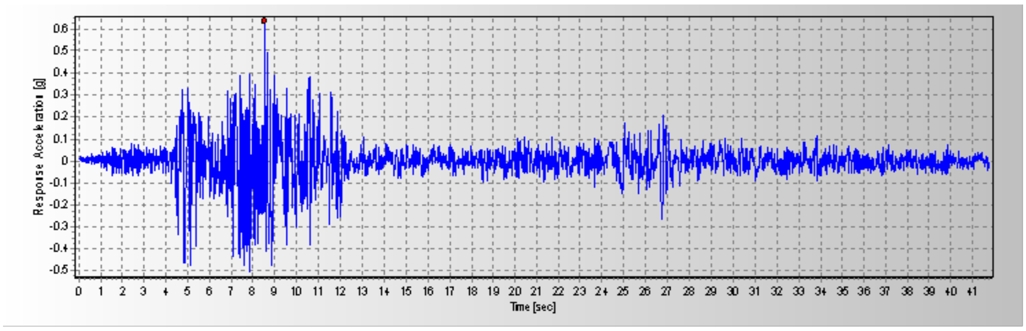
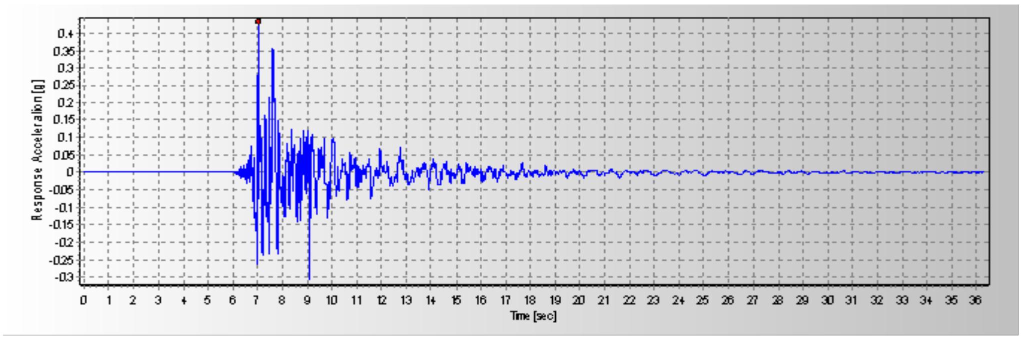


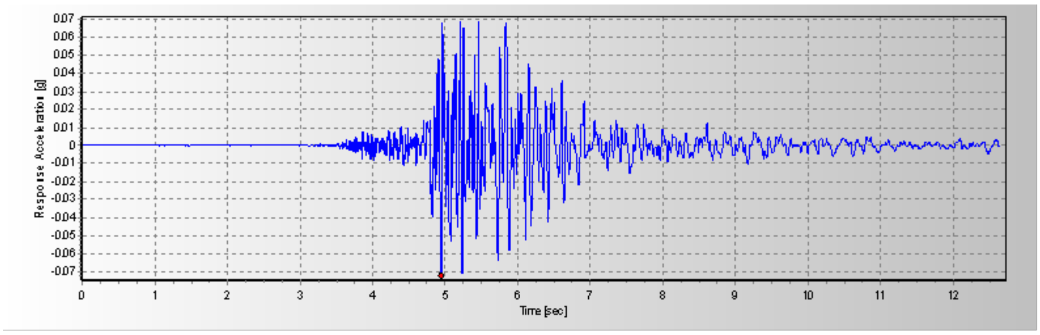
Figure 3. Niayesh tunnel model based on stability and prescribed displacements analysis.



a) Manjil Earthquake



b) Bam Earthquake



c) Kojour Earthquake

Figure 4. Modeling of waveform a) Manjil b) Bam c) Kojour earthquake.

Numerical analysis using limited elements is a constitutive model for soil or rock's non-linear, time-dependent, and anisotropic behavior. Tunnel projects include construction modeling and the interaction between the construction and the soil. Modeling the Niayesh tunnel was performed using the mentioned inputs. In the static method, the total displacement value after tunnel excavation based on the waveform of the largest earthquake (Mw=7.4) is shown in Figure 5. Displacement at the earth's surface is 22.24 mm. This value of the crown tunnel is 27.80, mm and the bottom tunnel is 24.47 mm. Displacement decreases with depth. This value is very small and is considered in the case of no movement. The tunnel restrains the movement of the ground around the tunnel.

In quasi-static analysis, the displacement obtained on the ground floor is less than the ground surface (Figure 6). This method is closer to reality than the static method.

Analysis of the time-dependent dynamic is modeled from the floor for Mw= 7.4. In this method, the lateral force of the earthquake is determined by using the dynamic reflection that the structure shows due to the movement of the earth caused by the earthquake, which is more realistic than the quasi-static method. The displacement measured at the earth's surface is 100 mm. In this form, the earthquake wave propagates from the ground's depth to the surface, , and its intensity decreases. This amount of displacement around the tunnel is 290 mm. The displacement decreases to some extent near the ground and increases again close to the surface (Figure 7).

Considering that the frequency of the earthquake is low and the number of stress periods is high, the number of oscillations of the building during the earthquake creates tension around the tunnel, which can damage it. The earthquake causes the re-arrangement of stresses around the tunnel, which causes the tunnel to stretch and compress. The tunnel in the rock mass is related to many complex issues due to the uncertainty of the rock mass's response to the earthquake. Determining the stress in the stability of the tunnel is crucial. If the stress around the tunnel is high, it will change its shape around the tunnel.

