Alteration of Ground Motion Acceleration at Ground Level Due to Tunnel Excavation

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Abstract

Underground tunneling is one of the alternative solutions to diminish traffic congestion in large cities. One of the most important effects of tunneling is the displacement of the ground surface, the settlement around the tunnel, and the variation in earthquake acceleration. The performance and behavior of underground structures have been studied by several researchers, but the impact of tunnel excavation on earthquake records and its effects on structures above the ground level have received less attention. This research emphasizes changes of earthquake acceleration at the ground level, structural response and Fourier spectrum by excavating a horseshoe tunnel. Results show that digging a horseshoe tunnel will change the characteristics of the earthquake record at ground level.

Keywords

1. Introduction

For decades, tunnel construction has been recognized as a substantial approach to reduce traffic congestion and ease of public transportation due to the population growth in urban areas and the urgent need for public and green transportation amenities. With this outlook, considerable studies have been done by various researchers, on the impacts of tunneling, tunneling stability, and tunnel-structure interaction, most of which tried to anticipate the settlement of the ground around the tunnels, which were experimental, analytical and numerical

methods.

By modeling a square tunnel in Nevada sandy soil, Abuhajar *et al.* (2011) studied the effects of tunneling on earthquake acceleration, taking into account various ground motion records, and reported that soil density affects the amplitude of earthquake acceleration. And it was found that the amplitude of the earthquake acceleration plays an important role in determining the earthquake acceleration decrease; whereas if the acceleration amplitude increases, a reduction for earthquake acceleration boosts [1] [2]. Further studies have been done on the basis of empirical relationships and analytical methods. In another study, Baziar *et al.* (2014) investigated the effects of a rectangular tunnel on ground surface acceleration using experimental and numerical models; by applying sine records (sine accelerograms) and actual ground motion records, they have concluded that the rectangular tunnels would respectively decrease and increase the short time-periods and long time-periods. Also, the construction of a rectangular tunnel would increase the maximum earthquake acceleration compared to the non-tunnel state, and since the actual earthquake records are totally unique, the effects of the rectangular tunnel on the earthquake acceleration record will be different [3].

Besharat *et al.* (2012) also examined the impact of underground structures on the ground surface during the earthquake and reported that tunnel excavation would increase the earthquake acceleration above the ground surface, the tunnel and the stresses around the tunnel [4].

Cilinger and Madabhushi (2011) inspected the effects of seismic forces of varying amplitude and frequency on the behavior of circular and square tunnels using the Abaqus software and stated that with increasing frequency or short period-time, the Fourier spectrum and acceleration decreased and at long period-time, the Fourier spectrum and acceleration would rise. Furthermore, with increasing earthquake amplitude, axial forces and flexural moments of the tunnel wall will increase [5]. In analytical methods based on the theory of elasticity, by using equations of equilibrium, they acquire the surface subsidence profiles. Experimental studies have also been based on the Pack relation and just some parameters of that relation have been altered [6]-[12].

Pack, by field studies on a number of circular tunnels dug in various soils, showed that the settlement profile of the ground surface is a Gaussian curve [13]. Ground surface acceleration is one of the important factors for seismic segregation of areas, so the influence of underground structures on ground acceleration is very critical. Recently, the effects of underground structures on the seismic response of above-ground structures have been investigated and concluded that underground structures have a direct impact on the seismic response of above-ground structures [14]. Several approaches have been used to describe the impact of underground cavities on above-ground structures under surface and volumetric waves (earthquake waves), but the methods are based on a number of simple assumptions and relations [15] [16] [17] [18] [19]. Sun and

Wang (2012) assessed the relationship between the acceleration of the ground surface with and without the tunnel situation and stated that the existence of the tunnel would change the acceleration of the ground surface [20].

Other researchers did different studies on differ aspect of Soil-Structure Interaction and ground acceleration due to tunnel existence and found good results of their researches [21]-[28].

The main target of this research is to extract the record of soil surface acceleration in two cases with and without tunnel by digging the horseshoe tunnel and applying actual and occurred earthquake records to the soil mass in PLAXIS software. Also, using SeismoSignal software, some of the features of the earthquake record, including the response spectrum, Fourier spectrum, and significant duration of ground motion, will be discussed in both cases.

2. Material Properties & Methods

For modeling soil, tunnel, earthquake records and structures a series of specifications are used as follows.

2.1. Soil Properties

The soil has one layer and no groundwater. The soil is homogeneous and its behavior is assumed to be governed by an elastic perfectly-plastic constitutive relation based on the Mohr-Coulomb criterion [28] [29] [30] [31]. The reason for choosing the Mohr-Coulomb behavioral model is the popularity and simplicity of the model. Relations of the behavioral model are formed by having five parameters such as elastic modulus, internal friction angle, dilation angle, and adhesion and the Poisson ratio of the soil [11].

