

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

EFFECT OF THE SHALLOW LINED TUNNELS
ON THE SOFT SOIL AMPLIFICATION

ASLI NUR KARAHAN

A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF CIVIL ENGINEERING

ADVISOR: ASSIST. PROF. DR. HADI KHANBABAZADEH

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ASLI NUR KARAHAN

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İNŞAAT MÜHENDİSLİĞİ ANABİLİM DALI

DANIŞMAN: DR. ÖĞR. ÜYESİ HADI KHANBABAZADEH

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JURY

MEMBER

(THESIS ADVISOR) : Dr. Öğr. Üyesi. Hadi KHANBABAZADEH

MEMBER

: Prof. Dr. Selçuk TOPRAK

MEMBER

: Dr. Öğr. Üyesi. Cem YENİDOĞAN

APPROVAL

Gebze Technical University Graduate Administration Board
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ABSTRACT

Under the effect of strong ground motions, surface damage is greatly affected by local site conditions. The local site conditions affect seismic waves' amplitude, frequency and duration parameters. The term soil amplification refers to increase in amplitudes of seismic waves when seismic waves pass close to the ground surface. The local site effect and a lot of coefficients are generally used for earthquake structural design in regulations. In urbanized areas, the change in site amplification and deamplification values due to the presence of underground irregularities such as tunnels is important for structural design features. In this case, including a limited ratio of the local site effect is insufficient. The effect of underground tunnels on earthquake frequency content should also be considered. The aim of this study is to investigate effect of dynamic behavior of the single and twin tunnels in soft clay soil on site amplification ratio. The dynamic behavior of tunnels is affected by various parameters, such as soil characteristics, burial depth of tunnel, interaction between twin tunnels and tunnel cross-section. Dynamic analyses will be performed to investigate the effect of different tunnel burial depths, tunnel cross-sections, motion intensities and interaction between twin tunnels on site amplification ratios. The two-dimensional (2D) dynamic analyses will be performed using Fast Lagrangian Analysis of Continua in Three Dimensions (FLAC3D) code, which uses the Lagrangian finite difference method. Acceleration-time histories, which are obtained from strong ground motion records, will be used to obtain acceleration response spectra. After that, the site amplification ratios will be obtained using the acceleration response spectra. Six different surface points will be used to present the understandable results and investigate the effect of position from the tunnel axis. Furthermore, spectral amplification ratios will be studied to investigate the effect of the underground tunnels in the time domain for each surface point. According to the results of dynamic analysis, it was observed that the maximum amplification ratios occur at lower periods, and the periods of site amplification ratio increase with increasing earthquake intensities for both burial depths. The results showed that the site amplification ratios are less under the effect of stronger motions compared to the effect of weaker motions with PGA of 0.1g. This result can be explained by the fact that the effect of weaker motion with PGA of 0.1g causes non-linear soil behaviour and earthquake energy is more effective under conditions of the model. It was observed that twin tunnels produce greater site amplification ratios than single tunnels.

Keywords: Site Amplification Ratio, Soft Clay Soil, Nonlinear Analysis of Site Response, Shallow Burial Depth, Circular and Square Cross-Section

ÖZET

Güçlü depremlere maruz kalan alanlarda yüzeyde oluşacak hasar yerel zemin koşulları ile bağlantılıdır. Sismik dalganın genliği, frekansı ve zamanı yerel zemin koşullarından etkilenir. Sismik dalgaların genliklerinde yüzeye yakın alanlardan geçerken bir artış olması durumu zemin büyütmesi olarak adlandırılır. Depreme dayanıklı bina tasarımı için yönetmeliklerde genel olarak zemin büyütmesi ve birçok katsayı kullanılır. Şehir ortamında, tüneller gibi yeraltı düzensizliklerinin varlığı nedeniyle oluşan ve düzensizliğin konumuna göre değişen zemin büyütmesi değerleri depreme dayanıklı bina tasarımı için oldukça önemlidir. Bu durumda yerel zemin etkisinin belirli bir oranda hesaplamalara katılması yeterli değildir. Aynı zamanda, yeraltı tünelinin varlığının deprem frekans içeriği üzerinde oluşturduğu değişimin etkisi de dikkate alınmalıdır. Bu çalışmanın amacı, yumuşak kil zeminde bulunan tek ve ikiz tünellerin dinamik davranışının zemin büyütme oranları üzerinde oluşturduğu etkilerin incelenmesidir. Güçlü depremlere maruz kalan tünellerin dinamik davranışı bulundukları bölgenin zemin özellikleri, tünellerin gömülme derinliği, ikiz tüneller arasındaki etkileşim ve tünel kesiti gibi parametrelerden etkilenmektedir. Bu nedenle idealize edilmiş tünellerin farklı sığ gömülme derinlikleri, tünel kesitleri, farklı pik zemin ivme değerlerine sahip deprem hareketleri altında nasıl davrandıkları ve ikiz tüneller arasındaki etkileşimin zemin büyütme oranları üzerindeki etkisini araştırmak için dinamik analizler gerçekleştirilmiştir. Lagrangian sonlu fark yöntemini kullanan FLAC3D kodu ile modellerin iki boyutlu dinamik analizleri gerçekleştirilmiştir. Analizlerde güçlü deprem hareketlerinden elde edilen ivme-zaman kayıtları kullanılarak ivme tepki spektrumları elde edilmiştir. Daha sonra ivme tepki spektrumları kullanılarak model yüzeyindeki noktalarda meydana gelen zemin büyütme oranları elde edilmiştir. İdealleştirilmiş modellerdeki tünel ekseninden uzaklığa göre değişen maksimum zemin büyütme oranlarını daha anlaşılır yapmak için altı farklı yüzey noktası kullanılmıştır. Ayrıca her yüzey noktası için zaman tanım alanında spektral zemin büyütme oranlarının değişimi incelenmiştir. Elde edilen sonuçlara göre yüzeyde bulunan noktaların düşük periyotlara karşı duyarlı oldukları tespit edilmiştir. Anakaya hareketinin kuvvetinin artmasıyla zemin büyütme oranlarının periyodunun arttığı görülmüştür. En büyük zemin büyütme oranları 0.1g deprem kuvveti altında elde edilmiştir. Bu durum, model koşulları altında daha zayıf deprem hareketlerinin zeminin doğrusal olmayan davranışına neden olmasıyla açıklanabilir. Modellere uygulanan deprem kuvvetinin artmasıyla elde edilen maksimum zemin büyütme oranlarının arttığı tespit edilmiştir. İkiz tünellerin oluşturduğu zemin büyütme oranlarının, tek tünellerin oluşturduğu zemin büyütme oranlarından daha fazla olduğu elde edilmiştir.

