

# Evaluation of Seismic Behavior and Earth's Surface Acceleration, by Interaction of Tunnels with Different Shapes and Different Types of Soils

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Received 21 January 2016; accepted 27 March 2016; published 30 March 2016

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## Abstract

With the increasing population and the consequent needs for transport facilities, the construction of tunnels in urban environments is fast growing. Tunneling at each depth of the soil, causes changes in the earth's surface; this is more important about urban areas tunnels, especially when crossing the residential areas, so having knowledge of their performance is really important. Some of the consequences of underground tunneling are earth surface moving around the tunnel, movement of tunnel's surrounding and changes in earthquake acceleration. The performance and behavior of underground structures have been studied by numerous researchers, but the effect of tunneling on earthquake records and its effects on aboveground structures have been getting less attention. The current article will try to study and examine the changes in seismic velocity at ground level, structural response spectrum, and Fourier spectrum with digging a circular tunnel. The results show that digging a circular tunnel at ground level will cause a change in the earthquake records profile.

## Keywords

Tunnel, Earthquake Records, Abaqus, Seismosignal

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## 1. Introduction

Due to the population growth in cities and urgent need to transport facilities, tunnels constructing is a key strategy in order to reduce the traffic volume; and easy transportation issue has been initiated from some decades ago. In this regard, some extensive studies have been done by different researchers, on the effects of tunneling, stability of tunnels and interactions of tunnels and constructions. Major research studies aimed to predict the movement of the earth around the tunnels and have tried to do that by experimental, analytical and numerical methods. Pack (1969) with drilling different soil profiles and doing field experiments indicated that subsidence of the ground level is a Gaussian curve [1]. Similarly, other studies have been done on the basis of empirical and analytical methods. The analytical methods that are based on the theories of elasticity, using balance equations, estimate surface soil profiles subsidence. Empirical studies are Pack relation basis, and only some parameters have been changed [2]-[7]. Earth's surface acceleration is one of the important factors in dividing the seismic zones; thus the impact of underground structures on the ground acceleration is very important. The effects of underground structures on seismic responses of structures above the ground are under investigation and the main conclusion is that the seismic responses of underground structures have a direct impact on above ground ones [8]. Several strategies have been used in regard to explain the effects of underground cavity structures on the surface structures which are under issues of waves and volumes, but the methods are based on some simple assumptions [9]-[13]; Sun and Wang (2012) studied the acceleration of the ground in tunnel position and in non-tunnel position and stated that there will be change in the velocity of the earth's surface in the presence of a tunnel [14]. In other studies, Baziar *et al.* (2014) using laboratory models and software, examined rectangular tunnel effects on the acceleration of the earth's surface; they applied sinusoidal records (acceleration) and real earthquake on the ground floor and stated that the rectangular tunnel reduces the whole momentum in short cycle time and increases the long-range acceleration in the long period of cycling time. The rectangular tunnel construction also increases the maximum earthquake acceleration compared to the situation without the tunnels and it is given that the actual earthquake records are different, so the effects of rectangular tunnels on earthquake acceleration records will also be different [15]. Cilingir and Madabhushi (2011) studied the effects of earthquake powers with different amplitudes and frequency rates on the circular and square tunnels behavior using Abaqus software, and stated that with increase in frequency rate or with low frequency time, the Fourier spectrum and acceleration decrease and at high frequency, acceleration and Fourier spectrum would have increase. Also by growing the earthquake amplitude, axial forces and bending moments of tunnel wall will extend [16]. Abuhajar *et al.* (2011) studied the effects of digging tunnel on earthquake acceleration by modeling different records and a square tunnel with studying on Nevada soil, and expressed that soil density affects the earthquake acceleration amplitude. They also noted that the earthquake acceleration domain has an important role in determining the acceleration of earth's surface earthquake reduction; so with increasing acceleration amplitude, earthquake acceleration decreases at ground level [17]. Rostami *et al.* (2016) [18] studied the types of tunnel maintenances and its effect on surface acceleration. They studied on Sadr-Niayesh tunnel and stated that digging tunnel causes the increase in earthquake acceleration at ground level and at top of the tunnel, and that stresses around the tunnel become increased [19]. The study tried to compare acceleration records in soil with tunnel and in the soil without tunnel by applying circular tunnel and actual earthquake records to the bottom of the soil with application of Palxis software. It also discussed some characteristics of earthquake records such as reaction spectrum, Fourier spectrum, and effective movement time in both cases of with tunnel and without tunnel, using Seismosignal software.

## 2. Materials and Methods

The specifications used in modelling the soil, tunnel, earthquake records, and structures are as following.

### 2.1. Soil Profile

The examined soil has one layer and lacks underground water. The mentioned soil is homogenous and has elastic-plastic behavior (elastic-perfectly plastic) obeying Mohr-Coulomb criterion. The reason of choosing this behavior model is its reputation and simplicity with having five parameters of elasticity modulus ( $E$ ), internal friction angle ( $\phi$ ), dilation angle ( $\psi$ ), viscosity ( $C$ ) and soil Poisson coefficient ( $\nu$ ), which are necessary in forming behavioral model equations. All these parameters are shown in **Table 1**.