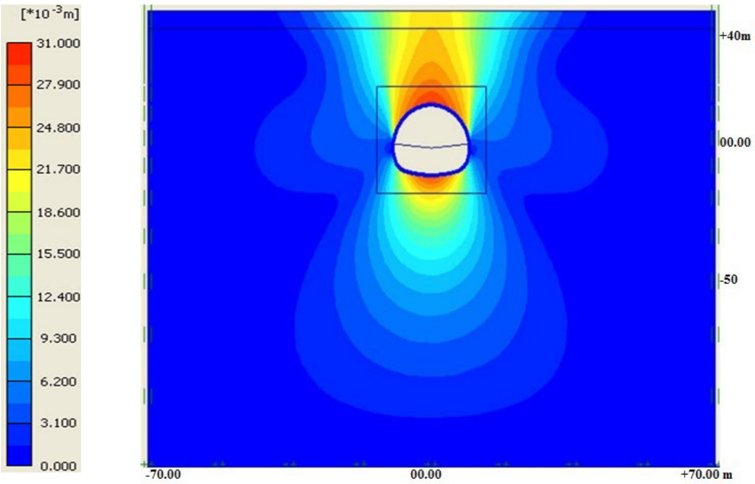


Figure 5. Static model of tunnel displacement.

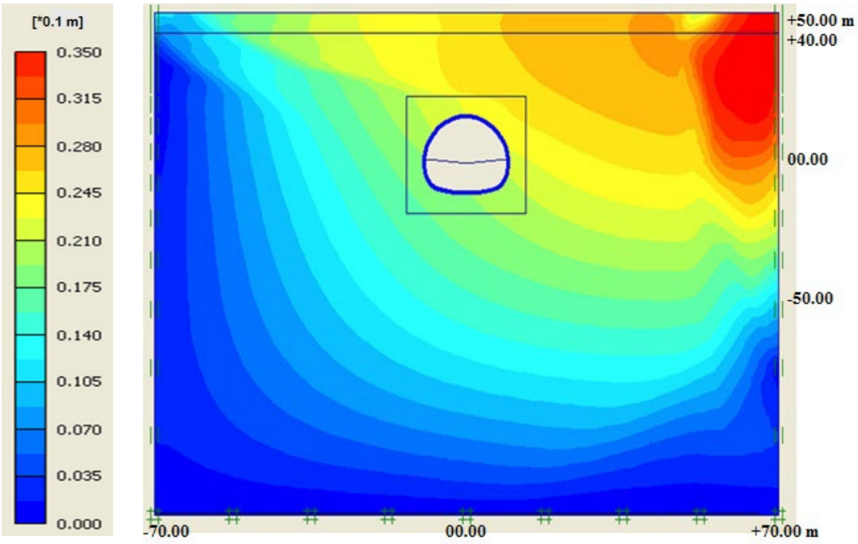


Figure 6. quasi-static model of tunnel displacement.

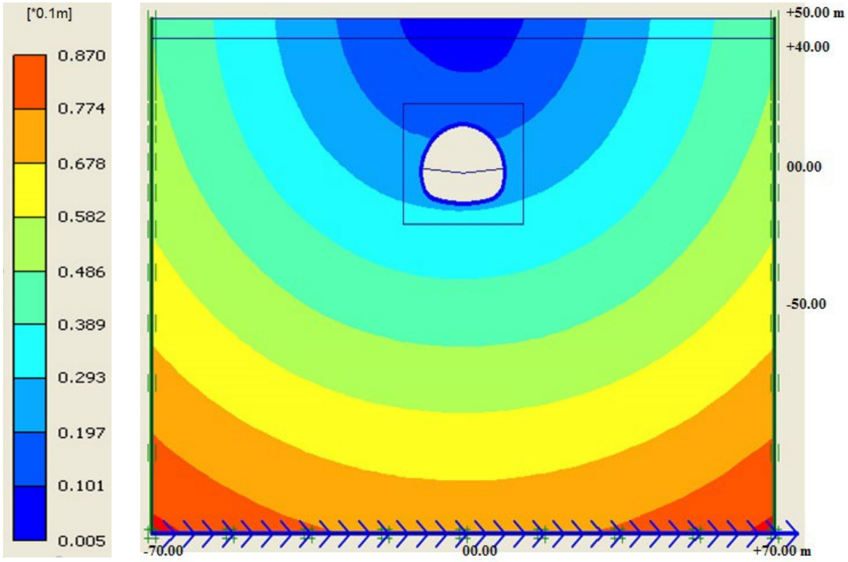


Figure 7. Dynamic model of tunnel displacement.

3 Analysis and Discussion

This research investigates the effects of various parameters, including peak ground acceleration, the content of the incoming motion frequency, and other earthquake characteristics on the seismic response of the tunnel. This article presents the results of dynamic numerical analysis on an underground tunnel with a circular cross-section under the loading of the acceleration time history of different earthquakes. In these analyses, a two-dimensional model of the circular tunnel was developed including the combined inelastic behavior of the soil through seismic accelerometer modeling.