Anahtar Kelimeler: Zemin Büyütme Oranı, Yumuşak Kil Zemin, Doğrusal Olmayan Analiz, Sığ Gömülme Derinliği, Dairesel ve Kare Kesitli Tünel

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LIST OF SYMBOLS AND ABBREVIATIONS

1D	One-Dimensional
2D	Two-Dimensional
3D	Three-Dimensional
c	Cohesion
ϕ	Internal Friction Angle
γ	Unit Weight
BEM	Boundary Element Method
D	Damping Ratio
FAS	Fourier Amplitude Spectrum
FDM	Finite Difference Method
FE	Finite Element
FEM	Finite Element Method
FLAC2D	Fast Lagrangian Analysis of Continua in Two Dimensions
FLAC3D	Fast Lagrangian Analysis of Continua in Three Dimensions
G	Shear Modulus
Hz	Hertz
IIEES	International Institute of Earthquake Engineering and Seismology
K	Bulk Modulus
KOERI	Kandilli Observatory and Earthquake Research Institute
P	Primary Wave
PEER	Pacific Earthquake Engineering Research Center
PGA	Peak Ground Acceleration
R_{jb}	Joyner-Boore Distance
SAMBE	Seismic Analysis of Multiple Boundary Element
SH	Horizontal Plane Movement
SV	Vertical Plane Movement
V_s	Shear Wave Velocity

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1. INTRODUCTION

In recent years, the population of urbanized areas has increased rapidly. Population growth in urbanized areas causes problems with transportation and environmental pollution that directly affect the quality of life. To solve these problems, underground transportation or infrastructure systems are necessary. The presence of underground tunnels or different shapes of underground irregularities exhibits complex behavior compared to free field motion during dynamic behavior, which depends on the local geological conditions of site, earthquake characteristics, and faulting mechanics. The complex behavior causes damage due to soil amplification on the surface. Researchers have investigated the response of underground irregularities such as tunnels and subways during seismic loading. Most numerical results show that underground irregularities cause significant damage on the ground surface during seismic loading.

1.1. Aim of the Study

Shallower tunnels are vital for underground transportation in metropolises. Tunnels generate soil amplification as a result of different parameters, such as cross-sections of tunnels and different burial depths of tunnels during seismic loading. This subject has been investigated using different parameters in many studies, and results show an important effect on the ground surface. The aims of this study are to investigate the effect of different tunnel cross-sections, which are circle and square cross-sections, different shallow burial depths of tunnels, and the interaction between twin tunnels subjected to strong ground motions on soil amplification. To achieve these aims, idealized tunnel models were analyzed under dynamic loads. Soft clay soil was chosen as the material characteristic of the idealized models.

1.2. Literature Review

Researchers have used analytical, semi-analytical, and numerical methods to investigate soil amplification caused by underground irregularities such as tunnels.

Analytical methods are limited to the solution of underground irregularities with regular and simple geometry. Moreover, complex equations used in analytical methods usually allow the solution of SH wave scattering and diffraction. Shaking table tests provide highly accurate results, although size of model is limited. The numerical methods are developed to investigate the local site effect according to the requirements of problem, which include one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) modeling.

The pioneering studies about scattering and diffraction waves by underground irregularities date back to the late 1970s. The study by Datta and El-Akily (1978) can be considered as one of the pioneering studies. They studied the diffraction of 2D elastic waves using an underground cylindrical cavity. The solution was realized in three sections. In the first section, the integral representation of asymptotic behavior of scattered displacement as a result of the impact of any incident wave on the underground cylindrical cavity was derived. In the second section, the integral representation and a matched asymptotic expansion approach were used to obtain scattering field on the model. In the last section, a numerical study was carried out to determine the ground surface motions of the cylindrical cavity subjected to Rayleigh wave with changing burial depth. The results showed that normalized displacements are affected by different burial depths of the cavity. The technique can be applied for other shapes of underground irregularities [1].

Crichlow (1982) investigated the ground surface response to vertically incident SH waves in the presence of various shapes of underground irregularities, such as cylindrical or rectangular anomalies. 2D FE (finite element) modelling was used in this study. Some conclusions were obtained by analyzing the response of the underground anomalies to the SH waves, considering parameters such as the shape, size, depth, and location of the anomalies. Eight numerical models with different diameters and burial depths were examined. A comparison was made between the response of cases, which were free-field and the presence of underground irregularities. Power spectral ratios were studied for parameters such as burial depth and shape of the anomaly. The diameter or vertical length of the structure/wavelength ratio was calculated for location of the anomaly. The results showed that response of cylindrical and rectangular anomalies produces more displacement [2].

Datta and Shah (1982) studied the scattering of plane SH waves and displacement caused by underground irregularities. To obtain surface motions, two solution methods were used: first method was a method of matched asymptotic expansion when wavelength was longer than underground irregularities diameter, and second method was a combined FE and analytical technique when wavelength was long to intermediate wavelength range. **Figure 1.1** shows that contour C defines the underground irregularity at a depth h from the ground surface. The cavity is enclosed by circle B and radius of circle is b .

