Effect of tunnel depth on the amplification pattern of environmental vibrations considering the seismic interactions between the tunnel and the surrounding soil: A numerical simulation

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Abstract
The amplitude and frequency of seismic waves caused by an earthquake are modified according to the physical characteristics of the subsurface. Further modification is due to soil - structure kinematic interactions between the subsurface medium and the seismic waves. Analysis of ground motion and subsurface propagation of a seismic wave in the presence of an underground structure needs to include appropriate ground input motion parameters. In order to ensure the protection of important engineering structures, and to prevent environmental damage under earthquake excitation, the dynamic response of the vibrating underground structure needs to be carefully analyzed in terms of wave propagation problems. The aim of this study is to evaluate the effects of the amplification on free field motions, including the underground structure, when considering the tunnel-soil interaction, using numerical tools. The 2-D finite element method was used as a numerical model to determine the magnification effect of seismic excitation with various frequencies, on surface vibration, in the presence of a tunnel structure. Results showed that the presence of underground structure amplified the seismic vibrations on the free field and tunnel, depending on the frequency of the external load and the local soil condition.

Keywords: Earthquake excitation, underground structure, tunnel-soil dynamic interaction, seismic response, FE analysis, tunnel depth, local soil conditions.

Introduction

Seismic waves produced by earthquakes may cause substantial ground motions and stress levels on underground facilities. Previous major earthquake data has shown that if the earthquake load is not taken into consideration in the design stage, the ground and underground structures might be seriously damaged by earthquakes. The Dakai subway station, damaged by the Kobe earthquake in Japan, is important evidence for this claim. In addition, some researchers have found that different tunnels suffer damages at different magnitudes, based on data obtained from the earthquakes of the Kanto, Kita-Mino and Hyogo-ken Nanbu ground motions (Okamoto, 1973; Uenishi & Sakurai 2000; Hashash et al., 2001). Earthquakes are potentially catastrophic to tunnel structures, according to the same studies, though the damage is usually localized. The design of a tunnel structure to mitigate ground instability problems is often possible, however, the cost of construction may be high (Dowding & Rozen 1978; Sharma & Judd 1991; Penzien, 2000). Several researchers have studied the seismic behavior of underground structures, and recent experimental (Chen et al., 2010; Moghadama & Baziar 2016; Guobo et al., 2018) and numerical investigation (Amorosi & Boldini 2009; Sedarat et al., 2009; Besharat et al., 2012; Gomes et al., 2015) confirms that the presence of an underground tunnel can affect wave propagation close to the soil surface.

The effect of the tunnel construction and the presence of underground structures have been examined thoroughly in the past, focusing mainly on the resulting dynamic interaction between surface and underground structures (Datta & El-Akily 1978; Lee, 1979; Dravinski, 1982-1983; Wong et al., 1985; Lee & Karl 1992-1993; Lee et al., 1999). Other researchers (Manoogian & Lee 1996; Surjadinata et al., 2005; Mitra et al., 2007) have analyzed the effect of circular underground structures on the surface ground motion. With rapid progress in complex wave propagation analysis, several numerical analyses of infinite domains have been performed to evaluate the seismic behavior of tunnels and soil-tunnel interactions during earthquakes (Stamos & Beskos 1996; Clouteau et al., 2004; Pakbaz & Yareevand 2005). In relation to the amplification pattern of surface and underground structure, vibrations mainly depend on the dimensionless period and dimensionless depth of the buried circular tunnels (Guobo et al., 2018; Amorosi & Boldini 2009).

Yiouta-Mitra et al. (2007) proposed a numerical tool based on the Finite Difference Method to investigate the effects of various parameters, such as the dimensionless depth, dimensionless distance, dimensionless period and flexibility ratio on surface seismic motion considering a harmonic SV-wave excitation, for a circular tunnel embedded in a viscoelastic half-space. Smerzini et al. (2009) studied the effects of underground cavities on surface earthquake ground motion, taking into account subsurface depth and the frequency content of the excitation. Amplification factors on response spectra were obtained with their study provided an overview of the effects of an underground cavity on surface ground motion during earthquakes. Alielahi et al. (2015) used numerical studies to measure the seismic response of a linear elastic soil region that contained an unlined tunnel linked to the propagating incident SV and P waves in vertical propagation, using the Boundary element method (BEM). As a result of these studies, simple and helpful relationships have been proposed to define seismic microzonation of the areas under the tunnels. The effect of tunnel depth, soil heterogeneity and shape of embedded tunnel on the magnification of free field motions, were also examined experimentally using input motion characteristic (Lanzano et al., 2012).

The Finite Element Method (FEM) is an important tool for examining the effects of such interactions. In the FEM solution approach, a continuous medium is divided into finite elements and individual equations are written for each element. Considering the differential equations governing the problem, finite element formulations can be developed for selected primary unknowns (displacements) and secondary unknowns (stress, strain), which are dependent on the displacements. Several researchers have used this approach to investigate different parameters on the amplification pattern of environmental vibrations. Abdel-Motaal et al. (2006) performed an analysis to show the effect of both tunnel geometry and site conditions on the magnification of the nearby ground free field accelerations, using nonlinear 2-D dynamic FEM. A 2D numerical model was developed by Sica et al. (2014) based on the time domain FEM, to investigate the effect on the surface vibration amplification of cavities located above the soil domain. In their numerical study, they evaluated the amplification pattern of ground motions including the effect of space and the depth of cavities. Hatzigeorgiou & Beskos (2010) used FEM in the time domain to investigate the effects of soil - structure interaction on seismic response of tunnels, assuming inelastic behavior of soil medium. These parametric studies identified and critically discussed the most critical parameters affecting the structural response, and the soil - structure interaction in lined tunnels. Asheghabad & Matinmanesh (2011) made important contributions to understanding the effects of a tunnel on acceleration response and amplification, and excitation frequency of input motion, for a range of sandy soils.

The present work describes a computational simulation of the wave propagation problem, and the effects of tunnel depth, on the acceleration of the free field motions, and the dynamic response of the embedded tunnel based on soil-structure interaction. For this purpose, the non-linear 2D finite element model was developed using a Mohr-Coulomb failure criterion modeling plastic deformations of surrounding soil medium under plane strain condition. In order to evaluate the magnification effect of tunnel depth on free ground and tunnel-depth vibrations, the effect of the local soil conditions and the frequency content of different input motions were considered. The analysis takes account of various local soil conditions with different shear wave velocity, in order to evaluate the seismic behavior of the vibrating tunnel-soil system and its environmental impact. To evaluate the changes in amplification patterns, the first analyses were performed on the free field. These results were then compared with the case where a tunnel structure is present. In the next stage, the numerical tool was used to evaluate the effects of other parameters, such as tunnel depths and soil characteristics. Finally, the numerical outcomes of these countermeasures were evaluated at the planning stage of the seismic response of the system.

Numerical model of the proposed tunnel-soil system

Numerical computations were performed using the two dimensional (2D) finite element Plaxis software package (Brinkgreve et al., 2002) to evaluate the amplification pattern of seismic waves at the ground surface, in the time domain. Moreover, the amplification ratios of the accelerations above and below the tunnel were investigated using this numerical tool. The schematic diagrams of the problem are shown in Figure1, where the geometry consists of a single circular tunnel with diameter (D=10m). The tunnel lining has thickness t = 0.45m, and is made of reinforced concrete, which is surrounded by a homogenous soil layer. Only the depth of the embedded tunnel (h) and lateral distance from the tunnel center (X) are variable parameters in the analysis.

Three types of soil (loose, medium and firm soil conditions), with a Mohr-Coulomb failure criterion, are considered. With this study, many important aspects of the nonlinear soil response associated with different shear wave velocity will evaluated by numerical investigations. The considered material parameters in Finite Element (FE) model for the soils, with various shear wave velocities, are summarized in Table 1.

Figure 1. Schematic geometry of the considered tunnel-soil system. Source: Author.