Numerical simulation in this research employs numerical model descriptions, soil behavior model descriptions, and boundary conditions. In the description of the numerical model, dynamic analysis can be used to simulate the complex interactions between the soil structure and practically simulate the behavior of the tunnel under earthquake movements. The dynamic analysis can incorporate the time history of ground motions and a wide range of frequency spectra. The reduction of shear modulus and damping dependent on soil strain during earthquake movements can be incorporated into dynamic analyses in a real way. Under earthquake motions, the response of the tunnel and the ground is simulated using the dynamic properties of the soil. FLAC finite difference software has been used to numerically simulate the seismic response of the Niayesh tunnel under different earthquakes. The dynamic time history analysis of the interconnected soil system of the tunnel has been performed under plane strain conditions. This research meshes the soil with second-degree flat strain elements and the tunnel with linear elements. Considering that in dynamic analysis, the frequency of the input wave and the speed profile of the wave affect the numerical accuracy of the wave transmission, to create the necessary accuracy in the wave transmission in the model, the dimensions of the meshes should be less than 0.1 wavelengths of the largest frequency of the input wave was considered.

In this study, the shear stress along the entire length of the Niayesh tunnel was investigated in three conditions: static, quasi-static, and dynamic states for the largest earthquake around the structure . Figure 8 illustrates the static condition, where the maximum shear stress around the tunnel is -120 KN/m^2; the concentration of stress in this part is tension. The minimum stress around the tunnel is 33 KN/m^2, which shows that the stress concentration in this part is compression.

Figure 9 shows the quasi-static condition; the maximum shear stress around the tunnel is -240 KN/m^2, and the stress concentration in this part is tension. The minimum stress around the tunnel is -152 KN/m^2, which shows that the stress concentration is low in the compressive condition.

Figure 10 shows the dynamic condition; the minimum stress around the tunnel is 29 60 KN/m^2, and the concentration of stress in this part is tension. The minimum stress around the tunnel is -232 and -110 KN/m^2, which shows stress compressive. This is more at the bottom of the tunnel, and the tension stress is more at the top. In both the static and dynamic methods, in the case of a small earthquake, the same amount of stress is obtained, and with the increase in the earthquake's magnitude, the amount of tension stress increases. In the quasi-static method, the tension stress is higher in each case.

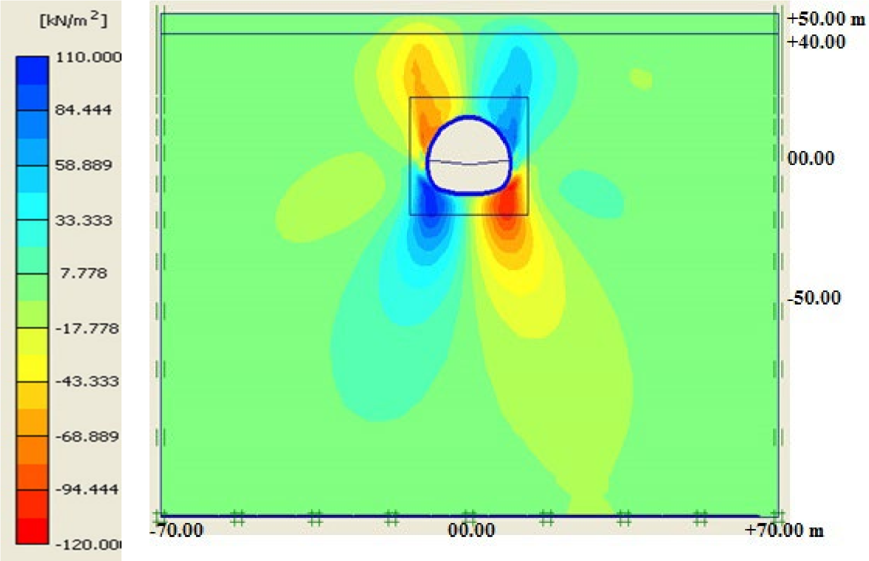


Figure 8. Shear stress created in the static method.

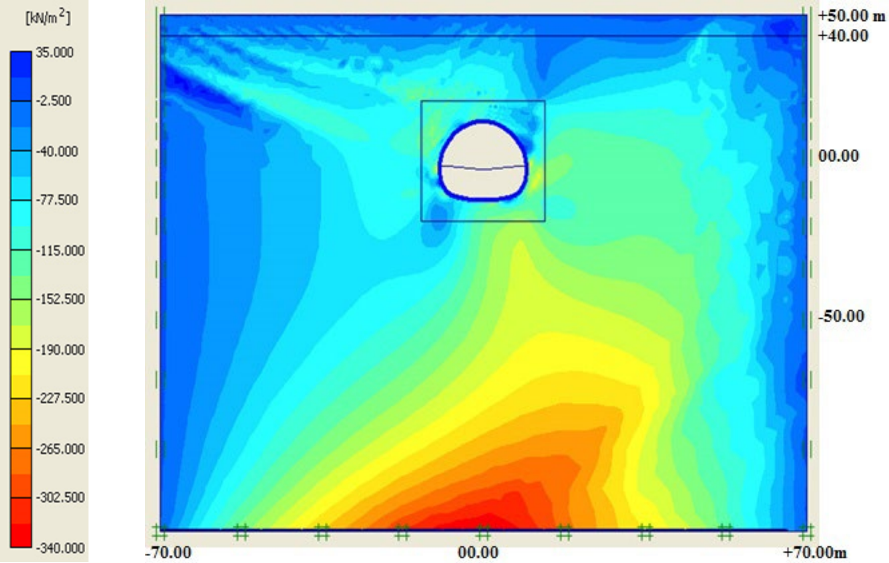


Figure 9. Shear stress created in the quasi-static method.

