

## Analyzing the dynamic data of Mashhad metro line 1 tunnel using seismic table

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**Abstract:** Metro is a type of public transportation system with high capacity, which is mostly established in urban areas. Unlike a bus or a tram, the subway is a type of electric rail system that works on its special tracks, and pedestrians or any other vehicles do not have access to this track, and it mostly moves in tunnels or elevated non-level rails. Modern metro services are usually provided by electric self-propelled trains that run on railway tracks, although there are also some trains with rubber wheels or magnetic levitation. Metro stations are usually higher than the train tracks and do not have any stairs to the train. These platforms usually have a space compared to the train, so to reduce this space between the platform and the train, custom trains need to be built. As the second largest religious city in the world, Mashhad welcomes more than 22 million travelers every year. The comprehensive transport studies of Mashhad required 4 metro lines. Line 1 has been constructed and operated using the slow method, and Line 2 is in the operation stage. Line 2 of the Mashhad metro runs north-south and is 14 kilometers long, with a diameter of 9.43 meters, and passes through important parts of the city. This research, using a quantitative methodology and using a model tunnel, and a seismograph, has recorded the incoming earthquakes and predicted the resilience of this subway line in the city of Mashhad in 2024. For all the tunnel tests, the bending moment and deformations of the tunnel increase with the increase of the maximum base acceleration, but the location of the minimum and maximum values of the moment remain constant. The largest bending moment values appear in the middle of the crown and shoulder of circular tunnels. For the acceleration of  $A=0.27g$ , with the increase of the applied frequency to the system, the bending moment is constant or slightly decreases, but for  $A=0.43g$ , the maximum moment decreases strongly with the increase of the frequency.

**Keywords:** Dynamic Analysis, Metro, Earthquake, Mashhad, Seismography.

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## 1. Introduction

Metro is a type of public transportation system with high capacity, which is mostly established in urban areas. Unlike a bus or a tram, the subway is a type of electric rail system that works on its special tracks, and pedestrians or any other vehicles do not have access to this track, and it mostly moves in tunnels or elevated non-level rails. Modern metro services are usually provided by electric self-propelled trains that run on railway tracks, although there are also some trains with rubber wheels or magnetic levitation. Metro stations are usually higher than the train tracks and do not have any stairs to the train. These platforms usually have a space compared to the train, so to reduce this space between the platform and the train, custom trains need to be built.

Metro systems are usually complemented by other transportation systems such as buses and taxis for maximum convenience and efficiency and are usually all operated by the same public or private entity. The world's first subway was the semi-underground Metropolitan Railway, which opened in 1863 as a regular rail system and now forms part of the London Underground. In 2021,

China will have the largest number of subway systems in the world, with a total of 40 and a length of more than 4,500 kilometers (Naghbi Iravani et al., 2024).

It has also had the largest share in the expansion of metro systems in the world in the last decade. The longest single-operator subway system in the world in terms of track length is the Shanghai Subway. The largest subway in the world in terms of the number of stations is the New York City Subway with 472 stations. According to recorded incidents, underground facilities have experienced lower damage rates than surface structures. Nevertheless, some underground structures have suffered major damage in recent large earthquakes, including the 1995 Kobe earthquake in Japan, the 1999 Chi earthquake in Taiwan, and the 1999 Kujali earthquake in Turkey (Wu et al., 2020).

In underground structures, if the kinematic force entering the structure by the surrounding ground overcomes the inertial forces caused by the oscillation of the structure itself, they show a different seismic response compared to the ground-level structures. Physical modeling may help to obtain important information and quantitative data on the seismic behavior of underground tunnels.

Several tests related to physical modeling under seismic loading are given in the research. Only a small number of experiments included the measurement of internal forces. Saud and Huang showed the time history diagram of tunnel strain under seismic load (Tsinidis et al., 2016).

They concluded that the performance of the ground and tunnel depends on the intensity of applied excitations as well as the physical boundaries of the centrifuge model. Also, the response of the ground is different under the conditions of the free field and the existence of the tunnel in the model (Singh et al., 2017). Lanzano and his colleagues evaluated the seismic behavior of tunnels by a series of plane strain centrifuge tests by dynamic loading on the tunnel model. They studied the response of a sample of uniform fine sand prepared at two different densities, in which an aluminum alloy pipe was installed at two different depths.

In another research, Tsinidis and his colleagues conducted a series of dynamic centrifuge experiments on rectangular tunnels buried in dry sand. These experiments were conducted at Cambridge University on square tunnel models buried in dry sand. The laboratory results were used to better understand the seismic behavior of buried rectangular structures, as well as confirm the correctness of advanced numerical models and improve design methods. According to the obtained results, the horizontal accelerations recorded in several places increased upwards.