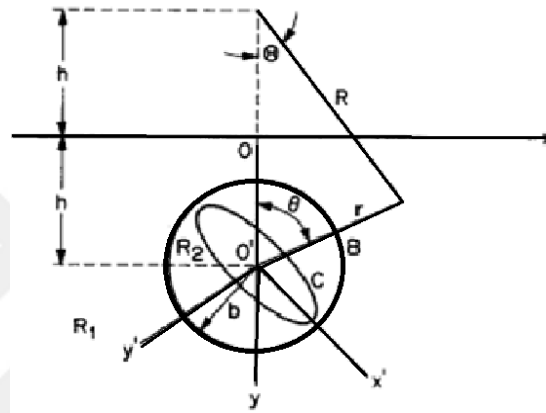


Figure 1.1: A cavity bounded by contour C [3].

In this study, results showed that the angle of incidence wave and orientation of irregularities affect scattering displacement area. It was also found that the results are dependent on the burial depth and size of underground irregularities. Moreover, it was observed that the results are compatible in long periods when the two methods are compared [3].

Dravinski (1983) studied the scattering of different underground irregularity shapes subjected to plane SH, P, SV, and Rayleigh waves. Numerical results for surface displacement field were obtained for single and two elliptic inclusions, assuming that the medium is composed of linear, isotropic, and homogeneous elastic materials. Methods were developed to predict amplification values caused by underground irregularities. A boundary integral method was used to determine the displacement field. For this purpose, Green's functions were employed. Underground irregularities affect ground motion at different burial depths. Therefore, for different burial depths, the displacement peaks occur at different locations.

It was found that the displacement field is strongly affected by the irregularity at shallow burial depth. In the presence of underground irregularity, the effect of P or SV waves is greater than that of SH wave on the surface. In addition, increasing the distance between underground irregularities causes to decrease amplification values on the ground surface [4].

Balendra et al. (1984) studied the response of twin parallel tunnels with radial cross-section, as shown in **Figure 1.2**, exposed to incident plane harmonic SH-waves. The aim of the study was to obtain the dynamic response of tunnels.

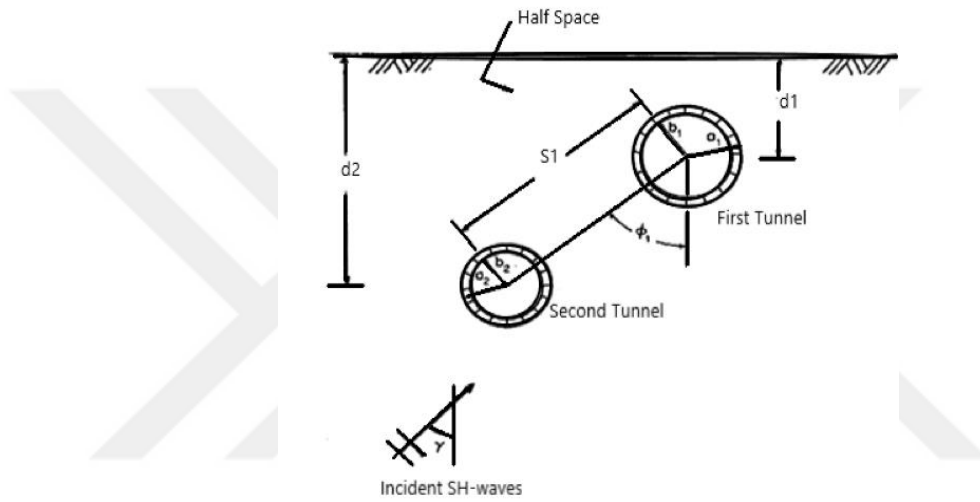


Figure 1.2: Parallel tunnels exposed to SH waves [5].

The method of wave function expansion was used to obtain the responses. The image technique was used to integrate the impact of the scattering of waves. A closed form solution was developed for interaction between underground tunnels. They concluded that the interaction between the tunnels is more distinct in soft clay and at higher frequency. Moreover, the numerical studies provided information about shear stress and tunnel wall displacement at low and high frequencies [5].

Lee (1988) developed closed form solutions of multiple boundary valued problems for elastic waves. These solutions were obtained using iterative method of successive constructions and one step method with an infinite matrix. In this study, the diffraction and scattering of elastic waves caused by an embedded spherical cavity in a homogeneous, perfectly elastic, and isotropic half-space were analyzed.

Moreover, the scattering and diffraction of elastic plane P, SH, SV, and surface Rayleigh waves caused by underground irregularities were generalized, and useful information about amplification and deamplification was obtained. The mixed boundary value problem was generated as 3D, the developed method proves to be more practical than traditional methods [6].

Lee and Karl (1993) investigated the scattering and diffraction of plane SV waves. Fourier-Bessel series were used for the boundary conditions and the wave equations when SV waves overran the critical angle. **Figure 1.3** shows the cavity model, assuming the medium to be elastic, isotropic, and uniform.

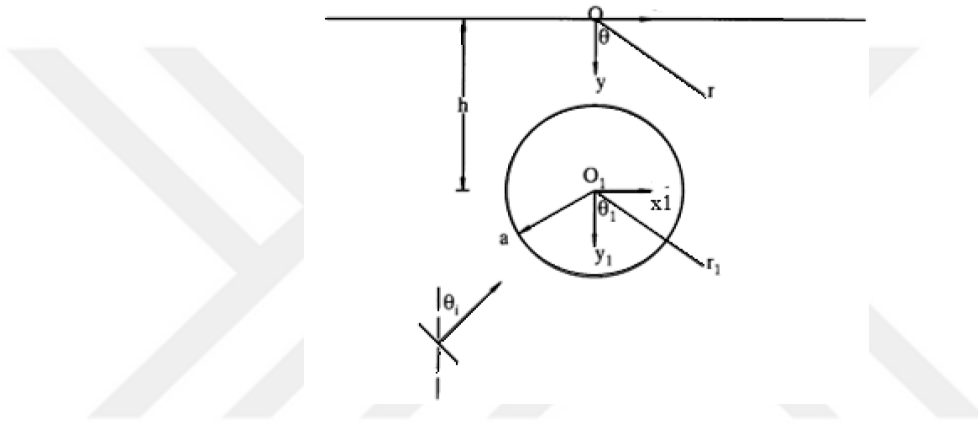


Figure 1.3: Schematic geometry of cylindrical cavity [7].