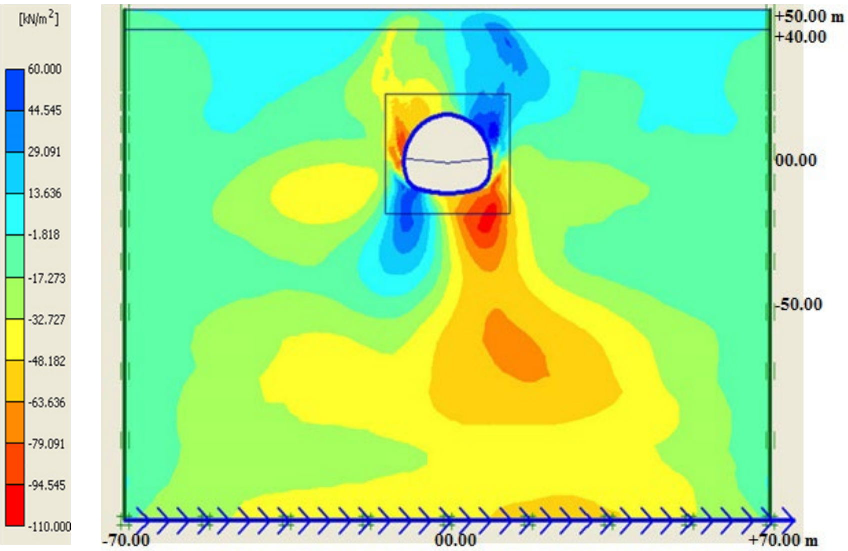


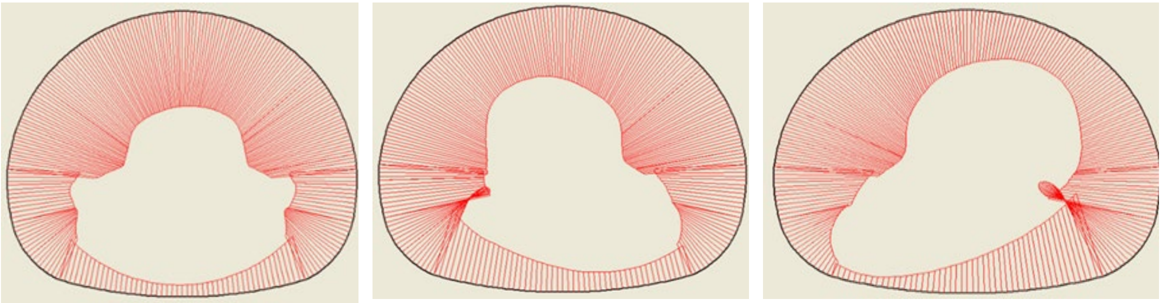
Figure 10. Shear stress created by dynamic method.

This study evaluated the effects of the earthquake's maximum amplitude, dominant frequency, and other earthquake characteristics on the seismic behavior of the Niayesh tunnel. It also investigated the tunnel's response and ground settlement. The model was analyzed without damping (free vibration analysis) to obtain its natural frequency in the software. Then, the periodicity of a complete cycle was obtained instead of a point on top of a model. The natural frequency equal to the inverse of this periodicity was calculated.

The force generated due to stress was investigated in three axial modes: shear and bending moment, shown in Figures 11-13. These forces generated in the tunnel construction during an earthquake become asymmetric with the increase in the magnitude of the earthquake and PGA. Calculations show that the initial subsidence of the tunnel is lower than that of the experimental condition. The force obtained in each mode is shown in Table 3. The acceleration created in the crown, wall, floor tunnel, and ground surface due to three selected earthquakes around the tunnel is shown in Figure 14.

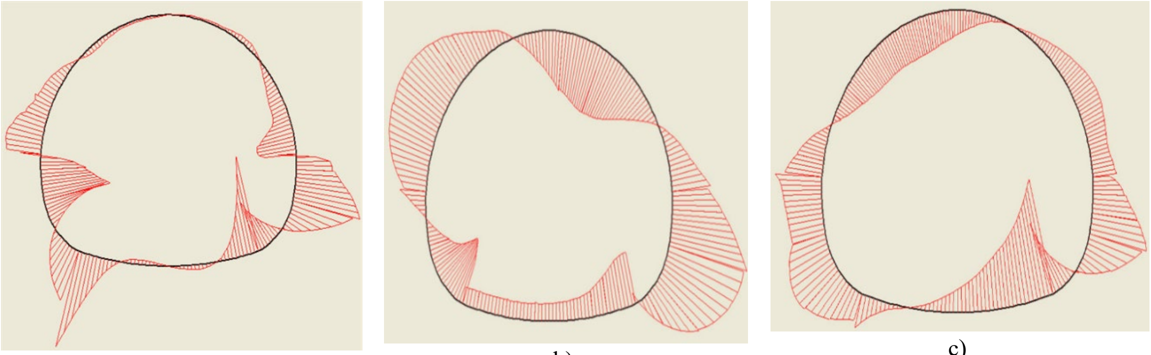
Table 3. Forces entering the tunnel in three conditions.