## 2.2. Tunnel Characteristics

Circular tunnel with constant exposure area and depth of ( $\frac{d}{h} = 0.64$ ) was drilled in the soil layer as shown in

Figure 1 and concrete lining was used as Table 2 for the wall of the tunnel. Tunnel wall was modelled by bending element with elastic behavior.

## 2.3. Structure Foundation Characteristics

Bending element that has elastic behavior is the foundation of the model. Concrete foundation with a width of 14 meters and a thickness of 0.7 m is in Radiye type and has characteristics of the Table 3. Also the concrete compressive strength is 2500 kn/m<sup>2</sup> and density of concrete is considered as 2400 kn/m<sup>2</sup>.

## 2.4. Boundary Conditions and Mesh

To define the boundary conditions; fixed border and energy absorber border are used. For boundary lines of vertical soil in fixed boundary, the captive roller is beard, and joint support is used for the bottom horizontal line and horizontal line above the soil mass is also lacking any kind of support; with it, the soil only moves in vertical direction and there is no movement in the horizontal path. Due to turbulence in applying dynamic loads waves reflect on the boundaries of the model; to avoid these intensive reflections at the bottom, left, and right of the soil mass, boundaries on energy absorber are investigated.

In order to do a better analysis, choose the structure mesh in software. The software Abaqus [20] consists of different levels of mesh with various sizes and methods that the size and method is easy to select and use with

Table 1. Soil characteristics [21].

$\beta$	$\alpha$	$\vartheta$	$R_{inter}$	$C$ kn/m <sup>2</sup>	$\phi$ Degree	$\psi$ Degree	$E$ kn/m <sup>2</sup>	$\gamma_d$ kn/m <sup>2</sup>	$\gamma_{sat}$ kn/m <sup>2</sup>	$L$ m	$H$ m
0.001	0.01	0.3	0.7	0.4	29	5	5e4	17	17	200	50

Table 2. Tunnel coverage characteristics [22].

$\beta$	$\alpha$	$\vartheta$	$EI$ kn·m <sup>2</sup> /m	$EA$ kn/m	$d$ m
0.001	0.01	0.25	8.218E4	8.05E6	0.35

Table 3. Structure foundation characteristics.

$\beta$	$\alpha$	$\nu$	$EI$ kn·m <sup>2</sup> /m	$EA$ kn/m
0.001	0.01	0.25	7.145E5	17.5E6

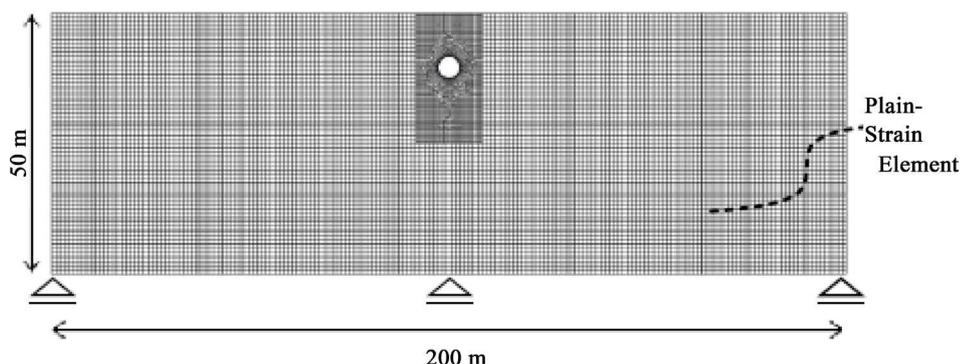


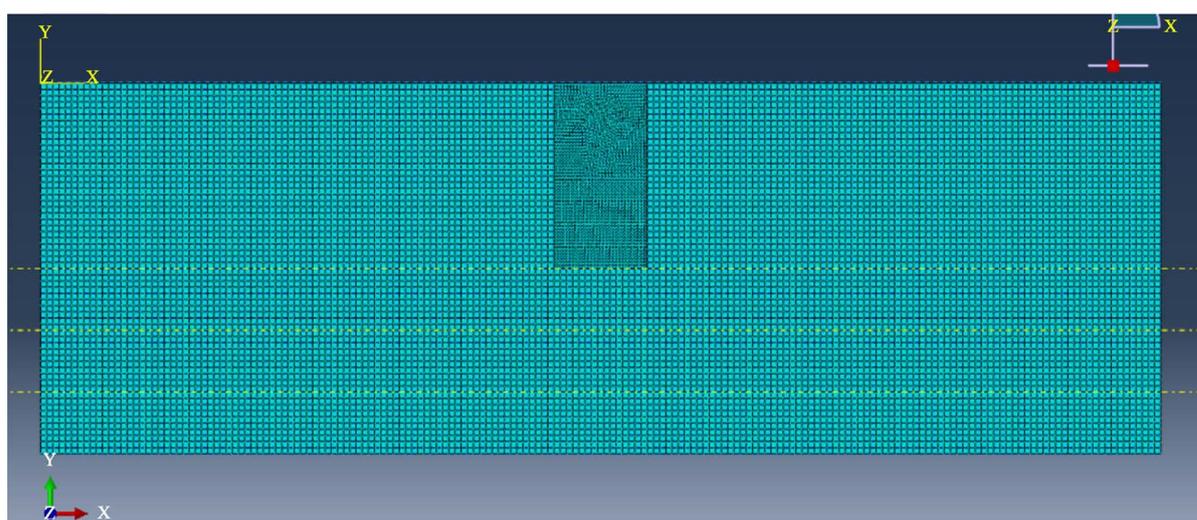
Figure 1. Models overview.