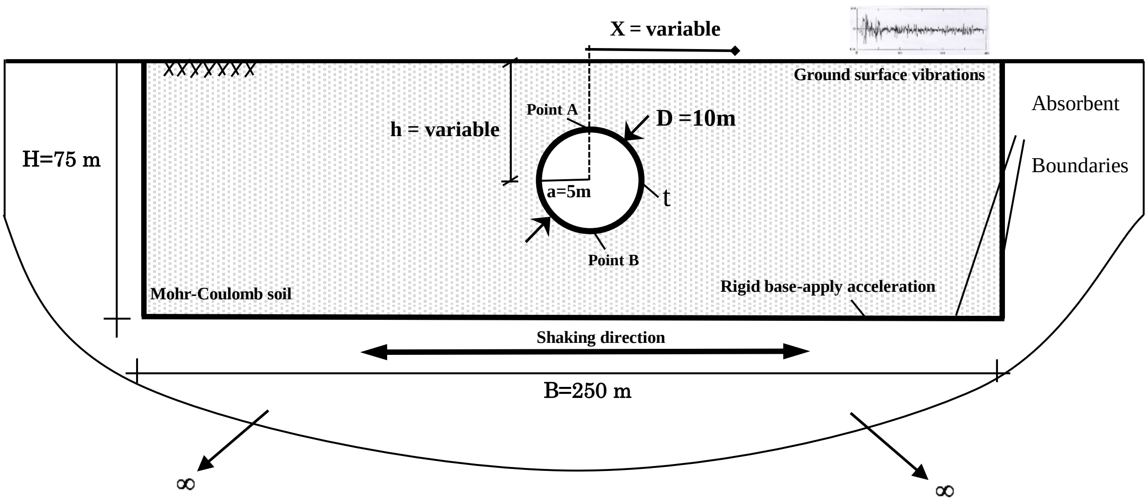


Table 1. Values of the Soil Properties Used for the Different Types of Soil (Çelebi et. al., 2012)

Soil type	Total unit weight (kN/m^3)	Young's modulus (kPa)	Poisson's Ratio (-)	Friction Angle (º)	Cohesion (kPa)	Shear wave velocity (m/s)	Interface strength reduction factor (-)
Soft Soil	17.00	$3.45x10^4$	0.30	33	0	88.32	0.67
Medium Firm Soil	18.64	$3.61x10^5$	0.30	35	0	270.00	0.67
Firm Soil	20.64	$5.68x10^6$	0.35	38	30	1000.00	0.67

Methodology

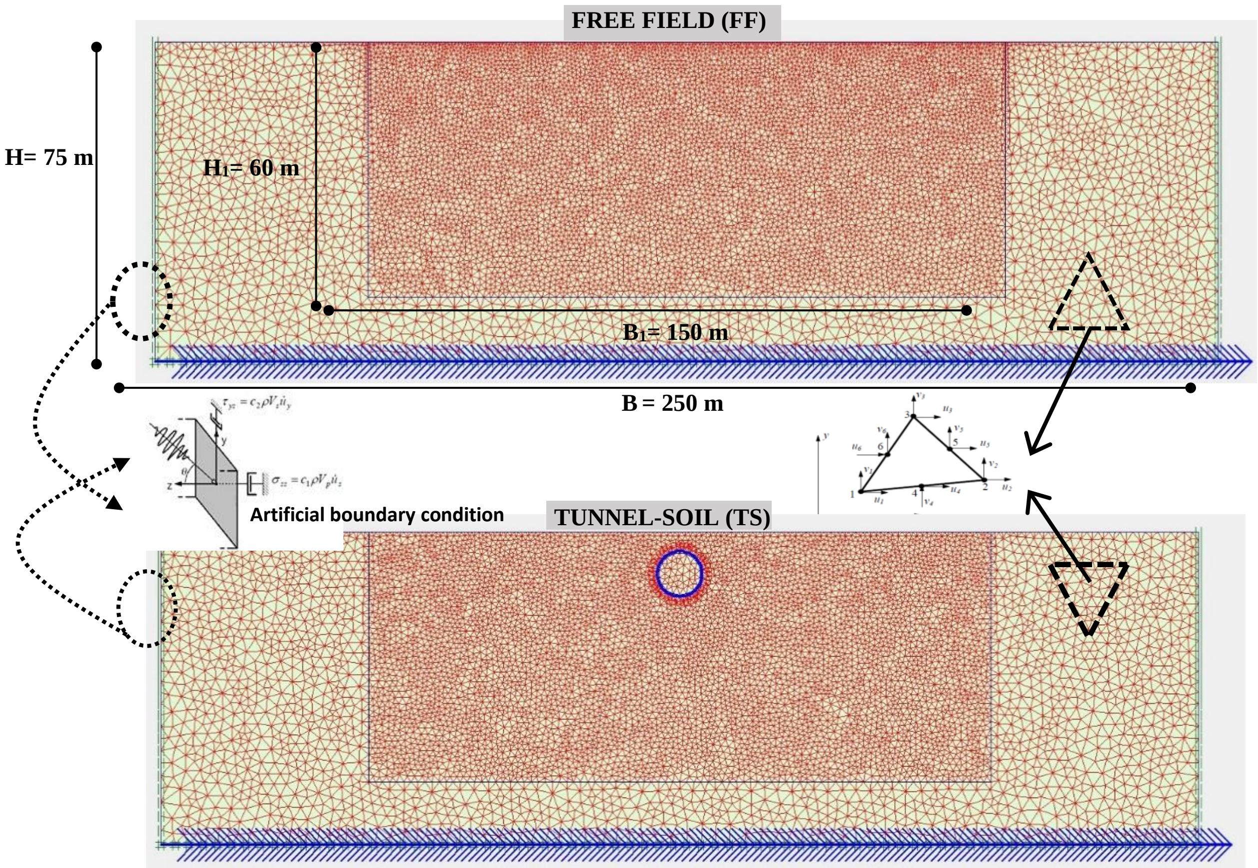
Meshing and validation of the proposed numerical model

The FE domain was discretized in order to simulate a two-dimensional soil - structure coupled system, including the free field (FF) and tunnel-soil (TS), as shown in Figure 2. The effects of lateral extent of the finite soil domain and total soil depth have been explored by other authors, for reliable results of the seismic response at the soil surface (Çelebi et al., 2012). In each computational model, different values of H and B were considered, and the optimal size of the calculation area was estimated as H=75m and B=250m. In order to make the tunnel - soil interaction analysis easier, special boundary conditions, identified as absorbent boundaries, were used throughout the imaginary interface of the infinite soil domain (Lysmer & Kuhlemeyer 1969).

To procure the requested certainty with a reasonable calculation time and memory requirements of the dynamic response of the the soil-structure coupled system, the effect of the discretization size of the proposed soil region, extending to infinite in reality, was analysed bearing in mind that the transmitting boundaries (Lysmer & Kuhlemeyer 1969; Çelebi et. al., 2012). According to the energy absorbing boundaries of Lysmer type (Lysmer et al., 1975), the largest grid space should not be larger than;

$$\Delta h \leq \frac{\lambda_{\min}}{5} = \frac{v_j}{5 f_{maks}} \quad (1)$$

Figure 2. Finite element mesh considered for the FF and TS coupled system. Source: Author.



where v_j is smallest wave velocity of softest soil layer in the numerical model. In compliance with this formulation, the distance of nodes in FE model could be taken around $\Delta h \leq 1.77$m for the SSI system. Thus, the finer FE mesh (*H_1=60m, B_1=150 m*) was used where the plastic deformations were expected to be able to transmit all vibratory wave patterns. This was achieved with the smaller element size ($\Delta h \leq 0.85$m) provided that the major components of the Fourier response spectrum do not exceed one-fifth of the shortest Rayleigh wavelength at the highest frequency. The mesh of the remaining sub-regions (*hereby, H = 75 m, B = 250 m; Δh =1.25 m*) was designed to be relatively coarse, from the above-mentioned distant elements near the lower edge of the localized area, gradually increasing to 1.77 m (the maximum allowable element size in this case) in size. For the numerical analyses, two-dimensional 6-node triangular elements with twelve stress points were used.

The accurate definition of the realistic geometric damping for the local soil condition is important in terms of the overall dynamic response on the soil-structure combined system. The wave transmitting behavior for waves propagating over a single soil layer is characterized by its natural frequencies and eigenmodes. No waves can propagate outward or no vibration eigenmodes can be induced below the cut-off frequency of the soil stratum, which equals V_s (2n-1)/4H for horizontal vibrations, with H denoting the depth of the soil stratum. Rayleigh damping given in the formula below was used to evaluate the viscous damping effects in this study.

$$\boldsymbol{C}=\alpha \boldsymbol{M}+\beta \boldsymbol{K} \tag{2}$$

The damping coefficients α and β are related with the circular frequency of soil as below;

$$\xi_i = \frac{\alpha + \beta\omega_i^2}{2\omega_i} \tag{3}$$

where, ξ is the damping ratio of soil. In addition, the dimensionless relaxation coefficients (c_1 and c_2) were used to improve the wave absorption limits in the computational steps, as suggested by the Plaxis finite element program (Brinkgreve et al., 2002).