Force (KN/m^2) Method	Axial	Shear	Bending moment
Static	-193.28	۶۰/۲۷	۹۹/۱۶
Quasi-static	-200.8	۱۰/۱۲۸	۹۳/۱۳۷
Dynamic	-491.40	۸۰/۱۵۴	72.200



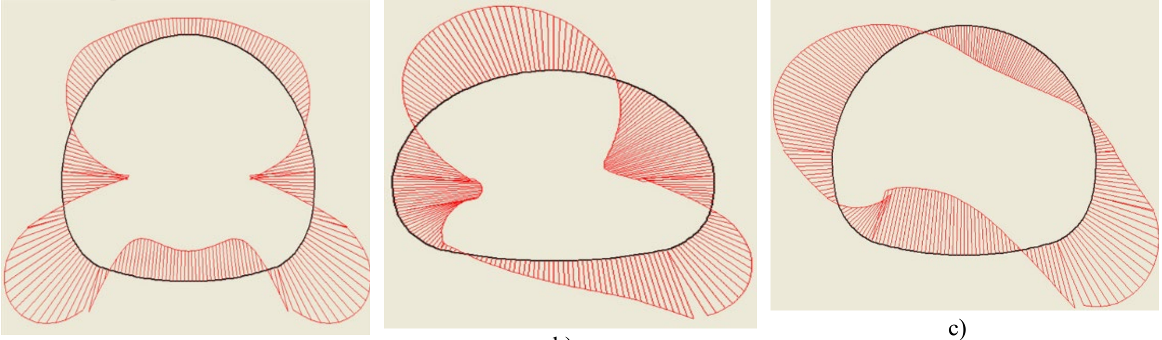
a) b) c)

Figure 11. Axial force in tunnel lining, a) static method, b) quasi-static method, c) dynamic method.



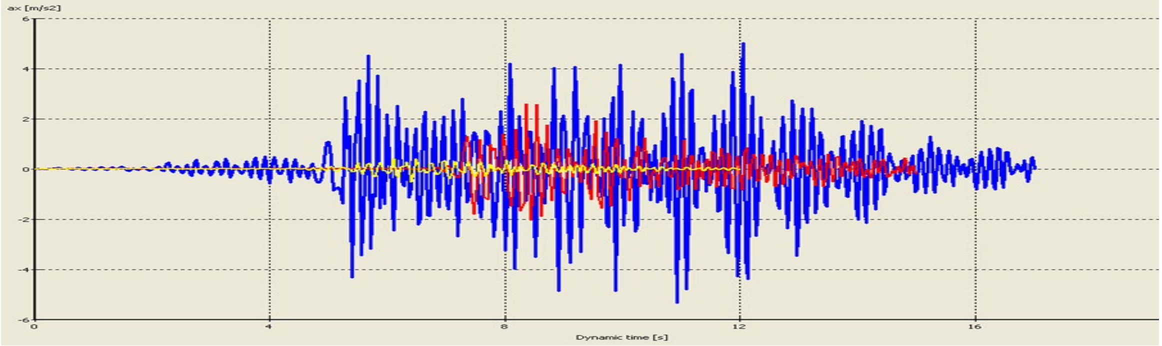
a) b) c)

Figure 12. Shear force in tunnel lining, a) static method, b) quasi-static method, c) dynamic method.

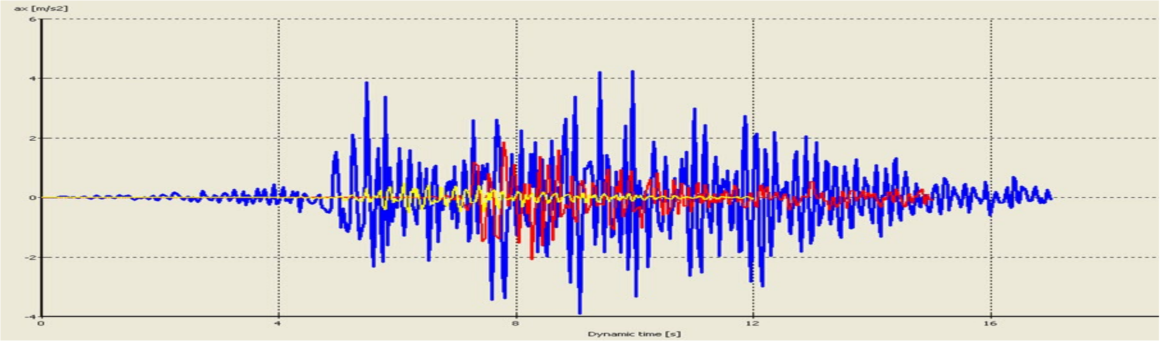


a) b) c)

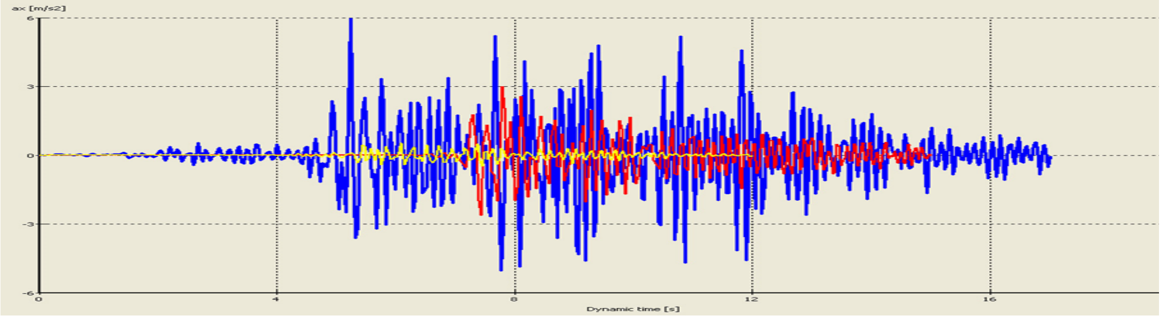
Figure 13. Bending moment force in tunnel lining, a) static method, b) quasi-static method, c) dynamic method