user. The way of making mesh depends on the importance of the subject, with a very large mesh the results would not be accurate, and choosing very fine mesh will increase the time of the analysis. As shown in **Figure 2** meshing in more sensitive areas such as the lining of the tunnel is considered smaller.

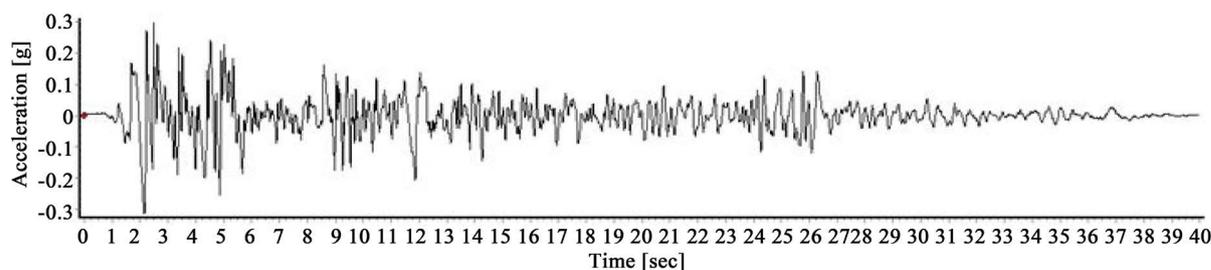
**Table 4** shows the characteristics of the actual earthquake records; in this table there are three records which are away from active faults and their maximum acceleration and their movement times are different. Maximum acceleration of all these records has been described as the scale number of 0.2 g; in other words three different records separately with maximum acceleration amplitude of 0.2 g would apply to the floor mass. Actual earthquake records are shown in **Figures 3-5**; these records are all in maximum acceleration of 0.2 g (**Figures 6-8**).

**Table 4.** Earthquake records characteristics [22] [23].

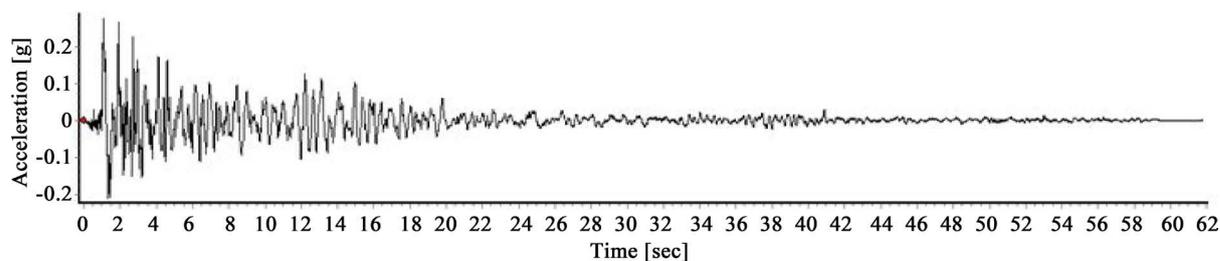
Effective Movement Time (s)	Distance from Fault (km)	Magnitude (Richter)	Maximum Acceleration	Record Name	Row
24.1	18.3	7.2	0.31	Elcentro	1
16.71	19.33	6.61	0.27	Sanfernando	2
17.84	63.34	6.19	0.011	Sanluis	3



**Figure 2.** Overview and mesh.



**Figure 3.** El Centro earthquake records.



**Figure 4.** San Fernando earthquake records.

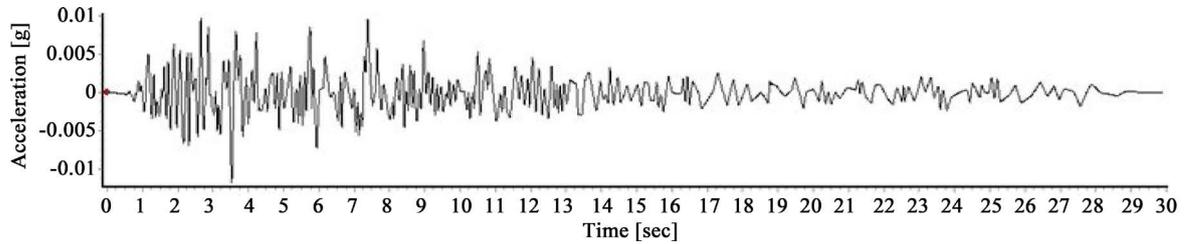


Figure 5. St Luis earthquake records.