The results include the effect of incidence wave angle, cavity depth and cavity radius ratio, Poisson's ratio, and the dimensionless frequency of the incident SV wave. The numerical results showed that the burial depth and angle of incident SV waves can change the surface displacement patterns; the amplification values are greater than free field motions [7].

De Barros and Luco (1993) studied the diffraction of harmonic waves by a cavity of circular cross-section. A point of interest in this research was to investigate and understand surface motions during the earthquake in a half-space including underground irregularities or underground structures. The response on the ground surface and the wall of the cavity is affected by horizontal angle of incidence wave. The results obtained from oblique incidence and horizontal incidence are quite different.

The effect of layers, vertical angle of incidence wave, and burial depth of the cavity are also obtained. The burial depth of the cavity and angle of incidence wave have an important effect on the responses [8].

The dynamic response of underground irregularities was investigated by Stamos and Beskos (1995). Boundary element method in the frequency domain was utilized to perform numerical analysis, the medium and underground structure behavior were assumed to be viscoelastic or linear elastic material. The aim of this study is to provide an accurate and efficient numerical methodology for determining the dynamic response of large 3D underground structures. The boundary element method (BEM) with the Laplace transform was utilized for all half-space. Also, the method presented several examples involving cavities and tunnels subjected to external dynamic loads and seismic waves [9].

Manoogian and Lee (1996) investigated the scattering and diffraction of incident SH waves for different shapes of tunnels, such as buried square, circular, elliptical, and rotated square, using the weighted residual method in a 2D half space. It was concluded that underground irregularities create amplification on the ground surface according to the amplitude of the incident waves. The main reason to investigate the flexibility of the weighted residual method was to use different shapes. For the underground inclusions, the closed form solutions and the weighted residual method approaches have similar results. For different shapes of inclusions, this method is effective. The results showed that the site amplification values are related to burial depth of the underground inclusions, the incident angle wave, the dimensionless frequency and the shape of the underground inclusion [10].

The method of successive reflections was used to investigate the 3D response of twin lined tunnels by Moore and Guan (1996). In the infinite medium, the tunnels were exposed to seismic waves (incident SV and P waves). The numerical method was used to investigate the interaction between twin tunnels subjected to seismic waves. In general, the plane strain condition is protective. Additionally, the responses depend on different spacing ratios between twin tunnels and incident angle of P and SV waves. It was also found that the tunnel half space interaction is not significant when the embedded depth of the tunnels is less than tunnel diameter [11].

Later, Lee et al. (1999) studied the 2D scattering and diffraction of SH wave, considering both a canyon and a cavity. **Figure 1.4** shows the 2D model of the problem. The model depicts a semicircular canyon positioned above the circular cavity.

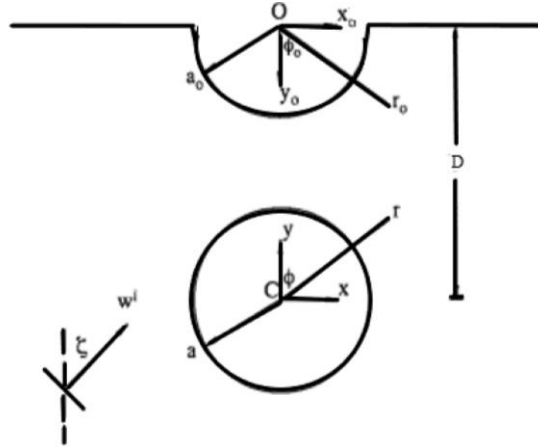


Figure 1.4: Model of canyon with cavity [12].

This study investigated various parameters, including the incidence wave angle. The ground motions depend on factors such as the angle of incidence plane shear horizontal wave, dimensionless frequency. It was found that the amplification values are greater when both the cavity and the canyon are presented [12].

The scattering and diffraction of plane elastic waves were investigated using the weighted residual method by Manoogian (2000). The method was employed to analyze shallow and deep lined circular, elliptical, square, and rotated square tunnels subjected to SH waves. The ground surface response depends on tunnel shape, burial depth, amplitude of the incident wave, frequency, and angle of incidence SH waves. As the frequency of the incident wave increased, the amplification values near the tunnel became more complicated, and the amplification value for shallower rotated square tunnel exceeded 7 value [13].

Jianwen et al. (2003-2004) studied the ground surface displacement of underground twin tunnels subjected to incident plane SV and P waves using the Fourier-Bessel series expansion method. **Figure 1.5** shows two circular tunnels in elastic, isotropic and homogeneous half-space, where d_1 and h_1 represent distance between twin tunnels and burial depth, respectively. Numerical results were investigated using different distance radius ratios and incident wave angles.

The numerical results showed that the amplification values caused by the twin tunnels can be greater than expected values and the ground surface displacement decreases with increasing distance between the two tunnels. In addition, the results showed that the amplification values decrease on average by a factor of 2.5 in the presence of a single cavity and by a factor of 6 in the absence of underground cavities compared to twin cavities [14-15].