Parametric studies and numerical results

A parametrical study was carried out to investigate the effects of tunnel depth on the amplification pattern at different soil conditions. The dynamic source was considered to be related to the frequency content of the input motions. The Kocaeli earthquake in Turkey (Mw =7.4 in 1999) with a frequency content between 0.5-10 Hz, and the lower frequency Upland earthquake (Mw =5.7 in 1990), with a dominant frequency of 3Hz, were considered. The epicentral distance of earthquakes was 5km and 10km for the Upland and Kocaeli excitations, respectively and such earthquakes are described as near field strong ground motions. The 1990 Upland earthquake is a very near ground motion, 5 km away from the epicenter. This earthquake triggered landslides which blocked roads in the Mount Baldy area, and it caused some damage to the San Antonio Dam, which lies across the path of the main watershed coming south from Mount Baldy in California. Thirty-eight people sustained minor injuries, and damage was considerable near the epicenter. This earthquake was a left-lateral strike slip with 4.5 km depth. By examining the frequency content of the Kocaeli earthquake record, it is obvious that this earthquake is a high-frequency ground motion when compared with other input motion considered in analyses. By examining the frequency content of Kocaeli earthquake record, it is obviously that this earthquake is a high-frequency ground motion when compared with other input motion considered in analyses. Moreover, because of its epicentral distance is 10km, this earthquake is defined as a near field ground motion with high-frequency content (Göktepe et al., 2014-2016). In order to adequately simulate the response of soils to cyclic loading conditions, advanced structural material models were used to properly model the dynamic stress-strain behavior of the soil domain. This type of material behaves highly nonlinearly under large amplitude forced vibrations, such as earthquake loading. The Mohr-Coulomb soil model was selected to investigate for numerical analysis the seismic interaction between the tunnel and the surrounding soil subjected to the earthquake loading.

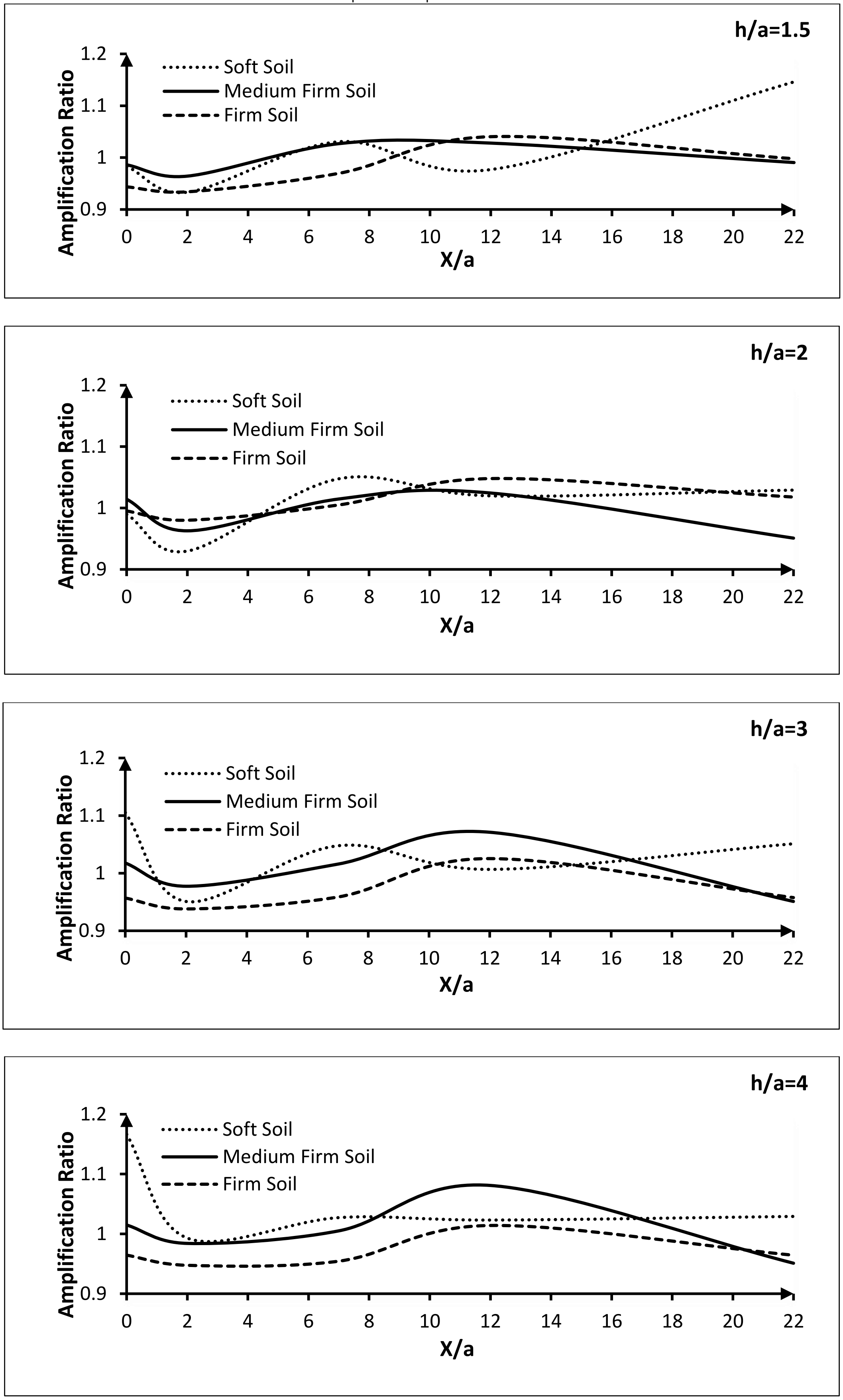
The amplification effect of tunnel depth on free field motions

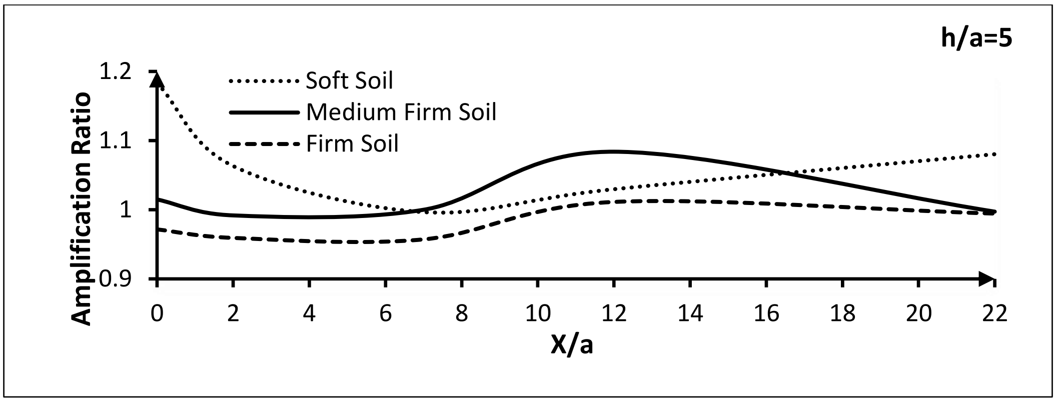
To examine the amplification of free field motions and tunnel vibrations, the tunnel depth was investigated under different soil conditions, using the non-linear finite element method. In the first phase of the study, the Amplification Ratio was identified as the following relationship at any dimensionless distance (X/a), for Peak Ground Acceleration (PGA) on the ground surface. The amplification ratio will be evaluated using the numerical results of the PGA to be obtained for the tunnel structure according to the free field motions. Note that, the dimensionless distance was evaluated with (X/a) where "X" represents the horizontal distance from the center of the tunnel, while "a" indicates the tunnel diameter.

$$Amplification\ Ratio = \frac{PGA\ in\ FEM\ with\ tunnel}{PGA\ in\ \ Free\ Field} \tag{4}$$

Depending on the tunnel depth, the magnification effect on free ground vibrations was evaluated for a tunnel with D = 10 m and t=0.45 m at various dimensionless depths (h/a). For this numerical study, the dimensionless depth was selected as h/a= 1.5, 2, 3, 4 and 5 to evaluate the amplification pattern of free field motions above and below the embedded tunnel. The shallowest tunnel was under 2.5 m of soil while this depth reached 20 m for the deepest tunnel. In order to assess tunnel depth effects on the amplification pattern at the free field motions, the numerical model was performed under two different input motions, namely, 1990 Upland (M_w=5.7) and 1999 Kocaeli (M_w=7.4) earthquakes. For the computational model, elasto-plastic soil layer was assumed to be supported by horizontally extended rigid base rock, therefore, total reflection of the incident waves from this boundary was assumed. To measure the effect of the tunnel depth on the amplification patterns of the ground response, peak values of lateral acceleration were investigated by comparing the results of FF and ST tests, as presented in Figure 3. The magnification effect was plotted against various ratios of dimensionless distance ($0 \leq X/a \leq 22$) for all soil conditions. As seen in Figure 3, the tunnel amplifies the seismic responses at the ground surface (X/a=0) for h/a≥3 under soft soil conditions, for the Upland earthquake. At the deepest depth (h/a = 5) the tunnel had the maximum amplitude ratio with the lowest shear wave velocity. The maximum amplification ratios on lateral acceleration for various dimensionless depth at h/a 1.5, 2, 3, 4 and 5 were estimated as 1.03, 1.04, 1.05, 1.16 and 1.18, respectively. The tunnel was not efficient on free field motions under medium firm and firm soil conditions. The corresponding amplification value was equal to 1 for low frequency motions. Therefore, the impact on the lateral surface accelerations at any dimensionless depth ($1.5 \leq h/a \leq 5$) can be ignored in the seismic design of a tunnel, for the cases of medium firm and firm soils with low-frequency excitation. Note that the h/a ≤ 3 means shallow depth tunnels. Nevertheless, the h/a > 3 was described as 'deep' in previous studies (Baziar et al., 2014).