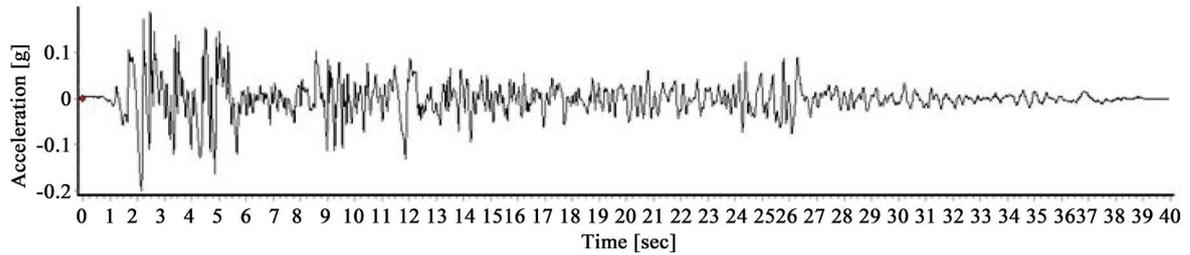


Figure 6. El Centro earthquake records with 0.2 g scale.

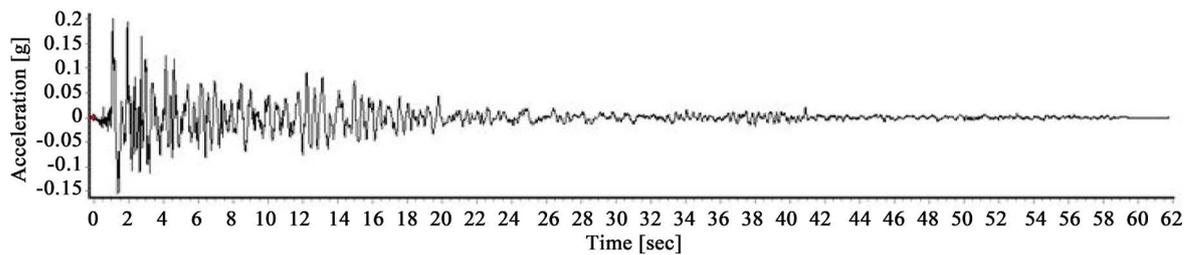


Figure 7. San Fernando earthquake records with 0.2 g scale.

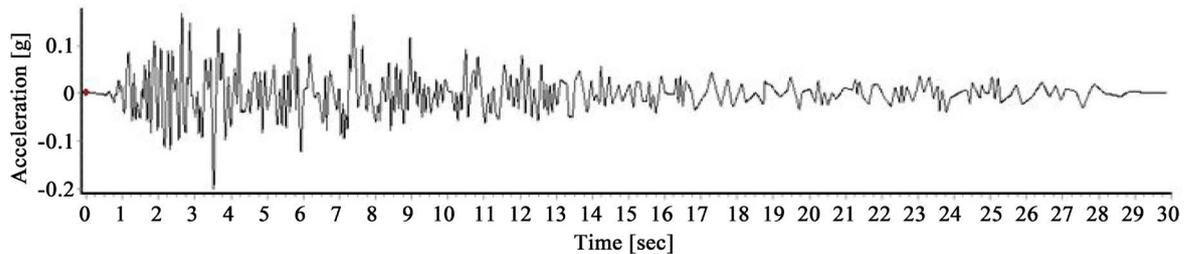


Figure 8. St Luis earthquake records with 0.2 g scale.

### 3. Results and Discussion

First we would apply the scale records with 0.2 g in the application of software on the mass floor soil and after doing dynamic analysis of surface soil at point A, located on the ground under the foundation; the coordinates of (0.50) will be incorporated. Again after digging a horseshoe tunnel in soil layers, same as not-tunnel position, scaled records of 0.2 g would be applied to the palm of soil mass and soil level records will be achieved. Finally, earthquake acceleration at the soil surface, response spectrum and Fourier spectrum will be compared with each other for both cases of with tunnel and without tunnel. In this study, WO means no tunnel and CT means circular tunnel. The EL, is El Centro earthquake, SANF is San Francisco earthquake and SANL stands for earthquake of San Fernando.

#### 3.1. Acceleration on the Soil Surface

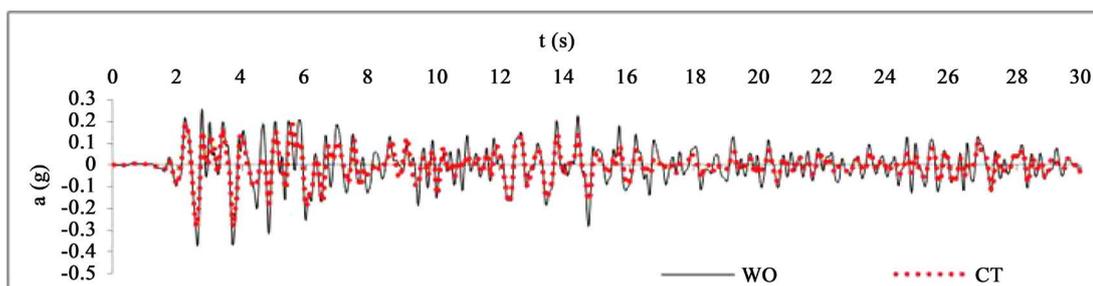
Figures 9-11 show the accelerated soil surface both with and without tunnels, under different earthquake records.