2.2. Tunnel Properties

A horseshoe tunnel with constant area and depth has been dug in the soil layer as shown in **Figure 1**, and the concrete cover has been used for the tunnel wall,
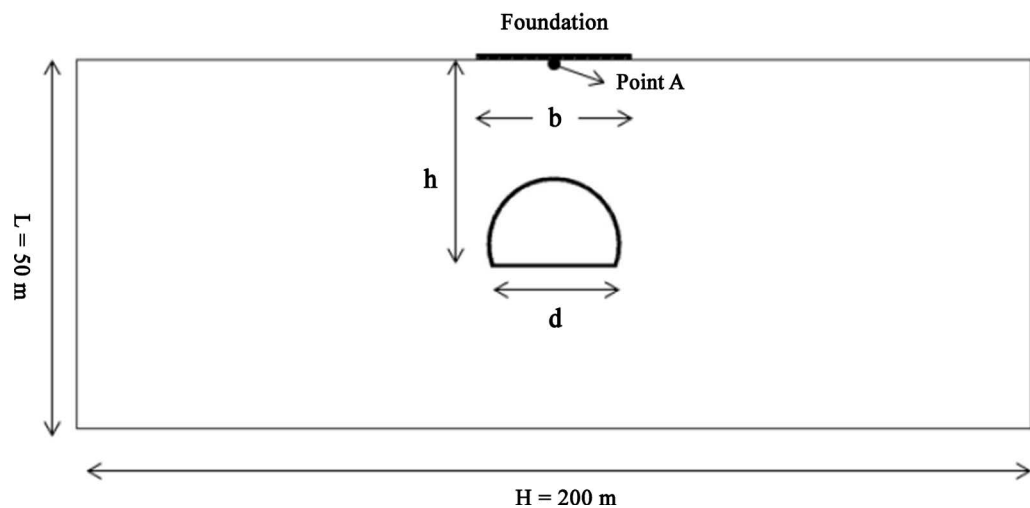

Figure 1. General scheme of tunnel.

as shown in Table 1. The tunnel wall was modeled using a flexural element which has elastic behavior.

2.3. Specifications of Structure Foundation

The foundation is modeled with a flexural element that has elastic behavior. The modeled concrete foundation is 2 m wide and 1.5 m thick. The compressive strength and the specific weight of the concrete are respectively 25,000 KN/m² and 2400 KN/m². And other required specifications are also taken into account. The specifications of the structure foundation and the tunnel coverage used in the simulation are summarized in Table 2 and Table 3.

2.4. Boundary Conditions and Meshing

In order to define boundary conditions, the constant boundary and the energy absorber boundary (infinite elements) are used. At the fixed boundary for the vertical lines of the soil mass, roller support is considered and for the horizontal line of the soil mass, hinge support is included and the horizontal line above the soil mass is without any supports (free-region). According to these descriptions, the soil only could move vertically and has no horizontal movement. During dynamic loads, due to perturbations, the waves reflect on the boundaries of the model; to avoid these severe reflections and unwanted consequences, energy-absorbing boundaries (infinite elements) are applied in the lower left and right parts of the soil mass.

Every FE software needs to lattice every part to analyze the simulated model, for this model; software used 6 nodes and 15 nodes triangle elements as meshing. In PLAXIS software, there are five types of meshwork including very coarse, coarse, medium, fine and very fine [32]. The method of meshing depends on the importance of the subject, with the mesh selection being too large, the results of the analysis will not be obtained precisely and also very fine mesh will increase the analysis time too. As a result, the medium-sized meshwork was selected.

Table 1. Soil properties [11].

β	α	ϑ	R_{inter}	C KN/m²	ϕ Degree	ψ Degree	E KN/m²	γ_d KN/m²	γ_{sat} KN/m²	L m	H m
0.001	0.01	0.3	0.7	0.4	29	5	5e4	17	17	200	50

Table 2. Structure foundation specifications [33].

β	α	ν	EI (KN·m²/m)	EA (KN/m)
0.001	0.01	0.25	7.145E5	17.5E6

Table 3. Tunnel coverage specifications [33].

β	α	ϑ	EI (KN·m²/m)	EA (KN/m)	d (m)
0.001	0.01	0.25	8.218E4	8.05E6	0.35

And, sensitive and vital areas such as the walls of the tunnel (tunnel coverage) are simulated with fine mesh. **Figure 2** displays the model geometry, meshing, and boundary conditions.