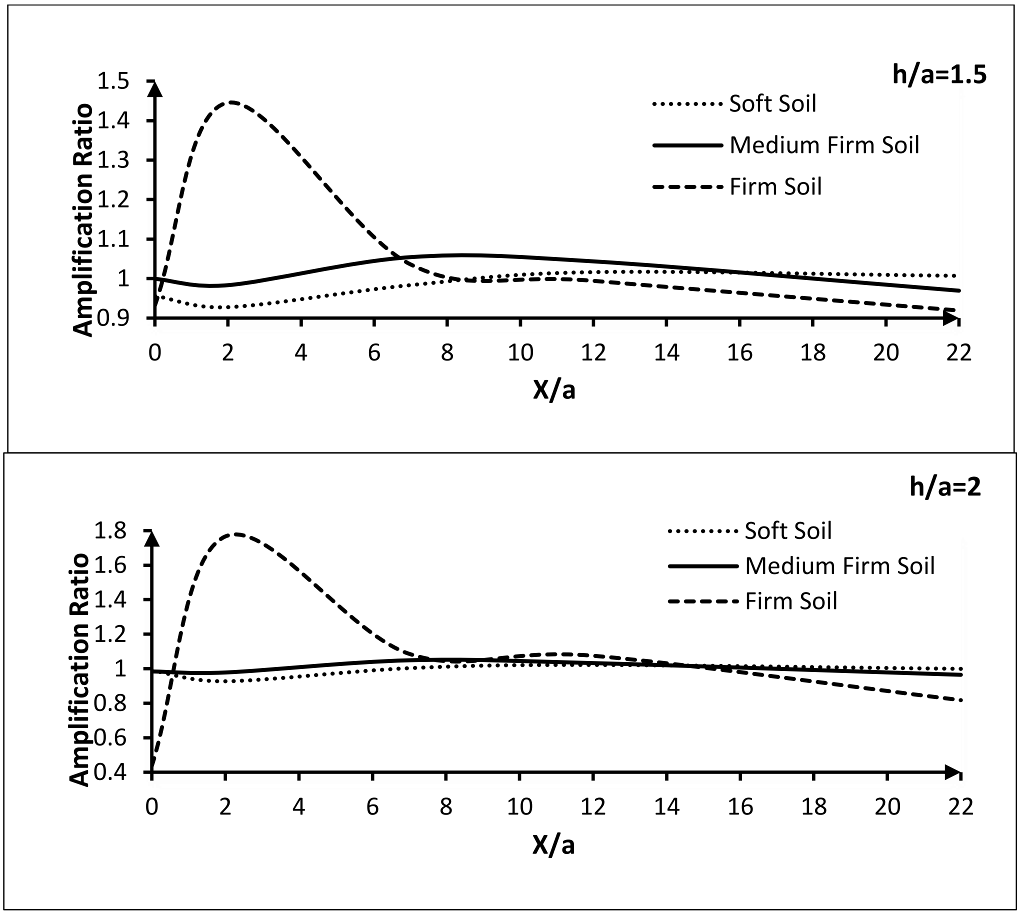
Figure 3. The lateral acceleration amplification effect of tunnel depth (h/a) depending on dimensionless distance (X/a) at the free field motions under different soil conditions for Upland earthquake. Source: Author.

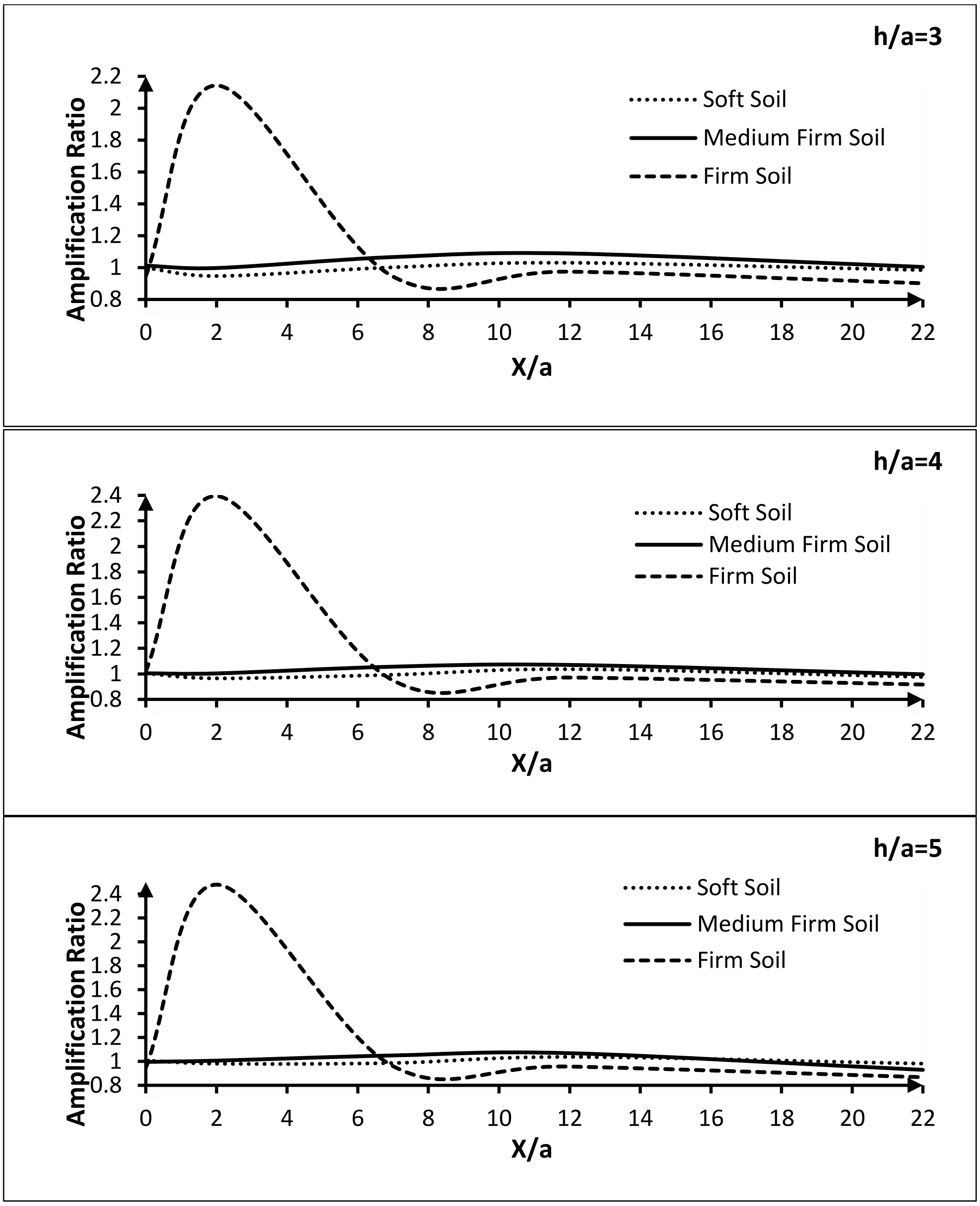




The plots of amplification patterns on the ground response, referenced to the peak values of lateral acceleration under different soil conditions, and taking account of tunnel depths, were compared to Kocaeli input motion, as given in Figure 4. From the obtained results, the influence of a tunnel on the amplification pattern was considerable in the case of firm soil, with V_s=1000 m/s for all depths. The maximum amplification ratio occurred at greatest depth (h/a=5) with highest shear wave velocity when compared with tunnel depth condition.