As it is clear, digging tunnel will cause changes in seismic velocity. **Figure 12** shows the maximum ground acceleration changes in tunnel mode in contrast with no-tunnel mode. According to the above-mentioned data in comparison with non-tunnel mode, digging a circular tunnel reduces the maximum acceleration on all records. In this figure, the value of  $A$  obtains from Equation (1); in which the maximum acceleration of surface soil in tunnel mode is  $a_T$ , and maximum acceleration of the surface soil in no tunnel mode is  $a_{WT}$ , the positive part of the vertical axis, shows the increasing percentage of the maximum acceleration and its negative part indicates reduction of the maximum velocity.

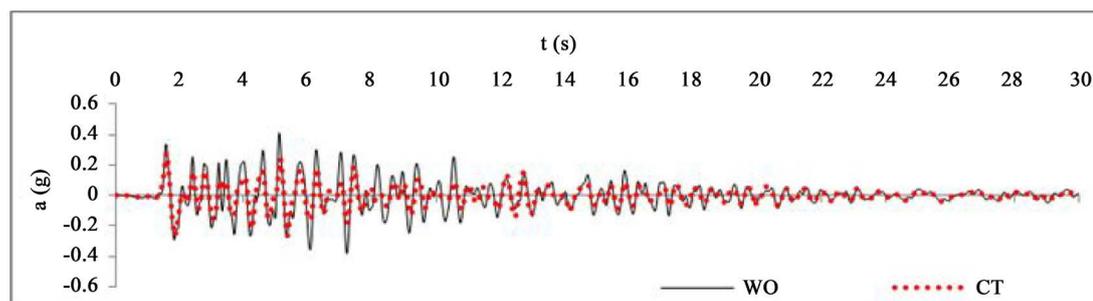
The percentage change in maximum acceleration time has been shown in **Figure 13**. The mentioned figure suggests that in El Centro earthquake, the maximum acceleration time has been increased due to the tunneling and in San Fernando earthquake this time has been reduced, but the time of maximum acceleration in the earthquake of St Louis in both modes of tunnel and non-tunnel does not have any change. In this figure the value of  $t$  has been obtained through Equation (2); in which, maximum acceleration rate in surface soil and in tunnel mode is  $t_T$ , and the maximum acceleration time in surface soil and in non-tunnel mode is  $t_{WT}$ . The positive part of the vertical axis shows the increasing percentage of the maximum acceleration and the negative part of the axis indicates the reduction percentage of the maximum acceleration time.

$$A = (a_T - a_{WT} / a_{WT}) * 100 \quad (1)$$

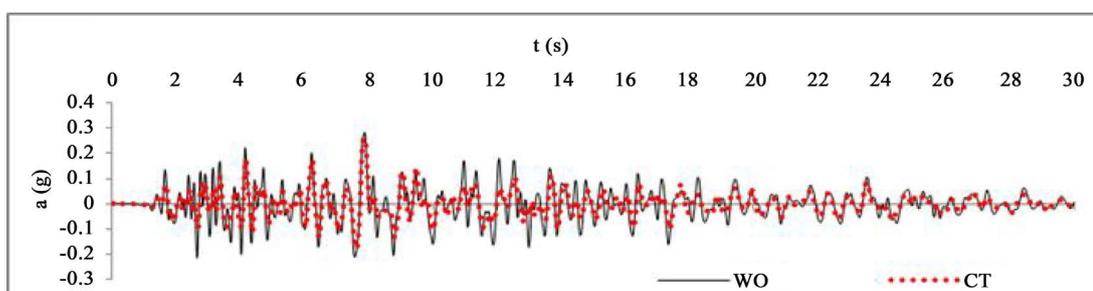
$$t = (t_T - t_{WT} / t_{WT}) * 100 \quad (2)$$



**Figure 9.** Soil surface acceleration in both modes of tunnel and non-tunnel in El Centro earthquake.



**Figure 10.** Soil surface acceleration in both modes of tunnel and non-tunnel in San Fernando earthquake.



**Figure 11.** Soil surface acceleration in both modes of tunnel and non-tunnel in St Louis earthquake.

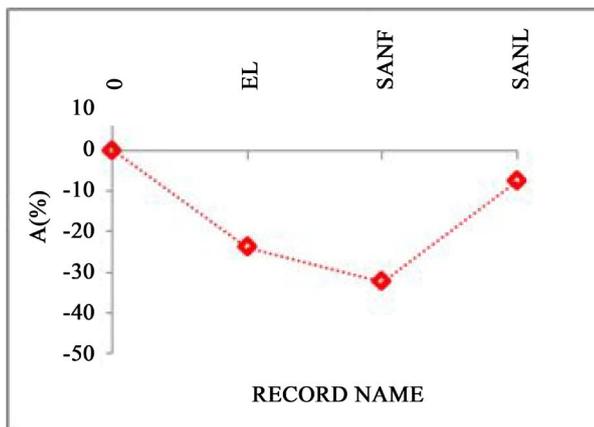


Figure 12. Changing percentages of maximum acceleration of the ground.