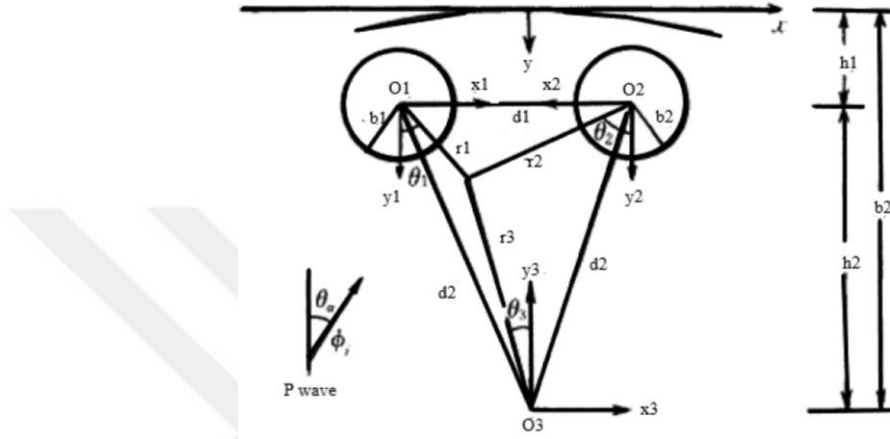


Figure 1.5: Model of two circular cylindrical tunnels [14-15].

The presence of elliptic cracks, planar cracks, and cavities affects motion of waves and this case causes the appearance of large resonant peaks. In order to investigate this case, 2D scattering of elastic P and SV waves was analyzed by Rodriguez-Castellanos et al. (2006). Resonant peaks and wave interaction were observed in frequency and time domain analysis. Scattering of elastic waves by underground irregularities near to the ground surface was modeled. When the $d/2a$ ratio is smaller, the resonance peaks occur at low frequencies. The cavities exhibit more uniform behavior regardless of the incidence wave angle, despite planar or elliptic cracks respond nearly identically to P wave. SV waves generate more complex behavior. The presence of two underground irregularities generates more complicated patterns for the horizontal component compared to a single underground irregularity. In general, underground irregularities with greater diameter generate significant wave diffraction; it was also found that the presence of two irregularities produces greater amplitude [16].

Yiouta-Mitra et al. (2007) investigated the effect of underground structures on surface structures during earthquake. In this regard, a circular tunnel exposed to harmonic SV wave in a viscoelastic half-space was employed for numerical analysis.

They aimed to investigate the effect of soil medium characteristics, tunnel diameter, burial depth, and excitation frequency using the finite difference method (FDM). The numerical results showed that wavelength is not affected by the presence of the tunnel when it is greater than the tunnel diameter. If the dimensionless depth is less than 3, the presence of a tunnel has significant effects. It was also found that stiffer lining reduces the ground surface response [17].

Hasheminejad and Avazmohammadi (2007) studied the dynamic interactions of parallel circular cavities subjected to harmonic plane waves. To develop a closed form solution for the dynamic response of cavities in a proelastic medium, the Biot dynamic theory of proelasticity was used. The main aim is to investigate multiple scattering in the proelasticity medium [18].

Smerzini et al. (2008) investigated seismic response of underground irregularities on the ground surface subjected to incidence of plane SH waves. The study focused on the theory of multiple scattering and diffraction to analyze an embedded circular cavity in a homogenous, isotropic and linear visco-elastic halfspace. The circular cavity was selected to be either empty, filled with a material or a ring shaped with varying thickness. The Graf addition theorem was used to solve boundary conditions and the wave functions' expansion in terms of Bessel and Hankel functions was utilized for diffracted and refracted wavefields. The analytical results concluded that the presence of cavities significantly affects ground surface displacement during seismic loading when underground irregularities are situated close to the ground surface. The surface ground response depends on parameters such as the frequency content of motion, the type of inclusion, and the incident wave angle [19].

An approach was used to investigate the antiplane seismic response of underground irregularities subjected to SH wave by Smerzini et al. (2009). In the analytical solution, the image method, Graf's addition theorem and Bessel and Hankel functions were used. Firstly, they developed a mathematical model related to circular cavity subjected to plane SH waves. Secondly, the method was generalized to affect a point source of cylindrical waves. Finally, the Rayleigh's method was used to investigate the ground surface response in time and frequency domains. Size of the cavity, burial depth, frequency content, incidence wave angle, and distance from the axis of the cavity parameters were used to analyze the ground surface amplification value during real earthquakes.

According to the results of synthetic seismograms, the reflected phase for the lined tunnel and elastic inclusion results occur before the direct phase due to velocity of S wave. Moreover, the presence of a lined tunnel or filled elastic inclusion significantly reduces the ground surface response subjected to vertical plane wave. According to previous studies, the presence of underground irregularities subjected to SH waves has been shown to have significant effect on the response spectrum acceleration at low period bands and spectral amplification factors increase up to nearly 1.5 [20].

Alielahi et al. (2012) investigated the response of an unlined infinitely cylindrical cavity subjected to SV and P waves. For this purpose, they used an advanced formulation of 2D BEM in the time-domain. The purpose of using the time domain is to solve the scattering and dynamic displacement problems of 2D underground irregularities with non-linear behavior. As mentioned in the formulation, an embedded circular cavity was performed using a computer code named Seismic Analysis of Multiple Boundary Element (SAMBE), and the Ricker type incident wave was applied to the model. Numerical results concluded that a shallow cavity subjected to vertically incident SV wave reduces the effect of horizontal component of the motion at the surface. The deeper cavity increases the effect of vertical component for the incident P wave, neglecting the effect of ground surface motion for the SV wave. It was also found that the effect of the displacement amplitude and cavity notably decreases away from the axis of the cavity [21].

Dravinski and Yu (2013) investigated scattering of plane harmonic P, SV or Rayleigh waves. The scattering of waves by a randomly corrugated inclusion in the half-space was investigated using the direct boundary integral equation approach. Ground surface displacement was evaluated using parameters such as impedance contrasts of the materials, frequencies, incident P, SV, and Rayleigh waves. The effect of the inclusion roughness on the ground surface motion was measured using the roughness factor. The roughness factor is related to the impedance contrast, the frequency and nature of the incident wave and the basic inclusion shape. The peak surface motion is generated by the random uniform and random normal interface, and the type of random interface slightly affects the surface displacement. The oblique SV incidence wave generates peak roughness factor [22].