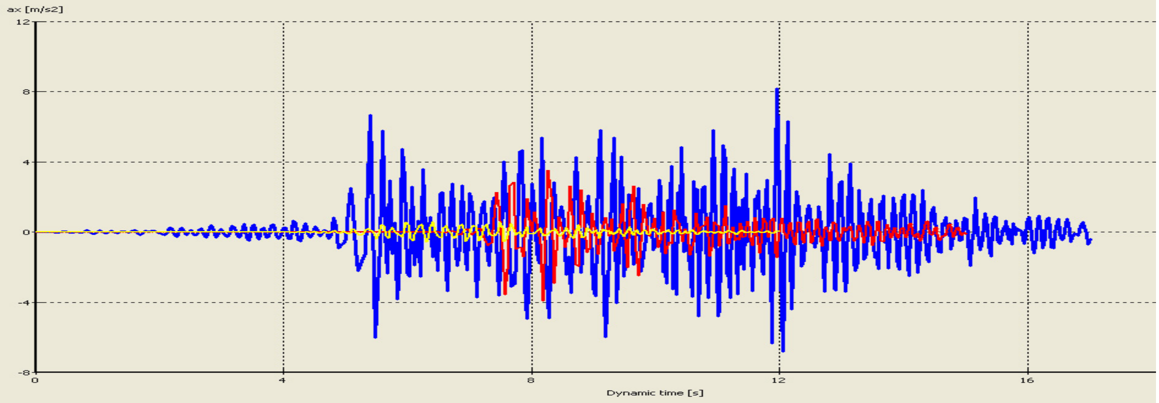
a) tunnel crown



b) tunnel wall



c) tunnel floor



d) Ground surface

Figure 14. Acceleration created in the crown, wall, and floor of tunnel and ground surface with three earthquakes, blue color is Mw=7.4, red color is Mw=6.6, yellow color is Mw=6.3.

4 Conclusion

The soil studies have been changeable (Koulivand et al., 2013). Therefore, increasing the modulus of elasticity increases the subsidence of the ground during the digging. This difference caused the creation of several conditions of the elasticity model, as shown in Table 4. The values of prescribed displacements and subsidence caused by three earthquakes are shown in Figure 15. Acceleration and time calculated from waveform modeling are presented in Table 5. In- situ Direct Shear test for soil, experimental and numerical methods show that the maximum subsidence by digging is 20, 29, and 26 mm (Khanlari et al., 2014), more than the allowed subsidence in the warning range.

Table 4. The subsidence caused by the earthquake in the Niayesh tunnel.

Magnitude	Modulus of elasticity (GPa)	Subsidence (m)	color
Mw=6.3	6.92×10^4	0.035	Blue
Mw=6.6	8.077×10^4	0.045	Red
Mw=7.4	12.59×10^4	0.05	Yellow

Table 5. Acceleration and time calculated from the modeling of waveforms.

Magnitude (Mw) and Acceleration (gal) of Earthquake	Color	Time (se)	Acceleration this study (gal)
Mw=7.4		10	0.428
a=0.6	Yellow	9.4	0.424
Mw=6.6		8.27	0.207
a=0.432	Red	7.7	0.187
Mw=6.3		6.12	0.049
a=0.07	Blue	6.19	0.0512

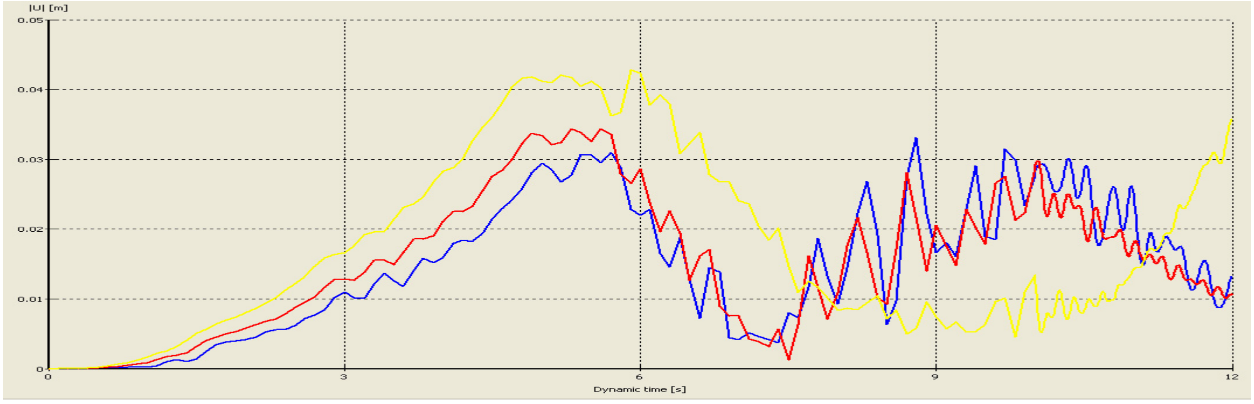


Figure 15. subsidence of Tunnel by dynamic modeling.