The vertical acceleration time histories recorded on the sides of the model in the roof slab were out of phase, indicating the oscillatory mode of tunnel vibration. Baziar and his colleagues have investigated the effects of the presence of the Tehran subway tunnel on the response of ground-level earthquakes in the range of linear soil behavior by conducting seismic table tests and numerical methods (Sadeghi et al., 2019). They studied the effect of the subway tunnel on the acceleration magnification pattern as well as its effect on the acceleration response spectrum on the earth's surface, and the effect of tunnel depth parameters and ambient shear wave velocity on the amount of magnification for real earthquake waves were studied parametrically (Yu et al., 2013).

Until now, there have been no comprehensive results in this area of technical literature due to the many parameters that affect the seismic behavior of underground structures. For this purpose, the present study aims to conduct a series of seismic table tests on the tunnel model to develop some aspects of the problem. In the present study, the effects of various parameters, including the frequency content of the incoming motion and maximum ground acceleration, on the seismic behavior of the Mashhad metro tunnel have been investigated (Pai & Wu, 2021; Naghi Iravani et al., 2024).

## 2. Theoretical

**Earthquake.** An earthquake is the result of a sudden release of energy from within the earth's crust, which creates vibration waves. Earthquakes are recorded by seismometers or seismographs. The deeper the center of the earthquake, the less the damage will be. The magnitude of an earthquake is proportional to the energy released by the earthquake. Earthquakes smaller than magnitude 3 Richter are often imperceptible and larger than 6 Richter cause serious damage, although Richter, each additional unit of which is about ten times the previous one (for example, 5 compared to 6), is

only a unit of the size and intensity of the discharged energy (Farrokhirad & Gheitarani, 2024).

But there are many other factors ranging from the distance (greater depth of impact from less than ten kilometers to 700 kilometers, as well as the greater horizontal distance from the epicenter) to the direction of the vibration (vertical or impact) and the type of vibration wavelength (the distance of the reciprocating displacement in each vibration). They affect the rate of destruction. Earthquake waves have three types: P and S (body waves) and the surface type P which comes first is known as pressure or longitudinal waves. Because its waves are shock waves and vibrate in the direction of propagation (like a game of tug-of-war) and move through the earth's crust at a speed of 1.5 to 8 kilometers per second (Bao, 2017).

On the contrary, S waves or scissor waves are up to 1.7 times slower and vibrate in the direction perpendicular to the propagation line (like shaking a table), but they cannot pass through liquids such as water or molten rock such as the outer core of the Earth (Khanian et al., 2019). A strong earthquake shakes the surface areas at an angle of 105 degrees, and the areas beyond this angle are called the shadow area. Therefore, experience has shown that P pressure waves cover a much wider range of the shadow area than S. And the P wave can vibrate a region very far from the epicenter by changing its direction and passing through the mantle or the outer core of the earth (Ghadarjani et al., 2013).

**Natural earthquakes.** Tectonic earthquakes will occur anywhere on Earth where enough elastic strain energy is stored to propagate a fracture along a fault plane. At the boundaries of the Earth's crust plates, which create the largest fault planes on Earth, the plates next to each other will move seismically. If no irregularity or roughness along their boundaries would increase the frictional resistance. Most boundaries have this roughness and this leads to stick-slip behavior. When the plate boundaries are locked, the continued relative motion between the plates leads to an increase in stress and, as a result, an increase in the accumulated energy in the masses near the fault surface (Mohammadzadeh et al., 2020).

This increase continues until the increased stress is high enough to suddenly allow slip from the locked part of the fault by breaking through the asperities, releasing the stored energy. This energy is released in the form of seismic waves and the frictional heat of the fault surface is radiated, and the rock is broken, which causes an earthquake. This gradual process of building stress and strain, which causes sudden failure and earthquake production, is called the elastic rebound theory. It is estimated that only 10% or less of the total energy of an earthquake is released as seismic energy.

Most of the earthquake's energy is spent on breaking rocks or turning into heat produced by friction; Therefore, an earthquake reduces the elastic latent strain energy of the earth near the fault and increases its temperature, although these changes are negligible compared to the convection currents and the conduction of heat released from deep within the earth. Earthquakes occur due to the sudden breaking of rocks inside the earth (Ghadarjani et al., 2013).