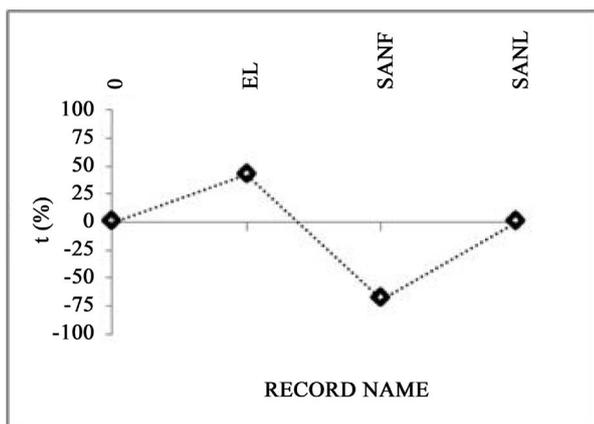


Figure 13. Time changing percentages of maximum acceleration of the ground.

### 3.2. Structure Acceleration Spectrum

Earthquake records have been applied into the soil mass in both cases of tunnel mode and non-tunnel mode, and dynamic analysis have been done for getting records of surface soil by software help. Records of the surface soil are attached to Seismosignal and whole structure acceleration has been drawn by a degree of freedom for each record. Figures 14-16 show structure acceleration spectrums of both modes with tunnel and without tunnel, under different earthquake records. As it is known digging a circular tunnel reduces the tunnel structures acceleration spectrum.

### 3.3. Effective Time of the Record

Each record of the acceleration has an effective movement time. The movement time is defined in different ways that among all the energy definition is the most accurate one. In this method the duration of 5 to 95 percent of energy-releasing in earthquake would be measured. Figure 17 shows the percentage changes of the record time in the tunnel mode and in the non-tunnel mode. According to this figure, in El Centro and in San Fernando earthquakes, tunneling had caused increase in effective time movement and in St Luis earthquake, tunneling has reduced the duration of the movement.

In this figure, the value of  $d$  obtains from the Equation [2]; in which  $d_T$  is the effective duration of the movement in the tunnel mode, and  $d_{WT}$  is the duration of the movement in non-tunnel mode. The positive part of the vertical axis shows the increase in maximum acceleration percentage and the negative part of the vertical axis indicates the reduction of the maximum acceleration percentage.

$$d = (d_t - d_{wt} / d_{wt}) * 100 \tag{3}$$

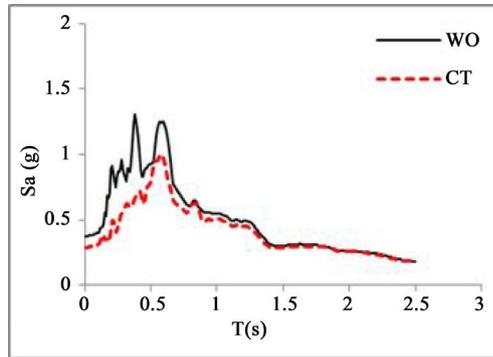


Figure 14. Structure acceleration spectrum in El Centro earthquake.

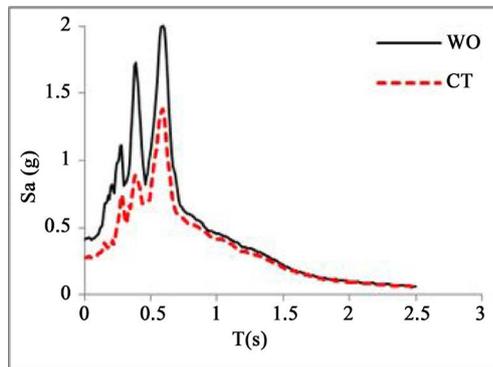


Figure 15. Structure acceleration spectrum in Sen Fernando earthquake.

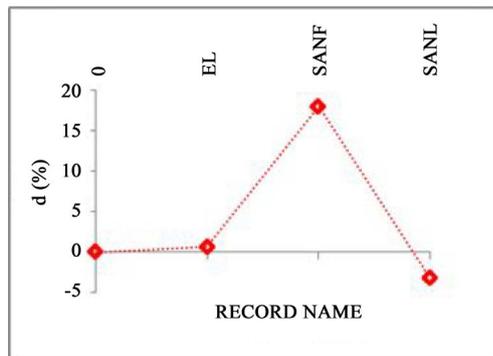


Figure 16. Structure acceleration spectrum in St Luis earthquake.