Figure 4. The lateral acceleration amplification effect of tunnel depth (h/a) depending on dimensionless distance (X/a) at the free field motions under different soil conditions for Kocaeli earthquake. Source: Author



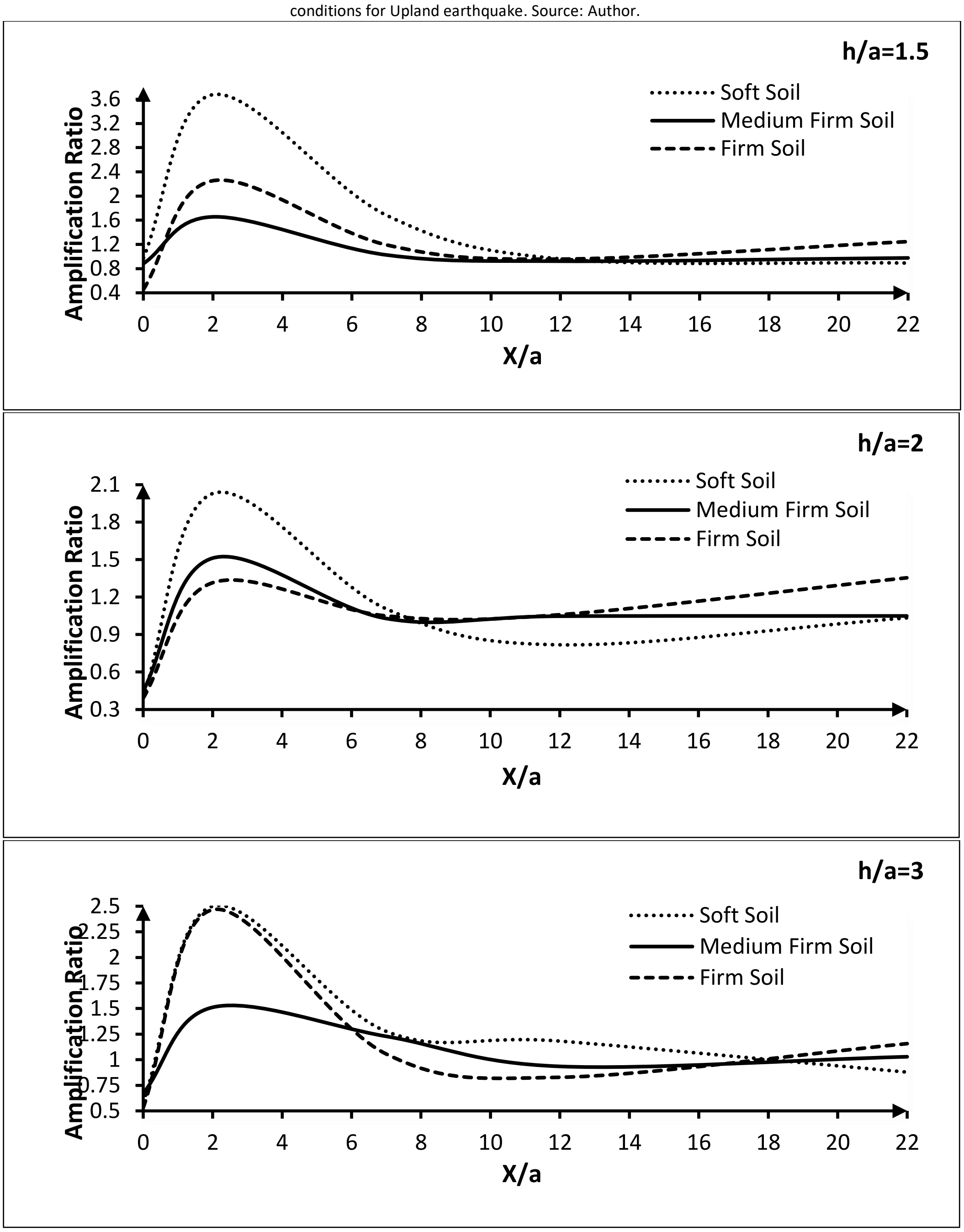


The maximum amplification ratios for lateral acceleration at various dimensionless depths, h/a 1.5, 2, 3, 4 and 5, were estimated as 1.45, 1.77, 2.14, 2.39 and 2.48, respectively, for ground surface motions at X/a=2. Thus, as the tunnel depth increased, the amplification rate at the ground surface increased for firm soil conditions. However, no significant change was observed for soft and medium firm soil conditions for the Kocaeli earthquake (Figure 4).

The other amplification patterns of the ground response, i.e. those related to the peak values of vertical acceleration under different soil conditions and taking account of the tunnel depth, were compared to Upland and Kocaeli input motion, as given in Figures 5 and 6. From these figures the maximum amplification was found to occur at h/a=1.5 for the soft soil condition for upland earthquake, whereas tunnel depth of h/a=5 had the maximum magnification ratio on firm soil, for the Kocaeli earthquake. The impact of dimensionless depth on the magnification pattern of surface vibrations was considerable at X/a=2 for all soil conditions under upland earthquake motion, according to Figure 5. The maximum vertical acceleration amplification ratio for the tunnel at shallowest depth, under soft soil condition, was 3.67 in respect to the low frequency seismic motion. The other amplification ratios for h/a = 2, 3, 4 and 5 were estimated at 2.02, 2.5, 2.29 and 2.06, respectively, on the free field motions for X/a=2. However, the ratio obtained for greatest tunnel depth had a considerable effect on free field motion. Nevertheless, the maximum ground response, in terms of peak values of vertical acceleration, were amplifications of 1.68 times and 2.47 times for tunnel parameters h/a=4 and X/a=2 under medium firm soil and firm soil, respectively, considering Upland seismic motion.

In contrast to the above-mentioned amplification of the ground motion for proposed tunnel-soil interaction system, for soft soil conditions the tunnel depth variable was found to have no significant amplifying effect on peak values of vertical acceleration for the Kocaeli earthquake. However, the presence of a tunnel influenced the vertical acceleration amplitude and amplified the surface response for firm soil with high shear velocity, for high frequency seismic motions. For firm soil conditions, the amplification rate increased for X/a=2 depending on the depth of the tunnel. Note that similar amplification patterns of lateral and vertical acceleration occurred at X/a=2 on firm soil under Kocaeli seismic motion. Furthermore, the tunnel at h/a=1.5 amplified the ground response 1.5 times at X/a=0 for medium firm soil. The maximum amplification ratio occurred for the dimensionless depth (h/a=2) at X/a=2 on medium firm soil (Figure 6). The obtained numerical results for the lateral and vertical acceleration show that the frequency content of the tunnel-soil system and seismic ground motion have a profound effect on the amplification pattern for free field motions.

Figure 5. The vertical acceleration amplification effect of tunnel depth (h/a) depending on dimensionless distance (X/a) at the free field motions under different soil conditions for Upland earthquake. Source: Author.