**Induced earthquakes.** Although most earthquakes have tectonic and natural origins, a significant number of earthquakes also have non-tectonic origins, which are known as induced earthquakes or earthquakes with artificial factors. In Iran, despite the presence of

many oil and gas fields, active mines, large dams, and geothermal sources, the characteristics of induced seismicity in these areas are not yet known correctly (Zakerhaghighi et al., 2015).

The Zagros mountain range hosts one of the largest hydrocarbon deposits on the planet, and many gas and oil fields are operating and being extracted in this area (Gheitarani et al., 2013). The existence of a high number of hydrocarbon fields and their extraction, as well as the natural tectonic activity in Zagros, has made this orogeny an unparalleled example on the planet. A study in the Zagros region has shown that although Zagros is classified as an active region from a tectonic point of view, the extraction of hydrocarbon deposits also causes induced earthquakes in this region (Khanian et al., 2013).

**Types of earthquake faults.** Three main types of faults may cause earthquakes: normal, reverse (axial), and strike-slip. Normal and reverse faults are examples of dip-slip, where displacement along the fault in the direction of the dip and movement on them includes a vertical component. Normal faulting mainly occurs in areas where the crust is being extended, such as a divergent boundary (Maleki et al., 2024). Reverse faulting occurs in regions where the crust is shortening, such as a convergent boundary. Strike-slip faults have steep structures where the two sides of the fault slide horizontally next to each other; Transform boundaries are a special type of strike-slip fault. Many earthquakes are caused by movement on faults that include both dip-slip and strike-slip, this slip is known as oblique.

**Earthquakes away from plate boundaries.** Since plate boundaries occur within the lithosphere of continents, the deformation is spread over an area much larger than the plate boundary. As with the continental transform of the San Andreas fault, many earthquakes occur far from the plate boundary and tend to develop in a wider region of deformation caused by irregularity associated with the trace fault (eg the "big bend" zone). Northridge was associated with movement in mountain drift within such an area. Another example is the convergent and strongly tilted plate boundary between the Arabian and Eurasian Plates, which is part of the northwestern Zagros Mountains (Oraee et al., 2010).

Deformation associated with this plate boundary is divided into nearly pure crustal boundary-perpendicular movements over a large area in the southwest and nearly pure strike-slip movements along major faults near the actual plate boundary. This is shown by the focal mechanism of the earthquake. All tectonic plates have an internal stress field resulting from their interactions with adjacent plates and sediment loading or unloading (e.g., deglaciation). These stresses may be sufficient to cause rupture along existing plate faults, triggering interplate earthquakes.

**Shallow focus and deep focus of the earthquake.** Most of the tectonic earthquakes in the Ring of Fire originate at a depth of less than tens of kilometers. Earthquakes at a depth of fewer than 70 km are classified as shallow-epicenter earthquakes, while those with a focal distance between 70 and 300 km are usually called 'intermediate-epicenter' or 'intermediate-depth earthquakes' (Zaker Haghighi et al., 2014).

In subduction zones, where older, cooler oceanic crust subducts into another tectonic plate, earthquakes may occur at much greater depths (in the 300-700 km range). These active seismic zones with subduction are known as (Wadati-Benioff) zones. The deep-center

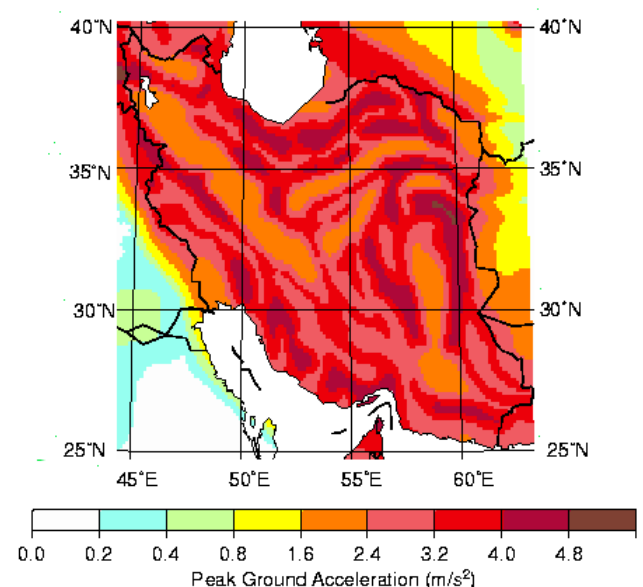
of earthquakes are at a great depth, in that area, the rock is no longer fragile due to the high temperature and pressure. A possible mechanism for the deep-focus generation of earthquakes is caused by the first phase transition to a rigid structure.