Table 4 shows the characteristics of the actual earthquake records; the three records, which are far-field kind, differ in their maximum acceleration and significant duration of ground motion. The maximum acceleration of all the records is scaled to 0.2 g; that is, three different records will be applied separately to the bottom of the soil mass with an acceleration amplitude of 0.2 g. Actual earthquake records are shown in **Figures 3-5**, and all scaled to a maximum
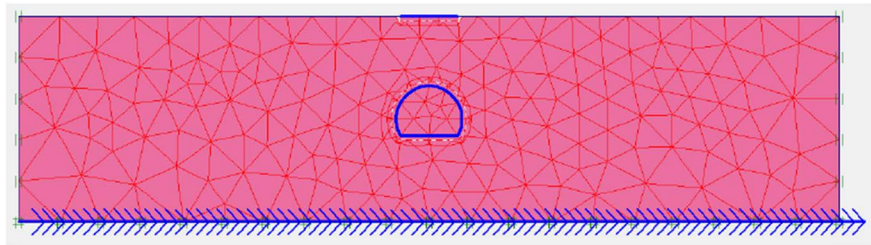
Figure 2. Model and meshing overview.

Table 4. Earthquake records characteristics [19].

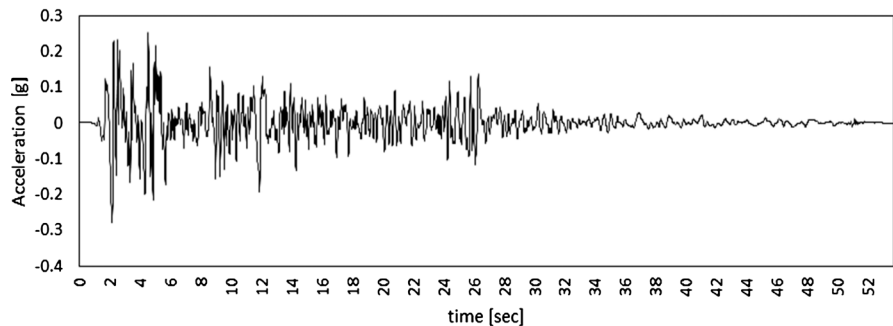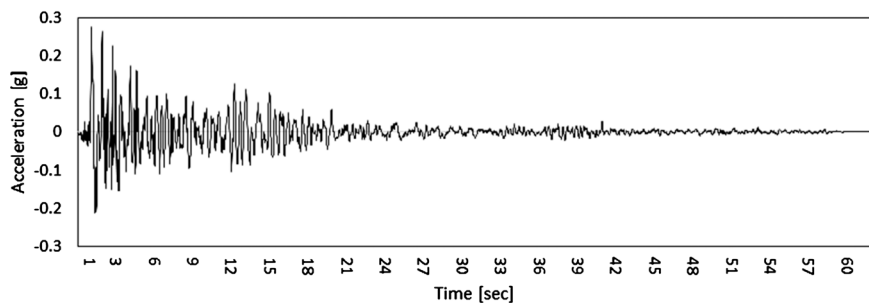| Effective Movement Time (s)	Distance from Fault (km)	Magnitude (Richter)	Maximum Acceleration	Record Name	Row
24.1	18.3	7.2	0.31	El-Centro	1
16.71	19.33	6.61	0.27	San-Fernando	2
17.84	63.34	6.19	0.011	San-Luis	3

Figure 3. El-Centro earthquake record.

Figure 4. San-Fernando earthquake record.

acceleration of 0.2 g (see Figures 6-8). Also, the characteristics of the selected ground motion records are listed in Table 4.

3. Results and Discussions

Firstly the scaled earthquake records (0.2 g) were applied to the soil mass in PLAXIS software and then the dynamic analysis of the soil surface record at
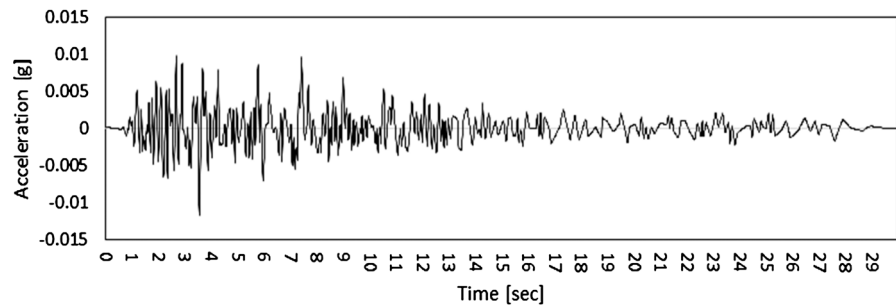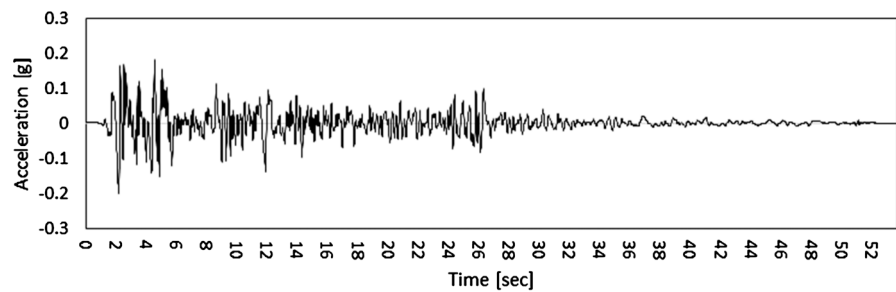