Changes must be made to the static model to allow for dynamic analysis to determine the natural frequency of the surface ground. (Pakbaz and Yareevand, 2005). Therefore, by actions of sudden gravitational force in undamped conditions, the model is made to vibration, and by recording the history of vertical movement, the natural frequency of the ground can be determined in a period. These changes include fixed boundary conditions, which must use wave-absorbing boundaries to prevent the reflection of earthquake waves inside the model. The earthquake and acceleration are applied to the model as a time history. After that, the calculated acceleration at the time of earthquake action to the tunnel structure, the diagram of the acceleration spectrum of Fourier amplitude, frequency, and period is drawn according to figures 16 to 18. According to the figures, the natural frequency of the building is 2.4 Hz, and the frequency during the earthquake is 1.2 Hz. The period is 0.41 seconds during construction and 0.74 seconds during earthquakes. In this study, the frequency created during the earthquake was lower than the natural frequency. Therefore, during an earthquake with Mw=7.4, the structure will not be seriously damaged. According to Afkar et al.'s study (2012), the displacement frequency value is 3.9 Hz; in this study, the acceleration frequency value is 2.4 Hz.

All parameters depend on time in the dynamic mode, and acceleration was obtained. Due to the lack of a time relationship, the created acceleration value is zero in static and quasi-static modes. By increasing the acceleration created, the displacement increases. Because the damage to underground structures is dependent on the earthquake parameters, this damage can be related to the peak ground acceleration (PGA), peak ground velocity (PGV), moment magnitude (Mw), and the epicenter of the earthquake. The time of the maximum acceleration created during an earthquake differs from that of the maximum acceleration of the environment. Because as the time of the strong ground motion, the earthquake becomes longer, the ruptures due to the fatigue of the materials increase, and significant deformations are created.

Stress Considering that the earthquake frequency is low and the number of stress periods is high, the vibrations of the structure during an earthquake create tension around the tunnel, contributing to potential damage.. Earthquakes cause both tension and compressiveness within the tunnel. The tunnel in the rock mass is related to many complex issues due to the uncertainty of the rock mass's response to the earthquake. Determining the stress in the stability of the tunnel is very important. If the stress around the tunnel is high, it will change its shape around the tunnel.

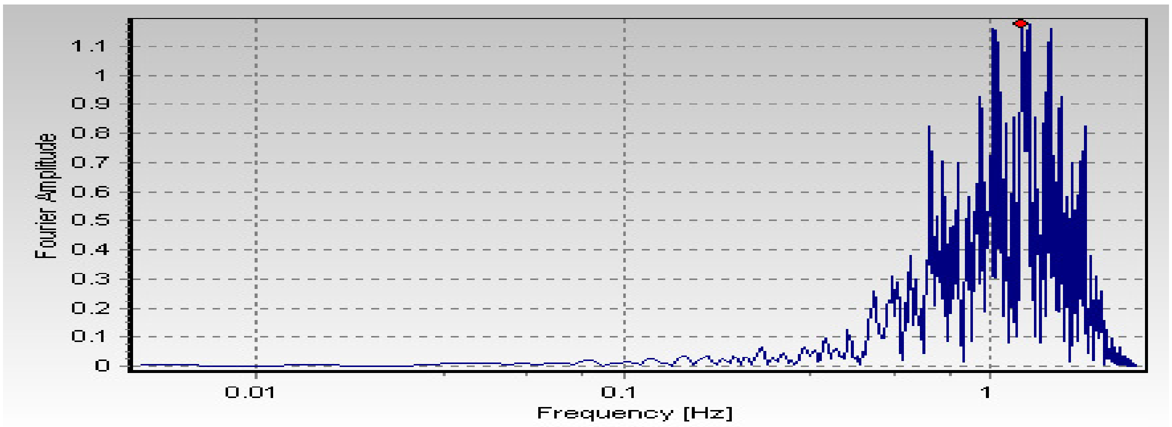


Figure 16. The Fourier amplitude of Niayesh tunnel construction during an action earthquake.

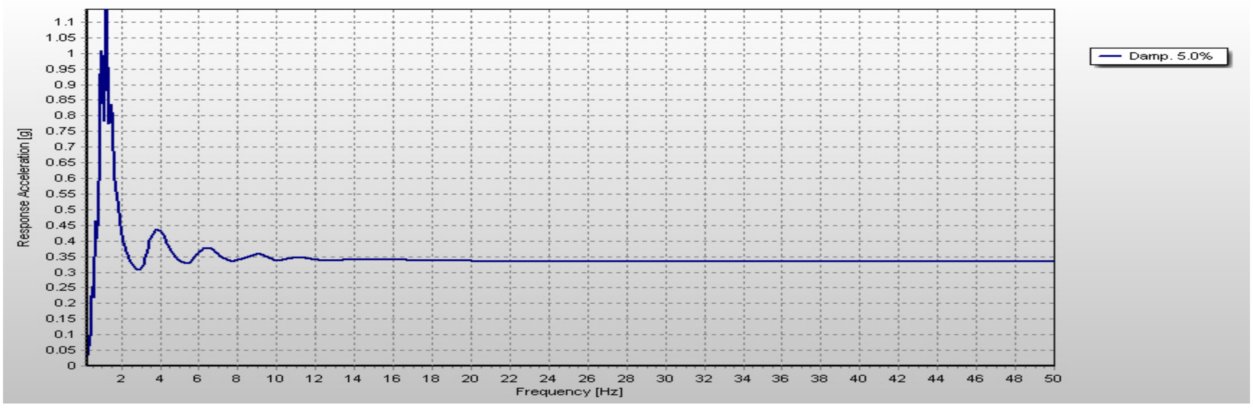


Figure 17. Frequency of earthquake acceleration, Mw=7.4.