**Earthquakes and volcanic activity.** Some earthquakes occur in volcanic regions, they are caused by the movement of magma in volcanoes. Such earthquakes can serve as early warnings of volcanic eruptions, such as those during the 1980 Mount St. Helens eruption. An increase in earthquakes around an active volcano can be a sign of impending volcanic activity. The increase in seismic activity before the eruption of a volcano can be recorded by seismographs and tilt meters.

**Aftershocks.** An aftershock is an earthquake that occurs after the main shock. The aftershock is in the same region as the main shock but is always smaller in strength. If the aftershock is larger than the main shock, the aftershock is called the foreshock and the main foreshock is called the aftershock. Aftershocks occur when the crust around the displaced fault plane adjusts to the effects of the main shock (Jiang et al., 2010).

**A swarm of earthquakes.** It is a series of earthquakes that occur in a certain area in a short period. They are different from earthquakes which are followed by a series of aftershocks (Moayedifar et al., 2020). Because none of the individual earthquakes are in the main shock sequence, none of them is significantly stronger than the others. An example of an earthquake swarm is the activity of Yellowstone National Park in 2005. Earthquake storm sometimes a series of earthquakes occurs as an earthquake storm, where an earthquake strikes a multicluster fault, causing shaking or redistribution of the stress transmitted from the previous earthquake (Gheitarani et al., 2020).

Similar to aftershocks but on fault-adjacent sections, these storms occur over years, with some earthquakes as destructive as the initial earthquakes. Such a pattern was observed in a sequence of earthquakes on the North Anatolian Fault in Turkey in the 20th century and inferred for old anomalous clusters from large earthquakes in the Middle East (Gheitarany et al., 2013).



**Figure (1): the earthquake-prone points of the Iranian plateau**

**Source: GHADARJANI & GHEITARANI, 2013**

### 3. Methodology

Tests of g1 seismic table and related equipment of g1 seismic table (Ferdowsi University). The seismic table of the Soil Mechanics Laboratory of Mashhad University with a steel deck equal to 1.5 x 2.8 meters was used to apply optimal dynamic loading to the model. The intelligent hydraulic jack connected to the table can apply a horizontal force of 90 kilonewtons and the ability to carry samples weighing up to 40 kilonewtons.

This table can apply the frequency range of input excitation from 0.02 to 18 Hz with a displacement range of  $\pm 100$  mm and an acceleration range of more than g1. The city of Mashhad with an area of 234 square kilometers in the northeast of Iran and a longitude of 13 degrees and 51 deg to 63 degrees and 96 minutes and a latitude of 91 degrees and 49 degrees to 97 degrees and 1 minute in the watershed of Kashfroud, between the mountain ranges of Binaloud And there are thousands of mosques.

The city of Mashhad is located at the meeting point of the Kope Dag and Eastern Alborz zones and is located in the Mashhad plain. The area of Mashhad is divided into three different areas. Which, from north to south, includes the Kepe Dag range, Mafsai range, and Binalud range. Benalud is a curved mountain range with an almost north-west direction and includes Paleozoic, Mesozoic, and Cenozoic rocks and sediments.

The Mefsa area is located between the Binalud and Kepeh Dag ranges and includes metamorphic rocks and ophiolitic complex. The area of Kopeh Dag is made up of various formations, which is especially the sedimentary basin and zone of the Kopeh Dag structure. The surface soil texture of Mashhad varies from sand to clay. The surface soil in the northeast margin is mostly clay, which turns into clay-silt and silt soils towards the south (Kahvand et al., 2015).

Sandy soils are seen in narrow strips in the western and southern parts. In the west of the city of Mashhad, as well as on the edge of the southern highlands, the texture of the soil is sandy, and in the area of the city center, the soil is predominantly clayey and sandy. The eastern and northern areas of Mashhad City are covered with fine-grained soil, which increases with the increase in depth. As the depth increases, the texture of the soil increases. Seismic characteristics of Mashhad metro line 2 construction. The city of Mashhad is built on young alluvial deposits that are bounded by the Hazar Mosque mountain range from the north and the Binaloud mountain range from the south with a northwest-southwest trend.

To determine the tectonic phenomena and their characteristics in the scope of the project, estimate the maximum magnitude of the prediction and the maximum acceleration of the ground movement resulting from it in the scope of the project, and introduce the active faults of the construction, it is necessary to investigate the seismicity of the construction. Along the way, at 3 points, tests have been carried out within the assumptions. This test was done within the stations so that the generalization is on the way. Based on the results of the earthquake test in the assumptions, the type of ground based on the division of Ayyenamah 2133, in the area of 9621 meters from the beginning of the route, is reported as type III, and the rest of the route as type II.