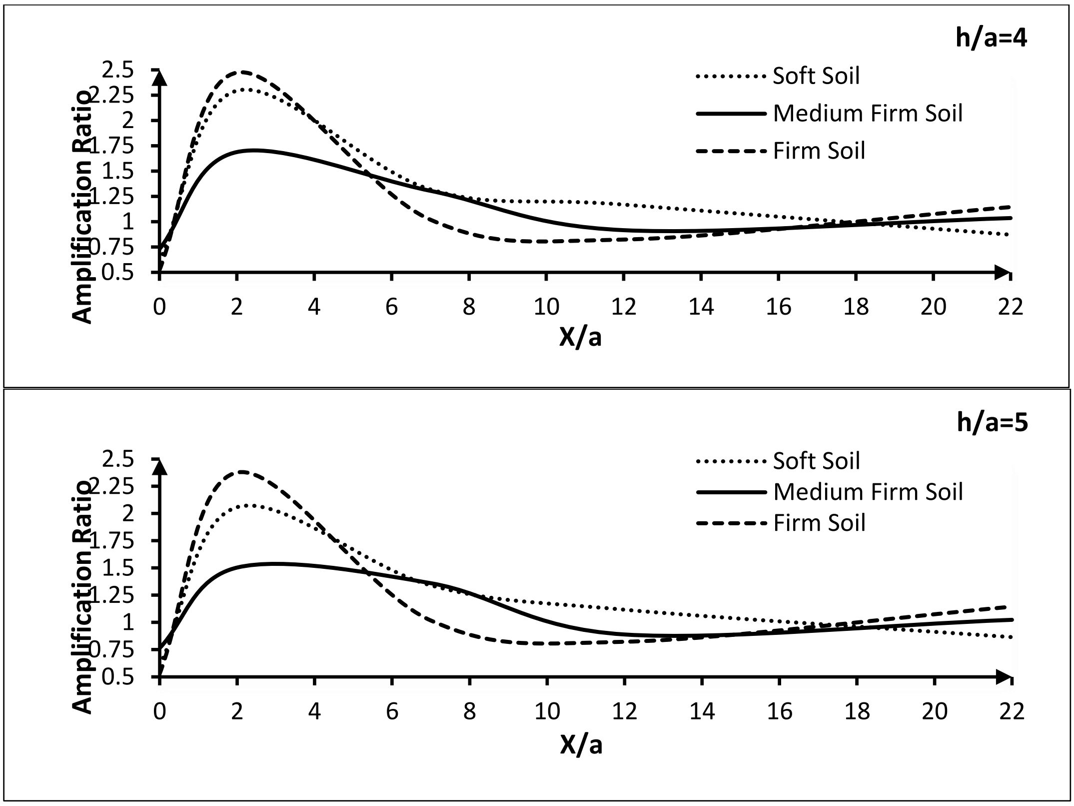
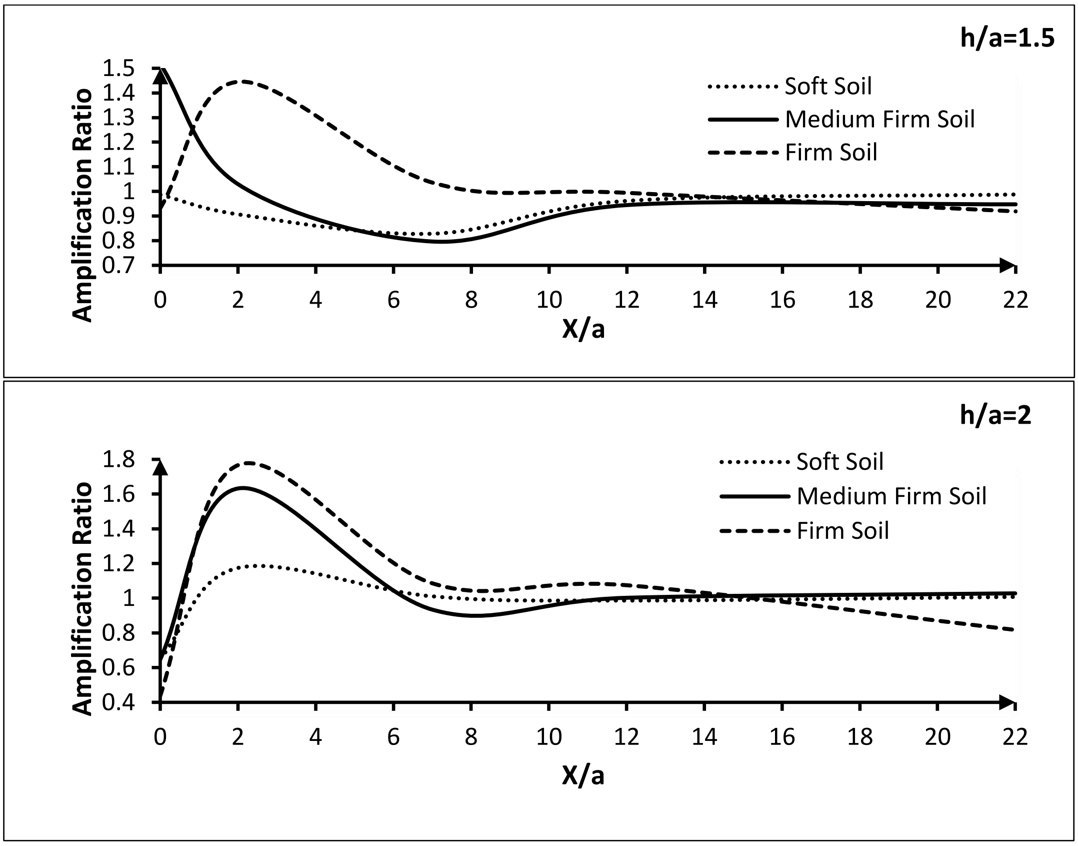
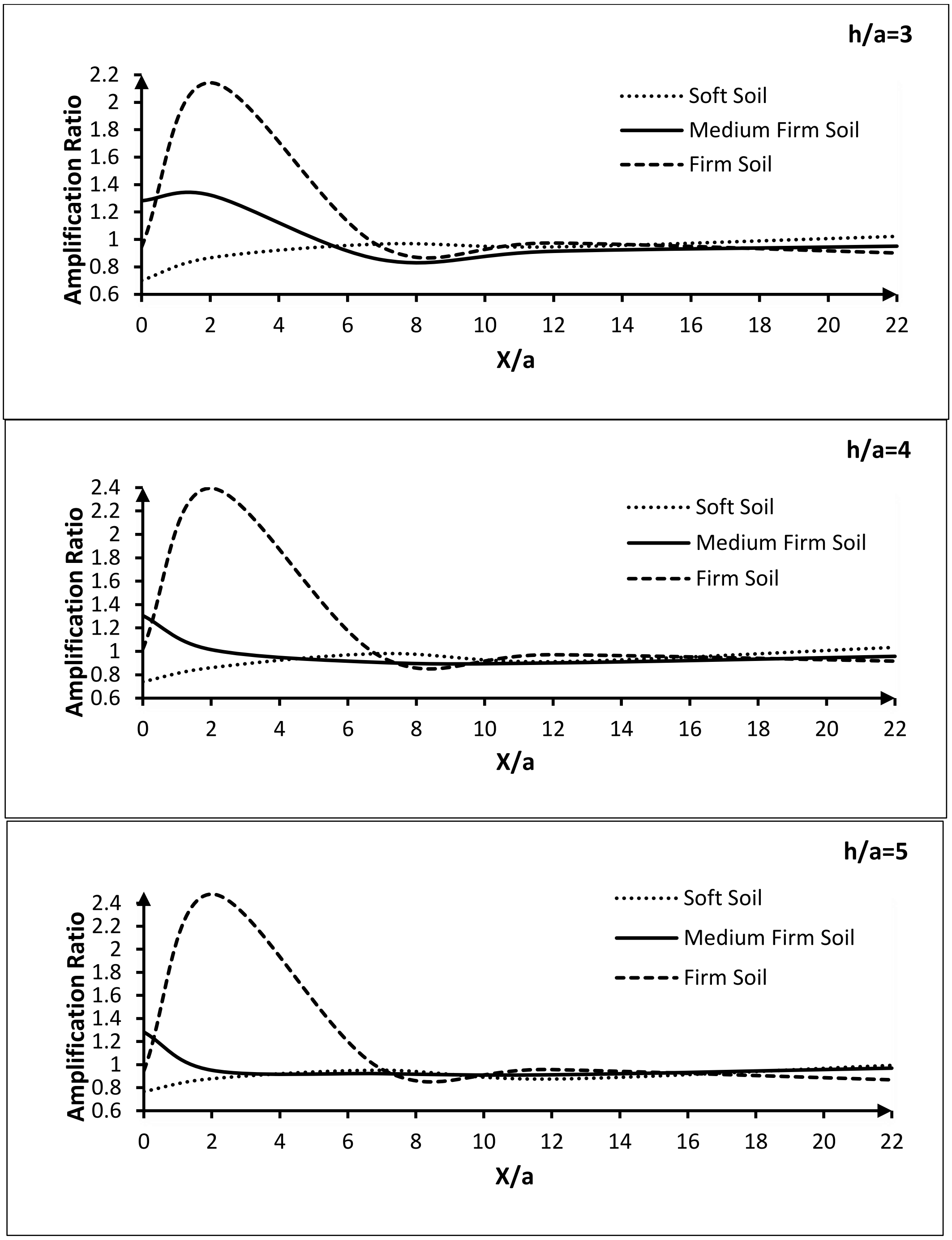


Figure 6. The vertical acceleration amplification effect of tunnel depth (h/a) depending on dimensionless distance (X/a) at the free field motions under different soil conditions for Kocaeli earthquake. Source: Author.