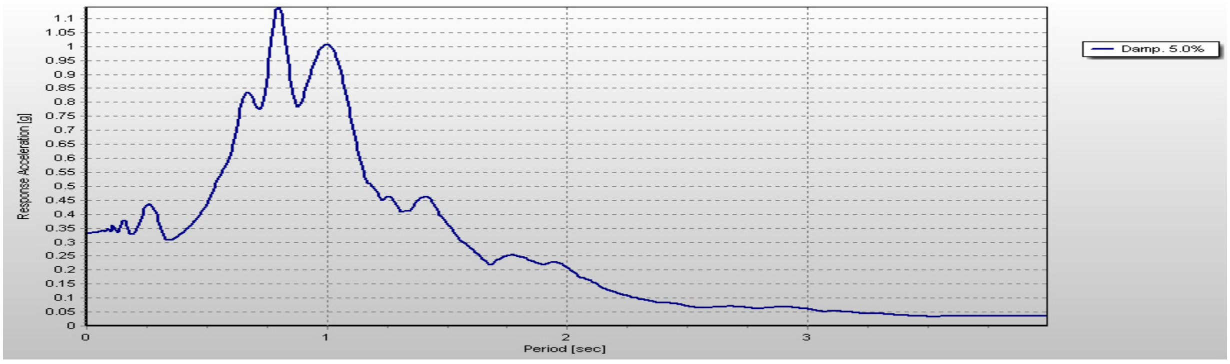


Figure 18. Period in an earthquake (Mw=7.4).

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Reference

Afkar, A. Raazi Rad, Z.S. Javadi Estahbanati, M. (2012). Evaluation of the effect of earthquake frequency on the stability of underground space, Proceedings of the 31st National Conference on Earth Sciences. (Persian)

Amel Sakhi, M. Shiri, T. Ali Ashrafi, H. Hosseinzadeh S. (2014). Quasi-static analysis of earthquake effects on tunnels using PLAXIS software, Proceedings of the National Conference on Geomechanical Engineering. (Persian)

Ashuri Ghaeh-Rodkhani, H. Nabizadeh, F. Ghorbani, A. (2015). Stability study of Tehran's Niayesh Tunnel using PLAXIS software, Proceedings of the Second National Conference on Construction and Project Management. (Persian)

Earthquake-resistant Building Design Regulations, Standard 84-2800, Third Edition, Publication: No. Z-253, Building and Housing Research Center. (Persian)

Hu, X., Zhou, Z., Chen, H., & Ren, Y. (2020). Seismic fragility analysis of tunnels with different buried depths in a soft soil. Sustainability, 12(3), 892.

Ilkhani, I. Yazdanpanah, M. Dehghanbanadaki, A. (2023). Analysis of drivers' preferences toward content and message format of variable message signs during tunnel emergency evacuation: A case study of Niayesh tunnel in Tehran, International Journal of Disaster Risk Reduction, 93, 103744.

Khanlari, K. Maleki, M. Heydari-Torkamani, R. Alipour, S. Naseri, F. (2015). Estimating surface settlement in the Niayesh highway tunnel using experimental, numerical and real settlements methods, Journal of Engineering Geology, 9(3), 2917-2940. (Persian)

Kolivand, F. Yathrabi, Sh. Ghorbani, M. Javadi Estahbanati, M. (2011). Evaluation of the effect of excavation step length and optimal distance between different excavation work fronts on the amount of ground surface settlement caused by staged tunneling using the finite element numerical method (case study of Mellat Tunnel), Proceedings of the First Asian Conference and the Ninth National Tunnel Conference. (Persian)

Majidian, S. (1400). Investigation of the effects of soil density and depth on the seismic response of the soil and tunnel system using numerical analysis, Journal of Tunnel and Underground Space Engineering, 10(4). (Persian)

Mohammadi-Haji, B. and A. Ardakani (2020). Performance-based analysis of tunnels under seismic events with nonlinear features of soil mass and lining. Soil Dynamics and Earthquake Engineering 134: 106158.

Motavak Khosrowshahi, A. Asghari Koljahi, A. Mashrafifar, M.R. (2013). Changes in groundwater level in the area of Tehran Niayesh Tunnel and its possible effects on the stability of the tunnel, Proceedings of the 8th Conference of the Iranian Society of Engineering and Environmental Geology. (Persian)

PLAXIS-B. V 8.2-2002: "Plaxis: Finite element Oackage for analysis of geotechnical structures", Delft, Netherland.

Road, Housing and Urban Development Research Center, https://www.bhrc.ac.ir/,2023

Tehran Municipality Engineering and Civil Engineering Organization, 2012.

Xu, Z., Du, X., Xu, C., Hao, H., Bi, K., & Jiang, J. (2019). Numerical research on seismic response characteristics of shallow buried rectangular underground structure. Soil Dynamics and Earthquake Engineering 116: 242-252.