Since the complexity of nature is such that it cannot be controlled by humans with current knowledge and the location of future earthquakes cannot be predicted. Statistical and probabilistic methods are used as an answer for earthquake risk prediction and estimation. The first step for conducting statistical studies is to prepare a catalog of earthquakes in areas with a suitable radius from the desired location.

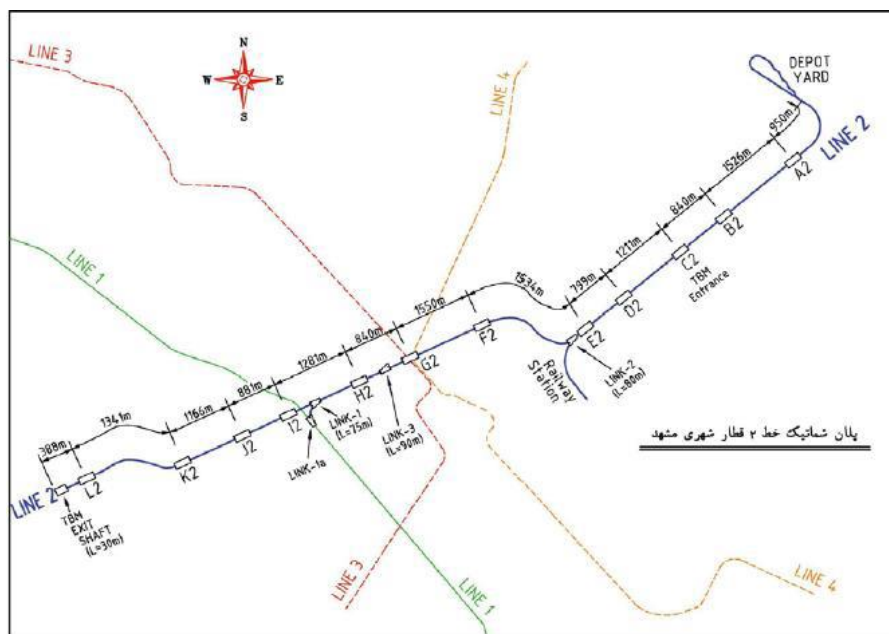


Figure (2): the route of Line 2 of Mashhad Metro

### 4. Results

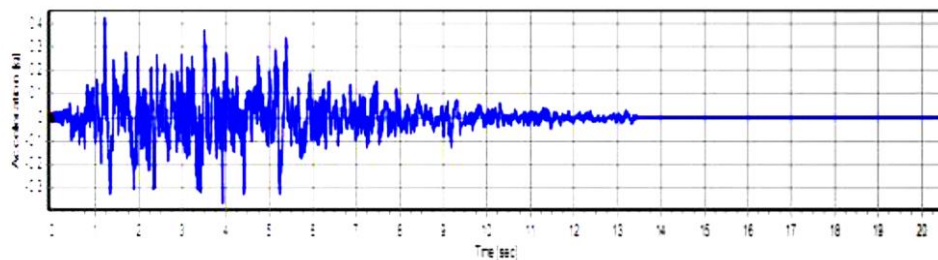
**Layer cut box.** A layered shear box designed at Mashhad University was used for these experiments. This box has 16 aluminum frames, the internal dimensions of each of which are 122x459 and their height is 2.8 cm. To reduce the friction between the frames and simulate the movement of soil layers, metal bearings inside the rubber belts have been used between the aluminum frames so that the distance between the frames is 4 mm.

**The scale of experiments.** Line 1 of the Mashhad city train (TURL2) with a length of about 13 kilometers connects the northern part of the city with its eastern part. In this study, the specifications of the metro tunnel line 1 in its central part between E2 and H2 stations have been used.

Line 1 tunnel was built using a TBM device with earth pressure balance with a turning diameter of 9.49 meters and a shield with an external diameter of 9.46 meters in front of the device. Precast concrete segments of the cover are installed right behind the shield. In the desired route, based on the geotechnical studies of Mashhad Metro Line 1, the soil types are ML and SM. The simulation rules of g1 seismic table tests proposed by Yai are used in the present study. Considering that the current research aimed to investigate the bending behavior of the tunnel under a transverse earthquake, the bending stiffness simulation was used.