Figure 5. San-Luis earthquake record.

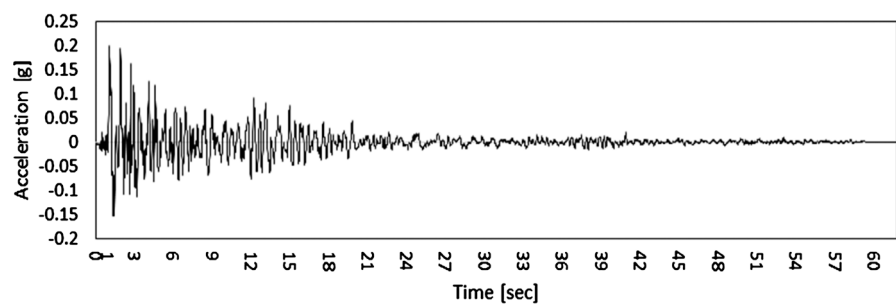**Figure 6.** Record scaled to 0.2 g of El-Centro earthquake.

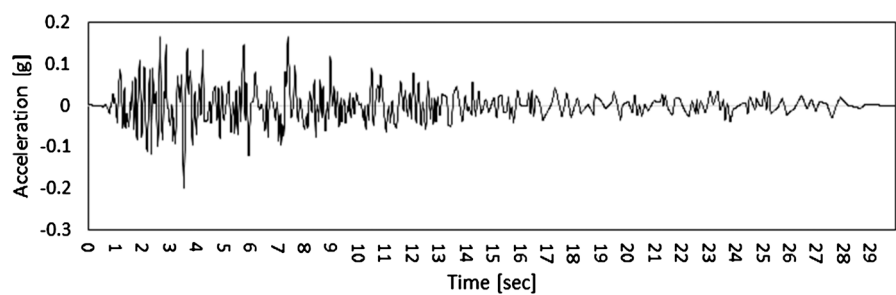**Figure 7.** Record scaled to 0.2 g of San-Fernando earthquake.

Figure 8. Record scaled to 0.2 g of San-Luis earthquake.

point A has been performed, which was located and found at ground level and below the foundation with a coordinate (0.50). This procedure has been done again with the horseshoe tunnel until the soil surface record is identified.

Finally, for both tunneled and non-tunneled states, earthquake acceleration at the soil surface, response spectrum, and Fourier spectra will be compared. In this study, WO, HT, EL, SANF, and SANL are referred respectively to non-tunneled state, horseshoe tunnel, El-Centro earthquake, San-Fernando earthquake, and San-Luis earthquake.