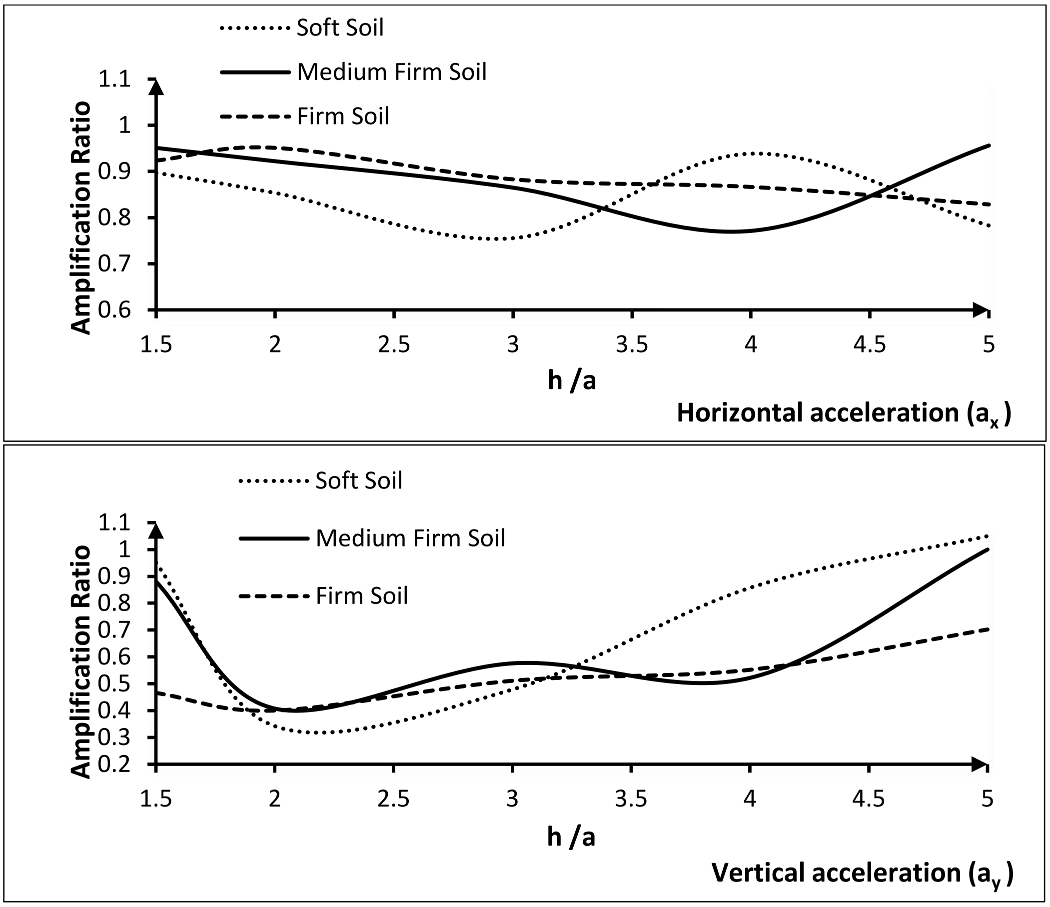
The amplification effect of tunnel structure on related depth vibrations

The amplification effect of tunnel structure on related deep vibrations for various tunnel depths under the different rigidity of soils, are examined in this section. The above equation was modified as follows to evaluate the amplification ratio of the accelerations at the upper point or bottom point of the tunnel due to dimensionless depth (h/a) variations, considering the soils with different shear wave velocity. The magnification rate in this section is defined by the ratio of the PGA measured at the upper and bottom points of the tunnel to the numerical results to be calculated in the absence of the tunnel.

$$Amplification\ Ratio = \frac{PGA\ at\ top\ or\ bottom\ point\ of\ the\ tunnel}{PGA\ at\ equivalent\ depth\ in\ the\ case\ of\ no\ tunnel} \quad (5)$$

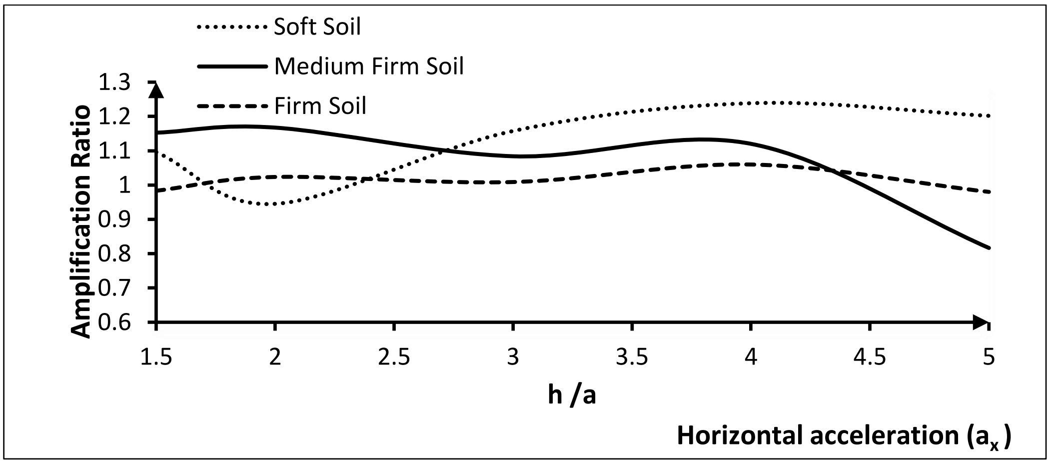
The resulting amplification ratio of the horizontal and vertical accelerations on the upper point (Point A) and bottom of the tunnel (Point B) under different soil conditions for various tunnel depths, for Upland earthquake, are plotted in Figures 7 and 8, respectively.

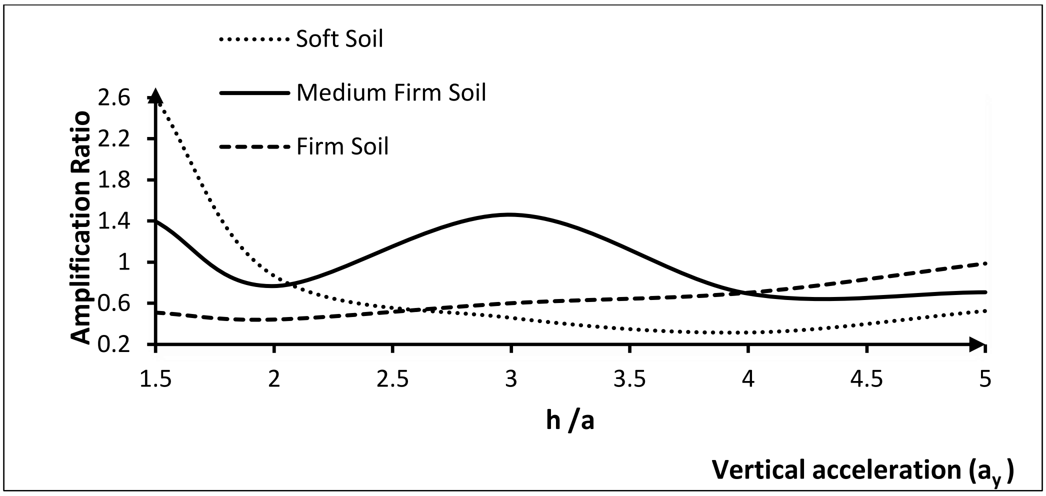
Figure 7. Variation of the horizontal and vertical amplification pattern under consideration the tunnel depth at the above of tunnel structure depending on different local soil conditions for Upland earthquake. Source: Author.



The analyses performed here show that the tunnel depth had no effect on the horizontal and vertical accelerations at the upper level of the tunnel. However, the existence of a tunnel at different depths was associated with amplification of the horizontal and vertical vibrations at the bottom of the tunnel under conditions of loose and medium firm soils. The maximum amplification value was 2.6, obtained for vertical accelerations at the bottom of the tunnel, under soft soil conditions, with V_s=80 m/s for h/a=1.5. Apart from this, the influence of the dimensionless depth on the magnification pattern at the bottom of the tunnel was considerable for the medium firm soil at similar depths (Figures 7, 8).

Figure 8. Variation of the horizontal and vertical amplification pattern under consideration the tunnel depth at the below of the tunnel structure depending on different local soil conditions for Upland earthquake. Source: Author.





The amplification ratio of the horizontal and vertical accelerations at the upper point (Point A) and bottom of the tunnel (Point B) is given in Figures 9 and 10 for all soil conditions, for high frequency seismic motions. Unlike the above mentioned excitation, the amplification effect on vertical accelerations at the upper level of the tunnel was considerable for h/a=1.5, for the case of medium firm soil conditions. Furthermore, the maximum amplification of 1.65 was obtained for vertical vibrations for the similar soil conditions at bottom of the tunnel. For each maximum, amplifications obtained on tunnel vibrations for related depths varied, not only with regard to soil conditions and variable shear velocity waves, but also to earthquake input motion with different frequency contents.

Figure 9. Variation of the horizontal and vertical amplification pattern under consideration the tunnel depth at the above of tunnel structure depending on different local soil conditions for Kocaeli earthquake. Source: Author.