Based on the characteristics of the original sample, shear wave velocity in the local soil and model soil, the dimensions of the layered shear box, and other parameters investigated in the problem, the scale factor of the original sample to the model was considered equal to 42 ( $42 \square$ ) for the experiments. Therefore, 38 meters of the soil layer of the original sample, one meter was modeled in the experiments. Also, the assumption of  $\square_\square=1$ , which is suggested for g1 seismic tests, was used.

The main example is a circular tunnel with an external diameter equal to 9.20 meters, a thickness of 0.28, and a rim length of 1 meter. By applying the mentioned relationships, the tunnel model according to Figure (3) was made of aluminum alloy with a diameter of 177.3 mm and a thickness of 2 mm.

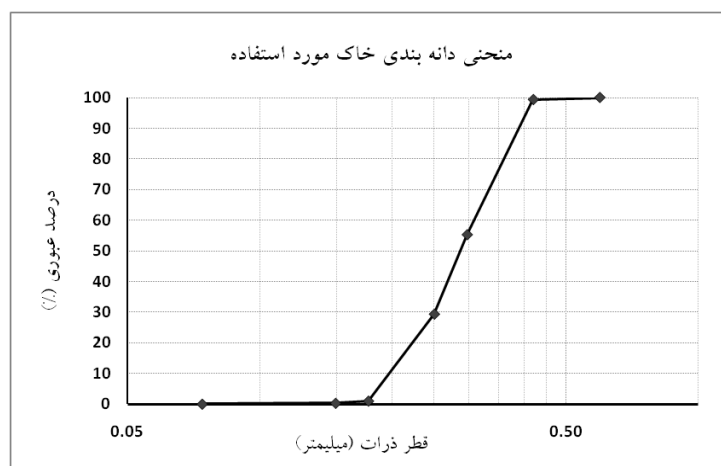


**Figure (3): acceleration mapping adapted to building conditions to create different earthquake design levels.**

Model soil specifications. The uniform sand that was prepared from the Qom Tepe area near Mashhad City was used in this study. The main characteristics of this uniform sand are given in table (1). Also, the granulation curve of this soil is shown in Figure (2).

**Table (1): The main characteristics of Tabas sand**

| SP    | Sample classification                    |
|-------|------------------------------------------|
| 1.34  | specific density                         |
| 41    | The angle of internal friction (degrees) |
| 0     | Adhesion (kN/m3)                         |
| 1.98  | Coefficient of uniformity                |
| 0.098 | Bending factor                           |
| 13.47 | Minimum dry weight (kN/m3)               |
| 16.28 | Maximum dry weight (kN/m3)               |



**Figure (2): Granulation curve of Qom Tepe sand**

Preparation of samples and tooling of models. The sand model was made by vibrating the sample on the seismic table with a constant frequency and amplitude until the desired density ( $Dr=58\%$ ) was reached. To measure the relative density in different layers of model soil, small molds placed at different levels were used.