3.1. Acceleration at Ground Level

Figures 9-11 illustrate the acceleration of soil surface in two states with and without tunnels under different earthquake records. It is clear that digging the tunnel will change the acceleration of the earthquake. Figure 12 presents the maximum acceleration of the ground surface in the tunneled state compared to
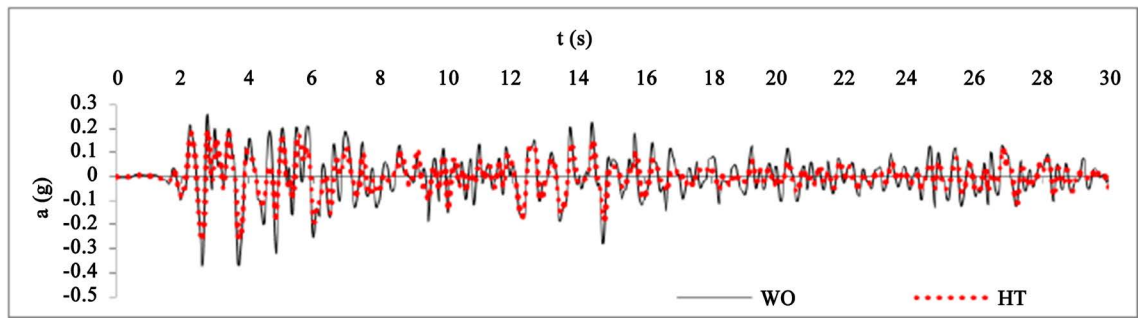
Figure 9. Soil surface acceleration in both cases of with & without tunnel for El-Centro earthquake.
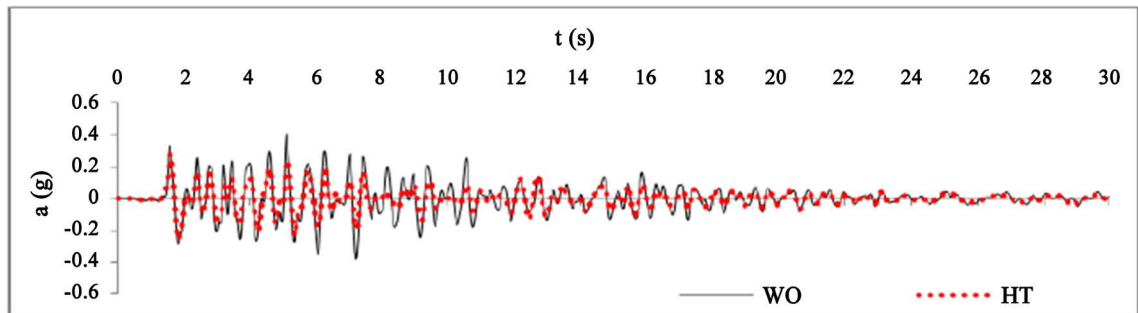
Figure 10. Soil surface acceleration in both cases of with & without tunnel for San-Fernando earthquake.
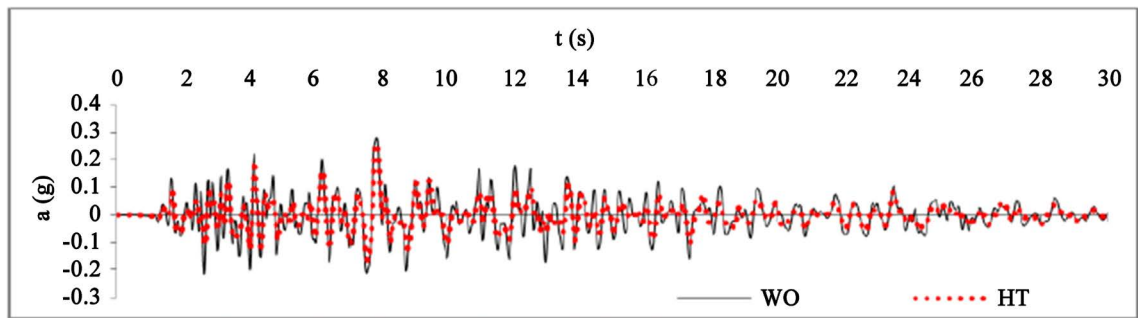
Figure 11. Soil surface acceleration in both cases of with & without tunnel for San-Luis earthquake.

the non-tunneled state. According to the presented Figure, digging a horseshoe tunnel will diminish the maximum acceleration in all the records compared to the non-tunneled-state. In this Figure, the value of A is obtained from Equation (1), where a_T is the maximum acceleration of the soil surface in a tunneled state and a_{WT} is the maximum acceleration of the soil surface in a non-tunneled state. The positive part of the vertical axis shows the increase of the maximum acceleration percentage and the negative part shows the decrease of the maximum acceleration percentage.

The percentage change in peak acceleration time is also shown in **Figure 13**. The Figure shows that in the San-Fernando earthquake, the time of peak acceleration due to tunneling is reduced; however, for two other records (El-Centro and San-Luis records) the time of peak acceleration is stayed constant (with & without tunnel cases).