Numerical analyses were performed to investigate the effect of factors such as size, burial depth, and incident angle parameters for a cylindrical cavity subjected to SV and P waves by Verrucci et al. (2012). The model is shown in **Figure 1.6**.

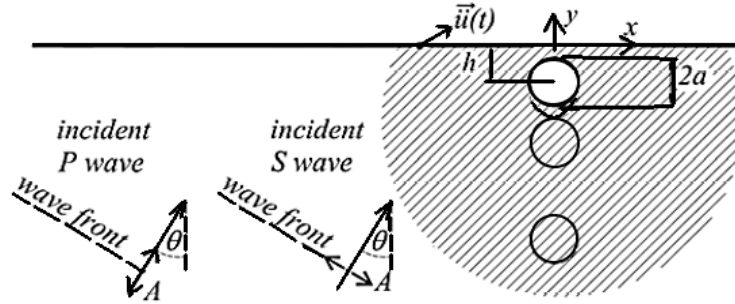


Figure 1.6: Cylindrical cavity subjected to SV and P waves [23].

Amplification and deamplification values were obtained as a result of the analyses in both the frequency and time domains using viscous boundaries to prevent reflection conditions. Ricker wavelength type was applied to analyses. Fourier spectrum was obtained from the seismograms at the ground surface. It was compared with the free field spectrum to obtain the amplification values. The results showed that when the cavity is subjected to seismic waves, it generates horizontal diffracted Rayleigh waves and reflected P waves on the ground surface; the direct S waves and scattered waves are effective on the ground surface motions. S waves affect the amplification values for horizontal component around the cavity. For the vertical component of P wave, the effect is concentrated in a small region due to the resonance angle relationship with the cavity crest and the ground surface. The burial depth parameter influences the amplification value, while the incident wave angle parameter does not have any effect on the maximum amplification value in both components [23].

Liu et al. (2013) studied an analytical solution for the scattering of plane harmonic waves propagated by a tunnel using plane complex variable theory and the image technique. The main point of this study is the orthogonality process along the cavity wall and half-surface. The lined cavity and half space scattered incident P, SV or Rayleigh waves and reflected waves. The analytical results showed that the burial depth of lined tunnel, the linear's thickness and shear modulus ratio are important [24].

The response of a buried box tunnel was investigated by Baziar et al. (2014) using a centrifuge test and numerical analyses. The model dimensions were reduced by 40% in the centrifuge tests, where the medium was selected to be dry crushed silicate sand. Different input motions, including Kobe and Northridge earthquakes, were applied to the models. In the sequel, Fast Lagrangian Analysis of Continua in Two Dimensions (FLAC2D) software was used to perform numerical analyses on modeled rectangular shape. The bottom boundary of the centrifuge tests and numerical modeling was assumed to be a rigid boundary. The model with side boundary conditions to simulate the behavior of the equivalent shear beam box was used. The centrifuge tests and numerical models produced same displacement values under these conditions. To perform the analyses, elasto-plastic Mohr Coulomb model and 0.03 Rayleigh damping were applied to the models. The results of centrifuge tests and numerical models show good agreement. Chi Chi and Kocaeli earthquakes and sinusoidal motion were chosen as seismic loading for analyses. The presence of the tunnel affects the incident wave characteristics. The analysis results showed deamplify in short periods and amplify in longer periods. They also emphasized the importance of underground tunnels for taller structures, which have a negative effect in longer periods [25].

Alielahi and Adampira (2015) investigated the dynamic response of single unlined tunnel exposed to vertically propagating incident SV and P waves. The effect of wavelength, depth ratio, truncated ratio, tunnel shape and incident wave type were investigated in this study. The geometry of the tunnel is shown in **Figure 1.7**. In general, the seismic amplification values occur in long period bands, and the deamplification values occur in short period bands. Maximum amplification values occur when wavelength of seismic waves is greater than the diameter of shallow tunnels. Trapped diffraction waves produce amplification between the tunnel crest and the ground surface. Subsequently, it was found that when the tunnel location is close to the ground surface, the ground surface response increases. It could be said that P waves produce greater amplification, which produces more scattering and diffraction. Different shapes of underground tunnels have different ground surface response. It was also found that trapped diffraction waves generated by square cross-section tunnels produce greater amplification values [26].

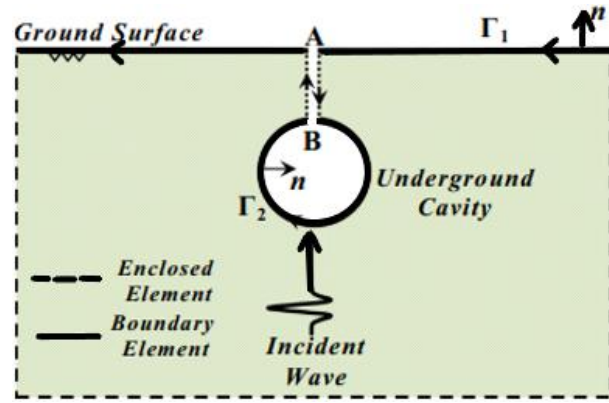


Figure 1.7: Schematic model of underground cavity [26].

Fu et al. (2015) obtained an analytical solution for displacement and stresses around twin parallel tunnels. They investigated the effect of twin tunnels using complex variable theory in the elastic half-plane. The tunnel burial depth and spacing between the twin tunnels were analyzed to understand the interaction of the twin tunnels. Following Verruijt's solution, an analytical solution was developed for the surface displacement caused by the twin tunnels, taking into account the interaction of the twin tunnels. Analytical results showed that increasing burial depth and spacing between twin tunnels reduce the interaction between the twin tunnels [27].