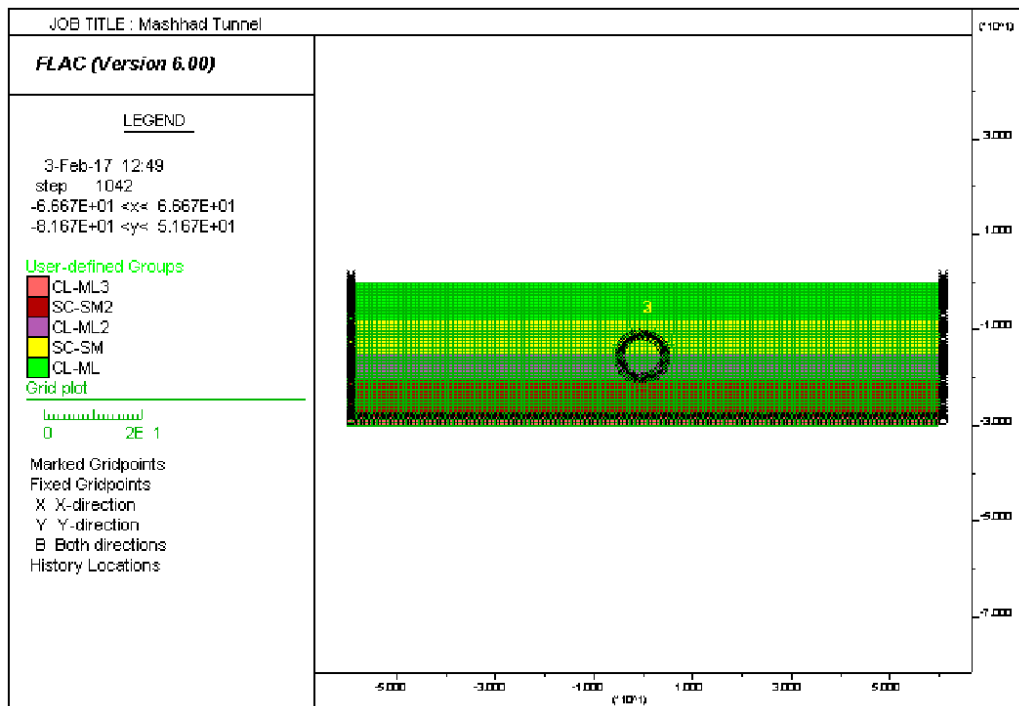


Figure (3): finite difference model for static simulation

During the compaction and after the completion of the test, the specific weight of the sand placed inside the mold was measured, and according to the maximum and minimum dry specific weight, the degree of compaction was calculated. During the construction of the model, several different measurement tools were used to check the behavior of the tunnel and the soil in the tests. The installed instruments included accelerometers, strain gauges, and linear variable differential transducer (LVDT). The first accelerometer, which was placed on the bottom of the box, was used to measure the input acceleration to the system.

All the installed tools were calibrated with sufficient accuracy before each test and were controlled after the test. All the measured data were recorded and transferred to the computer by a 16-channel dynamic data logger. Excitations applied by the seismic table to the models. The number of 64 excitations by the seismic table in the form of two groups of harmonic waves with high amplitude and irregular waves with high-frequency content and low amplitude were applied to each model and the input acceleration was recorded by ACC1 accelerometer.

Irregular waves with frequency content up to 47 Hz but with low amplitude up to  $g0.2-0.14$ , but harmonic waves included frequencies of 1, 3, 5, and 8 Hz and the maximum acceleration range was  $g0.28$  and  $g0.47$  (due to the limitation of the maximum displacement of the table, frequency 1 Hz and  $g0.47$  were not applied). The duration of basic excitation in harmonic waves was considered 6 seconds for all models. These input motions simulate shear wave excitations inside the plane relative to the tunnel section. The data obtained from the data recording system were converted into physical parameters such as acceleration, strain, and displacement.

## 5. Discussion and conclusion

Figure (4) shows the Fourier response spectrum of irregular waves (white noise) applied to each free-field (FF) and soil-tunnel (SF) two-model. It can be seen that the natural frequency of the free field is 14.2 Hz and the natural frequency of the tunnel-soil system is 14.3 Hz.

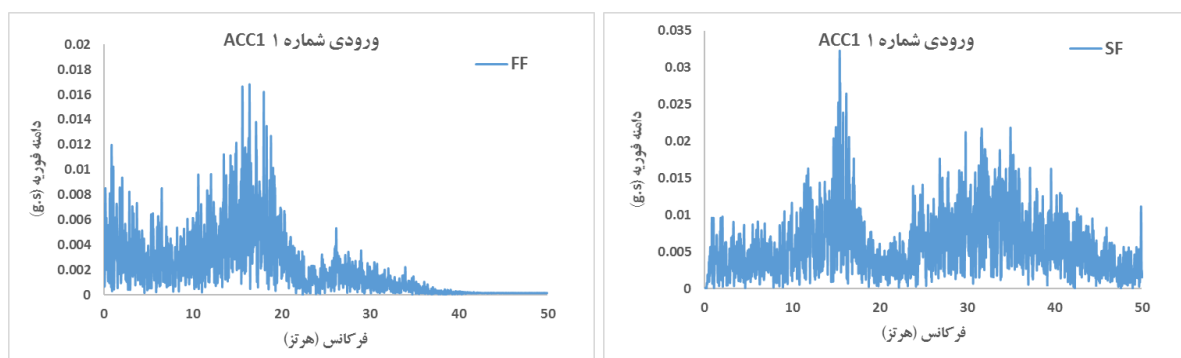
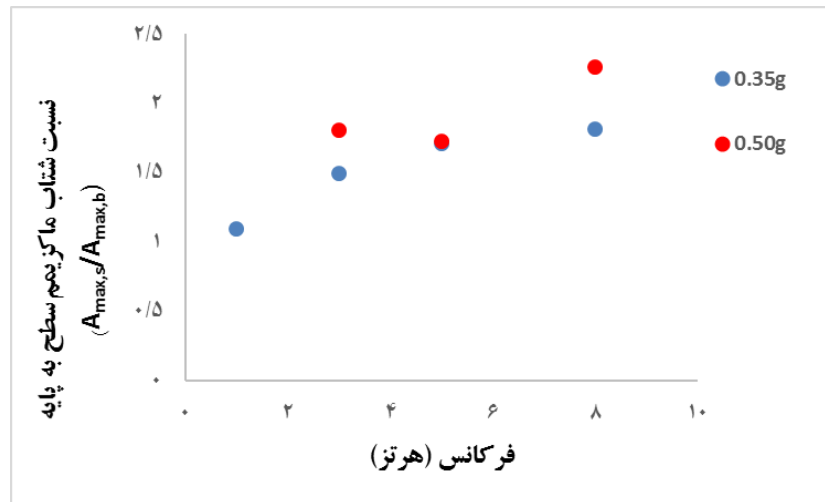