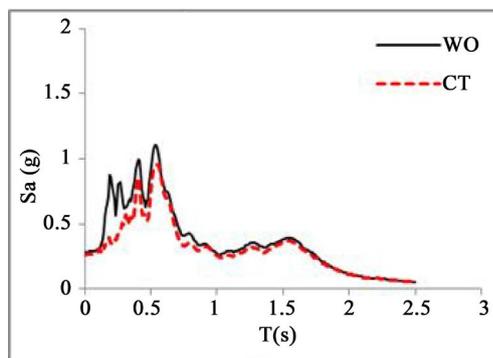


Figure 17. Change percentages in movements effective duration.

### 3.4. Fourier Spectrum Acceleration in Soil Surface

Figures 18-20 show the acceleration Fourier spectrum of soil surface in both with and without tunnel mode under different earthquake records. As it is clear drilling a tunnel will cause a change in the Fourier spectrum. Figure 21 shows maximum percentage changes of Fourier spectrum in both with and without tunnel modes. According to the above-mentioned figure, circular tunnel reduces the maximum amplitude of Fourier spectrum in all the records of the case without tunnel. In this way, the amount of  $FA$  obtains from Equation (4); in which  $FA_T$  is the maximum spectrum amplitude in tunnel mode, and  $FA_{WT}$  is the maximum range in without tunnel mode. The positive part of the vertical axis shows the percentage of the maximum acceleration and the negative part of the vertical axis indicates the reduction of maximum velocity.

Figure 22 shows the dominant frequency percentage changes of tunnel mode in compared with the without tunnel mode. In both El Centro and San Fernando earthquakes dominant frequency in both cases are the same and does not have any changes, but in the earthquake of St Luis dominant frequency is decreasing. In this figure, the value of  $f$  obtains from Equation (5); in which  $f_T$  is the dominant frequency in the tunnel mode, and  $f_{WT}$  is the dominant frequency in non-tunnel mode. The positive part of the vertical axis is showing the increase in the maximum acceleration time and the negative part of the vertical axis is indicating the reduction in maximum acceleration time. And in Figure 23 show the dynamic loading effect on soil deposit, the figure show the effect of tunnel on surface acceleration and displacement.

$$FA = (FA_T - FA_{WT} / FA_{WT}) * 100 \tag{4}$$

$$f = (f_T - f_{WT} / f_{WT}) * 100 \tag{5}$$

### 4. Conclusions

This study has applied some actual earthquake records of the soil floor in both conditions of without tunnel and with circular tunnel; earthquake records on ground-level have been collected through Plexis software and data such as acceleration, reaction range, effective duration of the movement, and Fourier spectrum are analyzed with Seisimosignal software aid. The results show that:

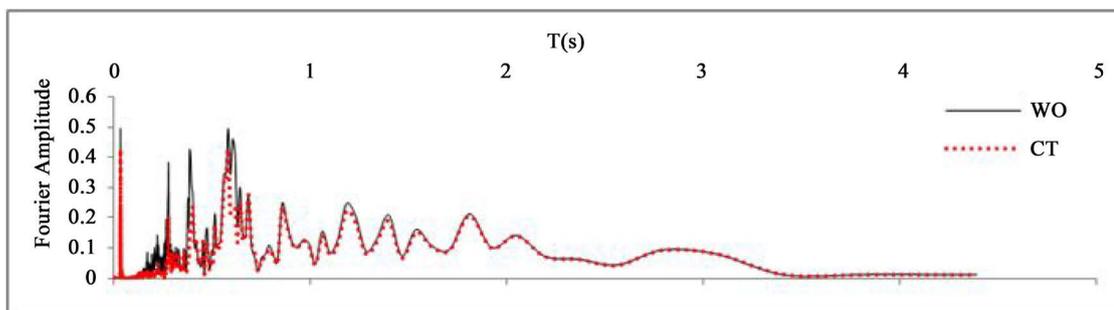


Figure 18. Comparing the Fourier spectrum acceleration of surface soil in two modes of with tunnel and without tunnel in El Centro earthquake.

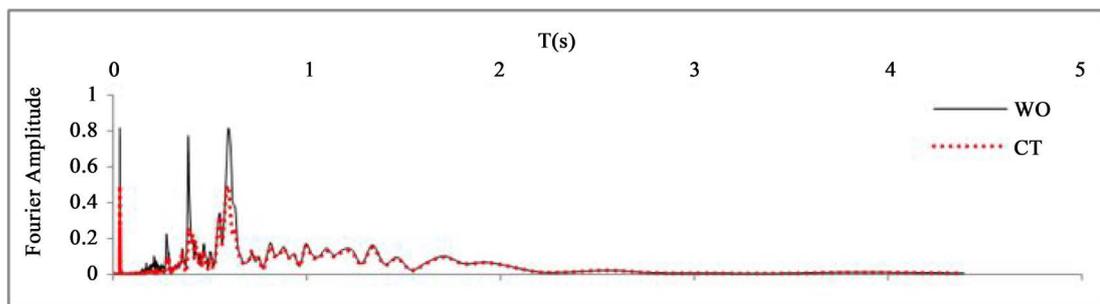


Figure 19. Comparing the Fourier spectrum acceleration of surface soil in two modes of with tunnel and without tunnel in San Fernando earthquake.