Alielahi and Adampira (2016) investigated dynamic response of the ground surface when parallel tunnels were exposed to incident SV and P waves. The geometry of the mathematical model is illustrated in **Figure 1.8**. The boundary element method was used to study the seismic behavior in the time domain. Single and twin tunnels were analyzed to investigate the ground surface amplification values with different parameters, such as the effect of the distance between the twin tunnels, the wavelength of the incident SV and P waves, and different burial depths. The results showed that decreasing the distance between twin tunnels causes greater amplification values. Incidentally, single tunnels do not have significant effect compared to twin tunnels. Also, the location of tunnels affects the amplification values. The greater amplification values are obtained when the tunnels are located at shallow burial depth. It is clear that the amplification values in the presence of the tunnels are different from the values in the absence of the tunnels. Finally, they suggested a few amplification coefficients for building design spectra [28].

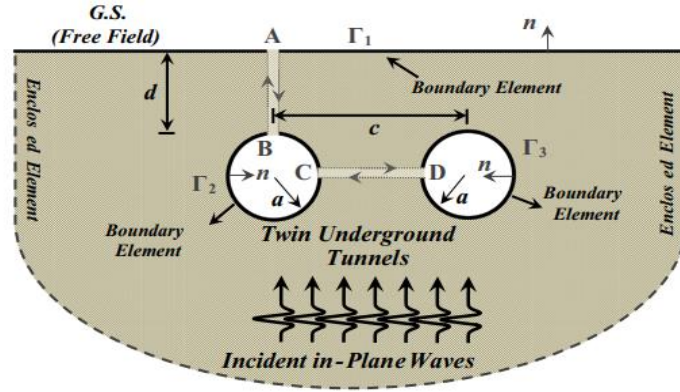


Figure 1.8: Schematic geometry of twin parallel unlined tunnels [28].

Moghadam and Baziar (2016) investigated the effect of underground tunnel on the amplification pattern; for this purpose, shaking table tests and numerical solutions were performed. Different parameters, including burial depth of tunnel, flexibility ratio, and shear wave velocity, were investigated in order to determine the effect of these parameters on the amplification patterns. A model without underground tunnel and a model with an underground tunnel were modeled for analyses. The soft materials were placed at the edges of the model to reduce the reflection of the waves from the boundary. The results showed that the tunnel without lining at the shallower depth produces greater amplification values on the ground surface. It was also found that the maximum amplification value is obtained in low period bands [29].

Alielahi and Adampira (2016) used BEM to investigate the response of shallow underground cavities on the ground surface. The objective of this article is to investigate the seismic amplification values and compare seismic response spectra. SV Ricker-type pulse was used as dynamic input to analyze tunnels with a cross-section of circular, square and horseshoe shapes. In this paper, the effect of burial depth parameter on the ground surface was investigated. It was observed that shallower tunnel generates more site amplification values due to trapped waves on the ground surface. Deamplification values are observed in short period and amplification values are observed in long period bands for circular and horseshoe cross-section tunnels. However, amplification values of tunnels with square cross-section are observed in short period bands [30].

Alielahi and Adampira (2016) investigated the ground surface response due to the presence of underground cavities subjected to SV and P incident waves. In this regard, they presented a numerical parametric study using BEM in the time domain.

The presence of a cavity produces different response compared to free-field response during seismic loading. Therefore, the amplification patterns of the elliptical cavity were analyzed to derive simple relations in the paper. After that, a computer code, SAMBE, was used to calculate deformations in the time domain. Different burial depths and cavity radius ratios were used to compare the effect of the elliptical cavities on site amplification. The non-negligible effect is caused by trapped waves, and the effect is calculated by dividing the Fourier amplitude motion component by Fourier amplitudes of free field motion. The cavity with smaller radius ratio produces greater amplification, since there is more trapped wave area. The greater area above the cavity with smaller radius ratio takes more time to dissipate the waves and maximum displacement values are obtained at the nearest position of the cavity. It was found that the amplification values steadily diminish when burial depth of the cavity increases. It was also obtained that greater amplification values occur at the center axis of the cavity when the cavity is subjected to P wave, and greater amplification values occur on both sides of the cavity when it is subjected to SV wave on the ground surface. When the wavelength of incident wave is greater than diameter of the shallow cavity, the maximum amplification factor occurs [31].

Panji and Mojtabazadeh-Hasanlouei (2021) studied the seismic ground response of a lined box shaped tunnel subjected to SH wave. Analyses were performed to investigate the effect of incident wave angle and frequency content on the ground surface response. **Figure 1.9** shows a box-shaped tunnel in the medium. The Ricker wavelet type was defined as seismic loads to obtain seismic response. The researchers concluded that underground tunnels with corners, such as square and rectangular tunnels, create greater amplification values [32].

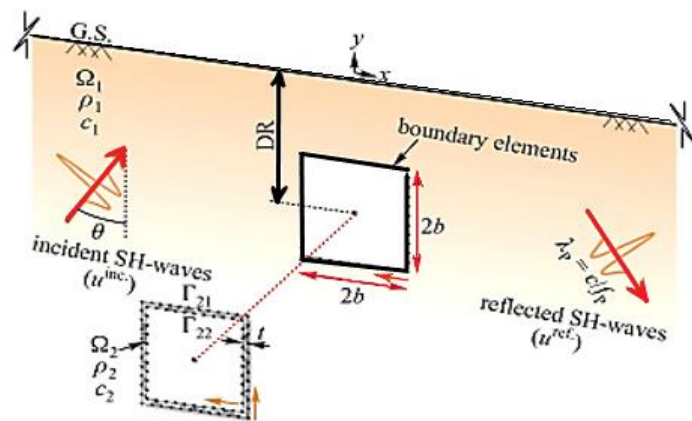


Figure 1.9: Model of box-shaped lined tunnel [32].