Figure (4): Fourier spectrum of FF and SF models for irregular input excitations in the model scale

Analysis and comparison of acceleration results. Although the time history recorded by the horizontal accelerometer in the rigid floor of the model was considered as single-frequency sine waves. However, the recorded signals are pseudo-harmonic and have some special characteristics that can be seen in the time domain.

When each signal was processed correctly, the maximum acceleration was determined as the maximum value of half-amplitude cycles in the acceleration time history. Acceleration ratios calculated along the tunnel arrangement are generally greater than one. This shows the tendency of the model to strengthen the base signal moving to the ground along the tunnel arrangement, which can be seen in Figure (5).



**Figure (5): Resonance ratio for horizontal acceleration for the experiments**

Analysis of the results of strain gauges. The laboratory results of the internal forces in the middle section of the tunnel model were obtained from the strain gauges during each test. Dynamic bending anchor is defined as an additional anchor applied to the tunnel lining after the earthquake.

Positive values of the bending moment indicate an increase in tensile stress on the surface of the tunnel lining. The measured values generally show that the lower part of the tunnel is more under pressure than the upper part, which is expected due to the slag stresses. During dynamic loading, tunnel lining forces generally increase from the static values measured before dynamic loading. Such an increase, which happens after seismic loading, is compatible with the compaction of sand and the accumulation of irreversible strains in the soil layer around the tunnel. During the first few cycles, the tunnel changes its shape towards an equilibrium stage. The second stage of the cycle continues after the start to the end of the dynamic loading.

The maximum dynamic bending moment on the tunnel lining is found by calculating the absolute value of the positive and negative bending moments and choosing the largest one. In this way, both positive and negative bending moments are considered. Experiments show that the maximum bending moment occurs near the crown and shoulder of the tunnel model. As can be seen in the graphs, for  $A=0.27g$ , the maximum anchor is constant or decreases slightly with increasing frequency. But for  $A=0.43g$ , the maximum bending moment decreases strongly for all strain gauges with increasing frequency.

Therefore, the mode of maximum acceleration amplitude with low frequency creates more bending moments and deformation in the underground tunnel. The surface settlement at the top of the tunnel was measured by LVDT during the earthquake. Small settlements of the ground were recorded on the soil surface during the earthquake due to the high density of the studied soil. In addition,

the experiments showed that the settlement of the soil surface increases with the increase of PGA.

The observations show that soil settlements are controlled by the uniform response of the sand mass below the tunnel level. In this laboratory research, the effect of important parameters such as the maximum acceleration of the ground and the dominant frequency of the earthquake on the seismic response of circular tunnels in dry sand was investigated by dynamic seismograph test. The recorded data determined the important features of the dynamic response of tunnel-type underground structures.

The main results of this study are summarized as follows:

The ground response is different in the free field model and soil-tunnel model, and the natural frequency of the free field is slightly higher. The horizontal acceleration recorded in several levels shows that the surface strengthening is carried out by the tunnel cavity, which acts as a barrier to the upward propagation of shear waves. The results of seismic table tests show that the dynamic behavior of circular tunnels can be divided into two stages: unstable state and steady state cycles. During the unstable state that occurs during the first several cycles, the tunnel structure reaches the dynamic equilibrium state. The unstable phase is followed by steady-state cycles during which the forces in the tunnel lining oscillate around the mean value.

For all the tunnel tests, the bending moment and deformations of the tunnel increase with the increase of the maximum acceleration of the base, but the location of the minimum and maximum values of the moment remain constant. The largest bending moment values appear in the middle of the crown and shoulder of circular tunnels. For the acceleration of  $A=0.27g$ , with the increase of the applied frequency to the system, the bending moment is constant or slightly decreases, but for  $A=0.43g$ , the maximum moment decreases strongly with the increase of the frequency.

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