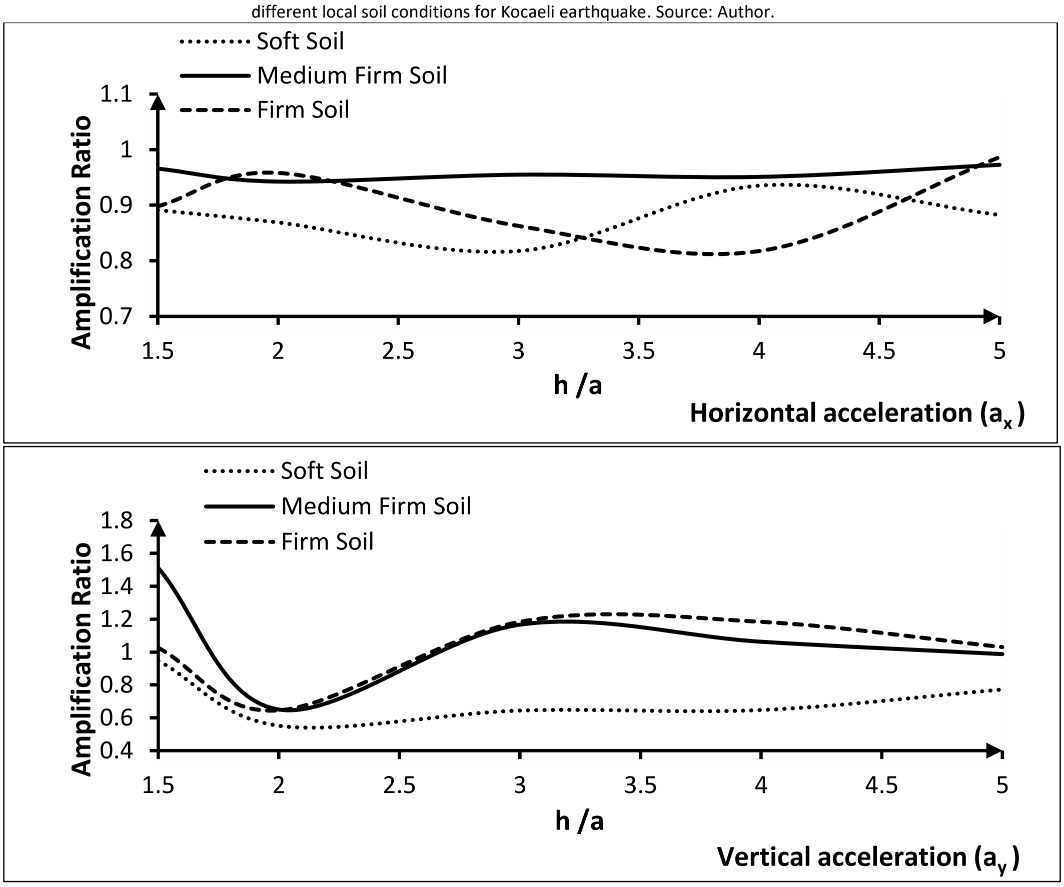
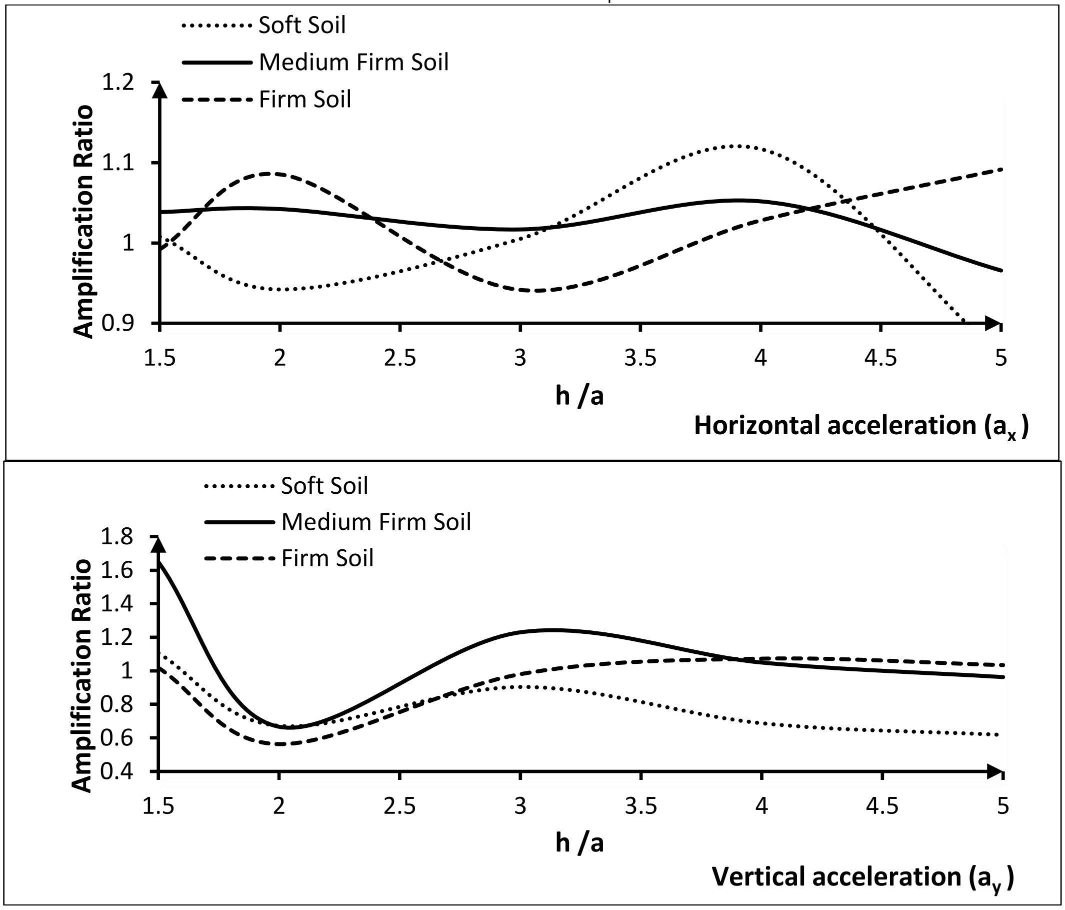


Figure 10. Variation of the horizontal and vertical amplification pattern under consideration the tunnel depth at the below of tunnel structure depending on different local soil conditions for Kocaeli earthquake. Source: Author.



Discussion and Conclusions

In this study, the magnification effects of a tunnel with circular cross-section on the free field motions were investigated by a numerical model, in which the nonlinear behavior and infinity of the soil are appropriately defined. In addition, the magnification effects at corresponding depth in the soil environment were evaluated in the presence and absence of a tunnel. All numerical analyses were performed to assess the seismic behavior of tunnel-soil coupled system, within a variable soil medium, for various shear wave velocities and frequency contents of the earthquakes. The waves formed in the elastic-plastic soils resulting from the propagation of strong ground motions, with different frequency content, can experience magnification effects not only on surface vibrations but also in underground structures.

The magnification ratio for the vibrations on the free ground surface was obtained for a dimensionless distance depending on the dimensionless depth. Results showed that the amplification ratio of the lateral acceleration was considerable at the tunnel center on the ground surface, for the deepest tunnels, under soft soil conditions, for the Upland earthquake. Moreover, the peak amplification ratio reached 2.48 in the case of firm soil, for the 1999 Kocaeli earthquake input motion. No significant impact could be obtained on firm soil condition for the 1990 Upland earthquake. The maximum amplification ratio was 3.67 at the distance (X/a=2) with minimum shear wave velocity, for the shallowest tunnel, under Upland earthquake. It can be concluded that the sudden increase in dynamic response is more prominent for reflection, scattering and diffraction of vibration energy for the shadow zone, when the tunnel amplifies the responses for the free field. Nevertheless, the constant obtained for similar effect is considerable for the h/a=2 at the same location on ground surface with highest shear wave velocity, when the frequency content is between 0-10 Hz. The conclusions of this study show that the vibration frequency of the external load and the shear wave velocity of the soil environment are important factors in the magnification of free field motions.

In the second stage of this numerical study, the magnification effects of the tunnel structure at the upper and bottom points of the tunnel were investigated, for different dimensionless tunnel depths. For this stage of the study, various local soil conditions ranging from 88.32 m/sn to 1000 m/sn and seismic input motions (1990 Upland and 1999 Kocaeli earthquakes) with different frequency contents were used to evaluate the structural vibrations of the tunnel. The maximum amplification ratio values of 2.6 were obtained at the shallowest depth for the vertical accelerations at the bottom point of the tunnel, under soft soil conditions, for the Upland earthquake. Nevertheless, the magnification pattern is considerably affected by dimensionless depth at the bottom point of tunnel for the loose and medium firm soils. Magnification of the horizontal and vertical acceleration at the upper level of the tunnel is not evident for the Upland seismic motion. Unlike the above mentioned excitation, the amplification effect on vertical accelerations at the upper level of the tunnel is considerable for shallowest depths in case of the medium firm soil conditions. It is understood from the numerical results that the structural behavior in the tunnel depends on local soil conditions, as well as the frequency content of the input motions. It can be concluded that the reflection and refraction of earthquake waves with different frequencies located in different soil conditions affect the vibrations above and below the tunnel significantly. Moreover, it has been understood that magnification effects are effective not only on surface vibrations but also in underground structures.

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