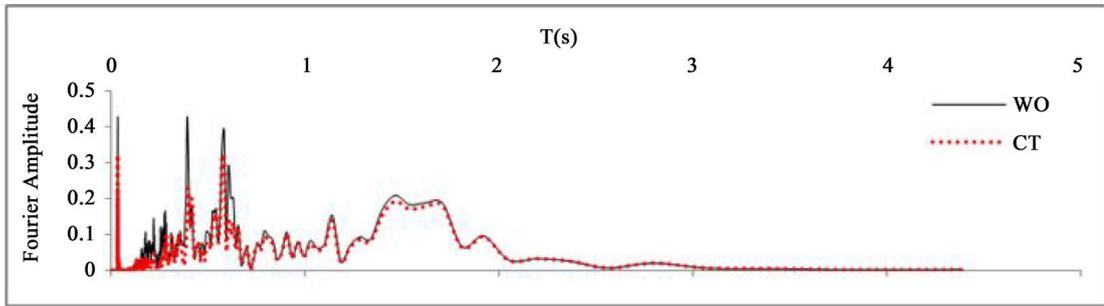


Figure 20. Comparing the Fourier spectrum acceleration of surface soil in two modes of with tunnel and without tunnel in St Luis earthquake.

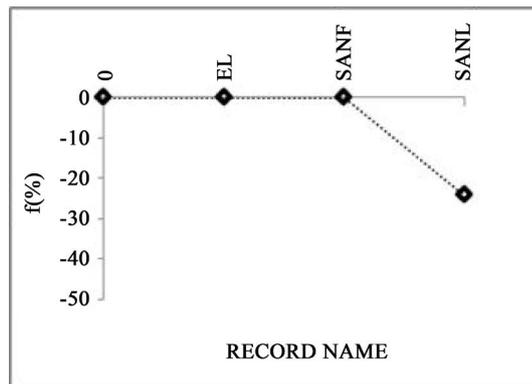


Figure 21. Maximum change percentages of Fourier spectrum amplitude.

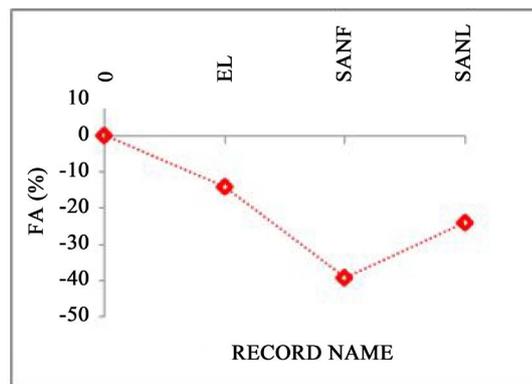


Figure 22. Dominant frequency change in records.

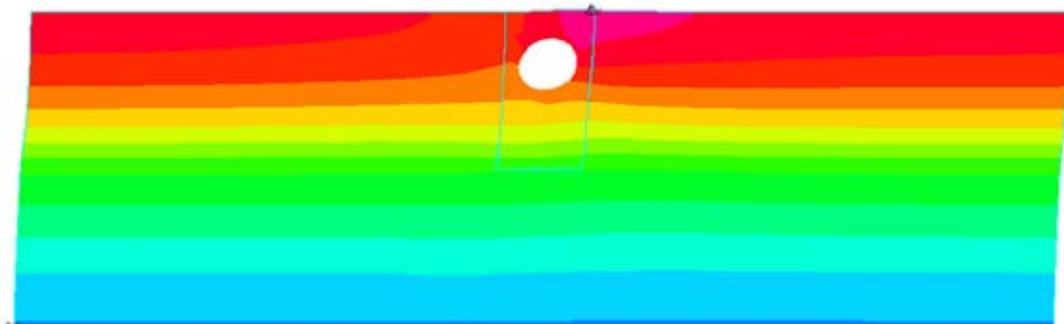


Figure 23. Dynamic effect on soil deposit.

1) Drilling circular tunnels have direct effect on earthquake acceleration at ground level so that maximum acceleration has been reduced in all three earthquake records; although earthquake duration, according to the type of record, has been affected by the tunnel digging operations.

2) Spectrum response of the structure is different in without tunnel and with tunnel conditions, so that if there is a circular tunnel, response spectrum is reduced in comparison with the condition in which there's no tunnel.

3) Digging tunnel affects earthquake's effective movement records. This parameter may be increased or decreased or may remain unchanged, depending on the record type.

4) The Fourier spectrum would be affected by tunnel digging operations. If there are tunnel drilling operations, the maximum amplitude of Fourier spectrum records would drop and its dominant frequency changes will vary according to the type of the records.

In general it can be said that, with the assumption of constant soil and tunnel profiles, tunneling alters earthquake records on soil surface, but these changes are directly in relation with earthquake records. By clicking on each record item, different responses than the other records would be obtained. Also in constructing superstructures on tunnels or vice versa analytical risk studies are necessary.

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