In this Figure, the value of t is calculated from Equation (2), where t_T is the time of maximum acceleration of the soil surface in a tunneled state, and t_{WT} is the time of maximum acceleration of the soil surface in a non-tunneled state. The positive part of the vertical axis shows an increase in the percentage of maximum acceleration time and the negative part shows a decrease in the percentage of maximum acceleration time.
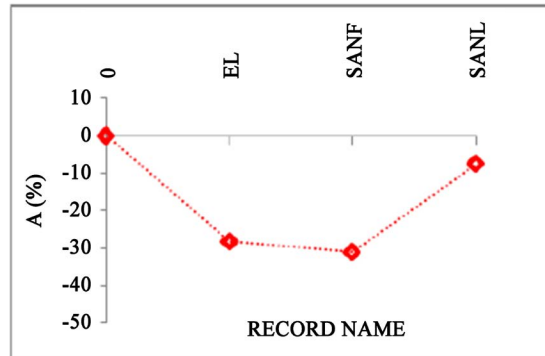
$$A == \frac{a_T - a_{WT}}{a_{WT}} * 100 \tag{1}$$

Figure 12. Percentage of time change in the maximum acceleration of the ground surface.
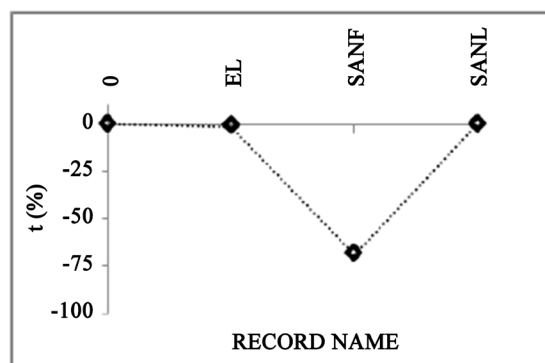

Figure 13. Percentage change of maximum acceleration of the ground surface.

$$t = \frac{t_T - t_{WT}}{t_{WT}} * 100 \qquad (2)$$

3.2. Acceleration Spectrum of Structure

In both tunnel-free and tunnel-like conditions, earthquake records are applied to the soil mass and the soil surface record is extracted by dynamic analysis that was done in PLAXIS software. The soil surface record is given to the SeismoSignal software and the acceleration spectrum of the structure is drawn by a Single Degree of Freedom (SDOF system) for each earthquake record.

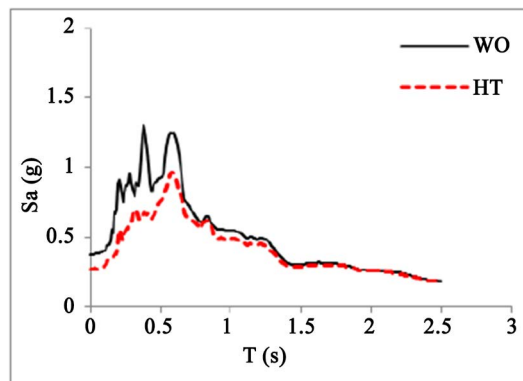Figures 14-16 indicate the acceleration spectrum of the structure in two

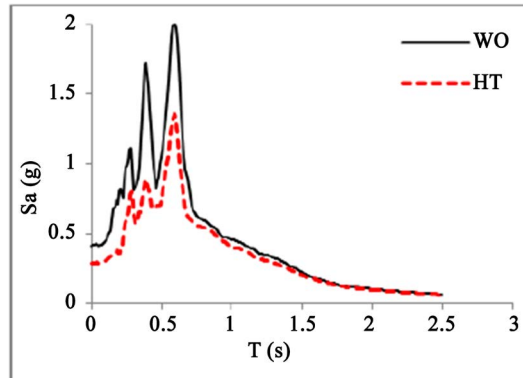**Figure 14.** Acceleration spectrum of structure for San-Fernando earthquake.

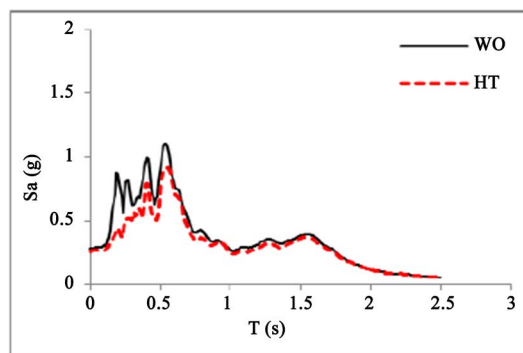**Figure 15.** Acceleration spectrum of structure for El-Centro earthquake.

Figure 16. Acceleration spectrum of structure for San-Luis earthquake.

previous conditions under different earthquake records. As is known, excavation of the horseshoe tunnel will lessen the spectrum acceleration of the structure.

3.3. Significant Duration of Ground Motion Record

The significant duration of the ground motion is defined in different ways, the most important and precise being the energy method. In this procedure, the duration of 5 to 95 percent of energy-releasing in an earthquake would be measured. Figure 17 depicts the percentage of changes in the significant duration of the ground motion in the two tunneled states. According to Figure 17, in the El-Centro and San-Fernando Earthquakes, tunnel excavation increases the significant duration of the ground motion, and in the San-Luis earthquake, the tunnel reduces the significant duration of the ground motion.

Also, the value of d calculated from Equation (3); in which d_T is the significant duration of the ground motion with tunnel state and d_{WT} is the significant duration of the ground motion without tunnel state. The positive part of the vertical axis displays an increase in the maximum acceleration percentage and the negative part shows a decrease in the maximum acceleration percentage.

$$d = \frac{d_T - d_{WT}}{d_{WT}} * 100 \tag{3}$$

3.4. Fourier Acceleration Spectrum of the Soil Surface

Figures 18-20 show the Fourier spectra of soil surface acceleration in two states with and without tunnels under different earthquake records. As is known, the tunnel excavation has changed the Fourier spectrum. Figure 21 shows the percentage change in the maximum amplitude of the Fourier spectrum in the tunneled state compared to the non-tunneled state. Based on Figure 21, excavation of the horseshoe tunnel will reduce the maximum amplitude of the Fourier spectrum in all the records compared to the non-tunneled condition. This part shows the calculation process of FA parameter that the FA_T variable is the maximum spectrum amplitude in tunneled state and the FA_{WT} is the maximum spectrum amplitude in the non-tunneled state (Equation (4)). The positive and negative parts of the vertical axis exhibits an elevation and reduction of the maximum acceleration percentage.
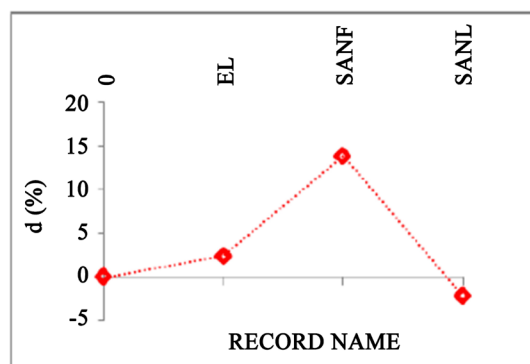

Figure 17. Percentage changes in significant duration of ground motion records.
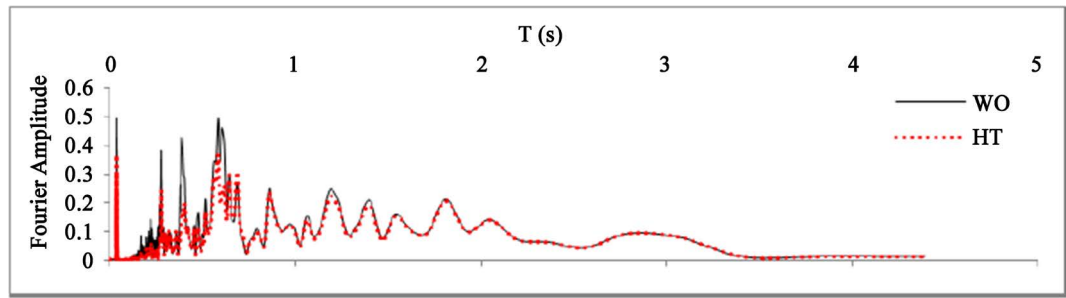
Figure 18. Comparison of Fourier spectra of soil surface acceleration in two states with and without tunnel for El-Centro earthquake.
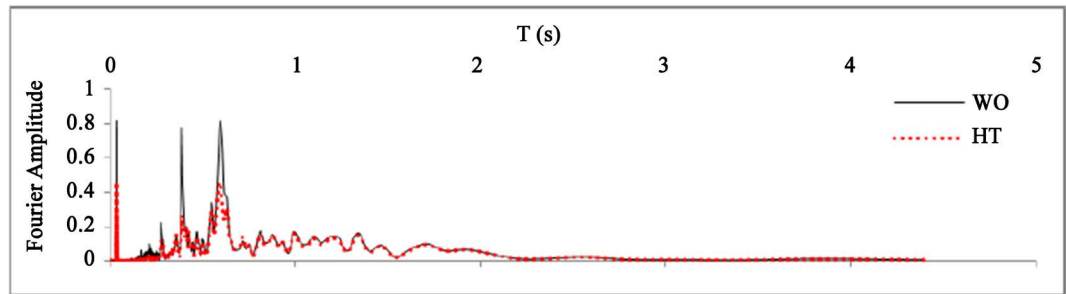

Figure 19. Comparison of Fourier spectra of soil surface acceleration in two states with and without tunnel for San-Fernando earthquake.
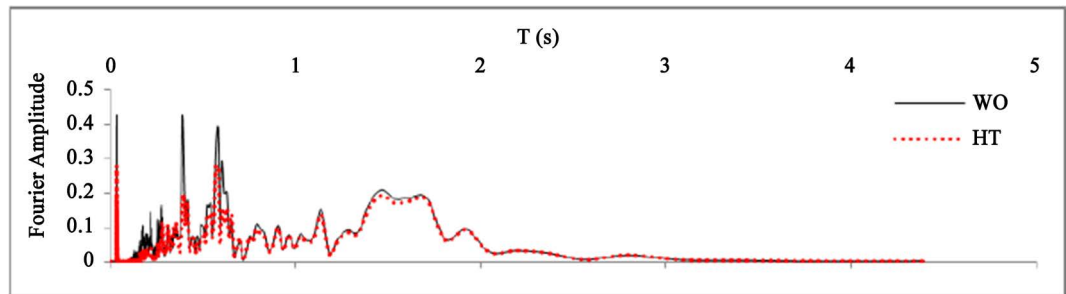

Figure 20. Comparison of Fourier spectra of soil surface acceleration in two states with and without tunnel for San-Luis earthquake.
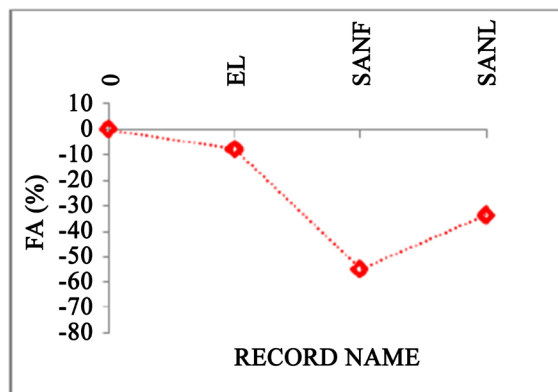

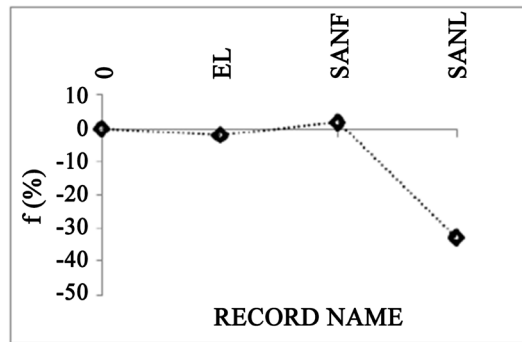**Figure 21.** Dominant frequency change for different earthquake records.

Figure 22. Maximum variation percentage of Fourier spectrum amplitude.

Figure 22 shows the percentage of dominant frequency changes in two modes with and without a tunnel. In the El-Centro and San-Luis Earthquakes, the dominant frequency decreases. But in the San-Fernando earthquake, the dominant frequency grows.

Then, the value of **f** is obtained from Equation (5); in which f_T is the dominant frequency for the first condition (with tunnel), and f_{WT} is the dominant frequency for the 2nd condition (non-tunneled state). The positive part of the vertical axis shows an increase in the percentage of maximum acceleration time and the negative part shows a decrease in the percentage of maximum acceleration time.

$$FA = \frac{FA_T - FA_{WT}}{FA_{WT}} * 100 \tag{4}$$

$$f = \frac{f_T - f_{WT}}{f_{WT}} * 100 \tag{5}$$

4. Conclusions

In this study, by applying actual earthquake records on the bottom of soil mass in two cases with and without horseshoe tunnel, earthquake record at the ground level was extracted by PLAXIS software and record characteristics such as acceleration, response spectrum, the effective duration of ground motion and Fourier spectrum in the SeismoSignal software were evaluated. Finally, the following results were obtained:

1) Drilling horseshoe tunnels have a straightforward effect on earthquake acceleration at ground level thus maximum acceleration has been mitigated in all three earthquake records: meanwhile, the time of maximum earthquake acceleration due to the type of earthquake record is affected by the tunnel excavation.

2) Structural response spectra for two states differ so that in the case of horseshoe tunneling, the spectrum of response is reduced relative to non-tunneling conditions.

3) By digging tunnels, the significant duration of the earthquake record will also be affected. Depending on the record type, this parameter may increase or decrease or remain unchanged.

4) The Fourier spectrum will also be affected by tunnel excavations. If the tunnel is dug, the maximum amplitude of the Fourier spectrum of the record is reduced and its dominant frequency variations will vary with kind of the record.

Generally, it can be stated that assuming soil and tunnel characteristics are constant, tunnel excavation will alter the earthquake record profile at the soil surface, but the magnitude of these changes is directly related to earthquake records. By selecting each record, different responses can be extracted from other records. Also for the construction of ground surface structures on tunnels or vice versa risk analysis studies are extremely necessary.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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