Afterwards, Panji and Mojtazadeh-Hasanlouei (2021) investigated the seismic response of the shallow twin tunnels to determine the effect of various cross sections. The different cross-section tunnels are shown in **Figure 1.10**. The results were investigated using BEM in the time and frequency domains. The effect of seismic response was investigated using different parameters, such as the burial depth of the twin tunnels, cross-section of the tunnels, distance between tunnels and angle of incident waves. The maximum amplification values for horseshoe and square cross-section tunnels are greater than 2.5 at the tunnel axis. Ultimately, it was concluded that the cross-section of tunnels and the incident wave angle play a crucial role for seismic response [33].

Next, Li et al. (2022) modeled the nonlinear soil-tunnel interaction to investigate the influencing factors of shield tunnel lining under seismic loads of South Iceland Earthquake (2000). The single and twin tunnels models were analyzed to investigate the effect of burial depth, liner thickness, liner diameter and interaction of parallel tunnels. The shallower tunnels noticeably affects the nonlinear effect [34].

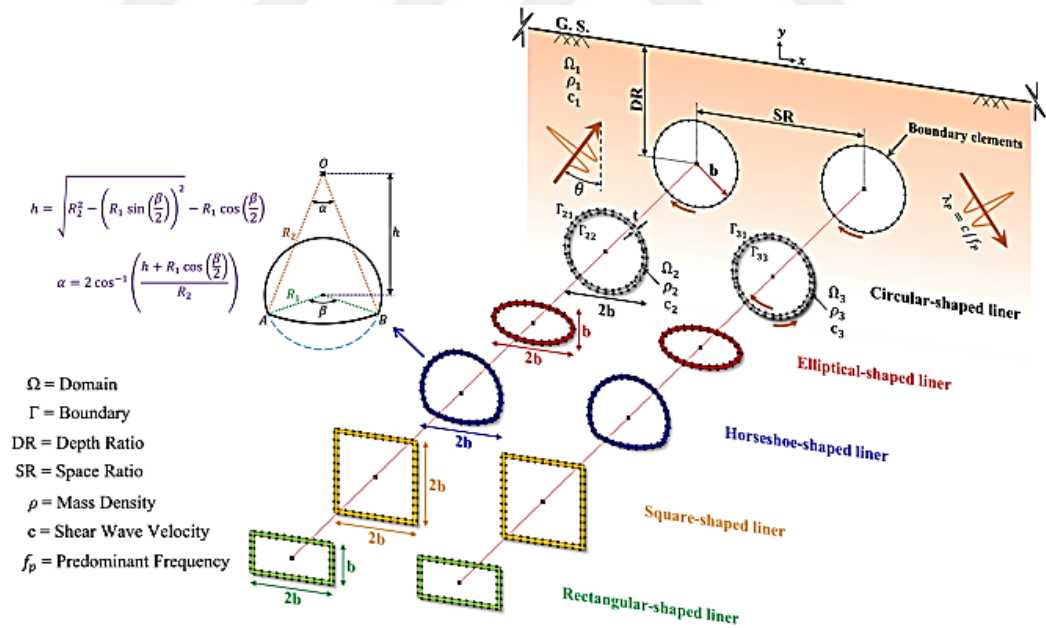


Figure 1.10: Model for twin tunnels with different cross-section [33].

One of the latest studies on this subject is Feizi et al. (2022), who investigated the seismic ground response of single and twin square cross-section tunnels exposed to SV waves using FLAC 2D.

In this study, the effect of significant parameters, such as the burial depth and the distance between the tunnels, were investigated using various tunnel models. **Figure 1.11** shows the tunnel geometry.

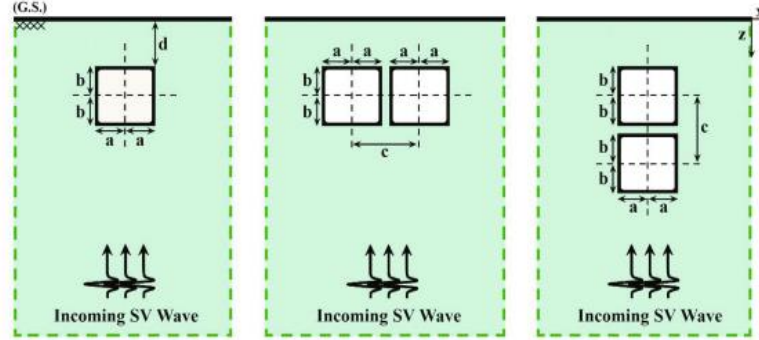


Figure 1.11: Box-shaped tunnels subjected to SV wave [35].

Feizi et al. (2022) analyzed the response of single and twin square cross-section tunnels using seven earthquake records. Firstly, they concluded that greater amplification values are observed for single and twin square cross-section tunnels, and shallow square cross-section tunnels produce two amplification peaks. According to other results, maximum amplification values for separated horizontal twin tunnels occur at the tunnel axis, while maximum amplification values for the other cases occur near the tunnel axis. When the elasticity of tunnel lining decreases, the maximum amplification values occur away from the tunnel axis [35].

2. SOIL AMPLIFICATION AND FACTORS AFFECTING SOIL AMPLIFICATION

2.1. Introduction

The waves, which separate from the bedrock layer due to tectonic earthquakes, are affected by local geological features and soil conditions. These effects increase amplitude of seismic waves and this phenomenon is called site amplification. There are theoretical and experimental studies and empirical and analytical models to describe the effect of geological features and earthquake waves on idealized models. The idealized models can be modeled as 1D, 2D or 3D for dynamic analyses. In the last few years, a number of methods have been developed for more detailed examination, including 3D FDM, the finite element method (FEM) and BEM. More realistic results of analysis can be obtained by using these methods [36]. The following sections contain more details about site amplification.

2.2. Effect of Local Site Conditions on Soil Amplification

As previously mentioned, increasing amplitude of seismic waves passing through a soft soil layer close to the ground surface is called to as site amplification. In this regard, local site conditions affect amplitude of seismic waves and play a significant role in surface damage. **Figure 2.1** shows parameters that increase amplitude of seismic waves.

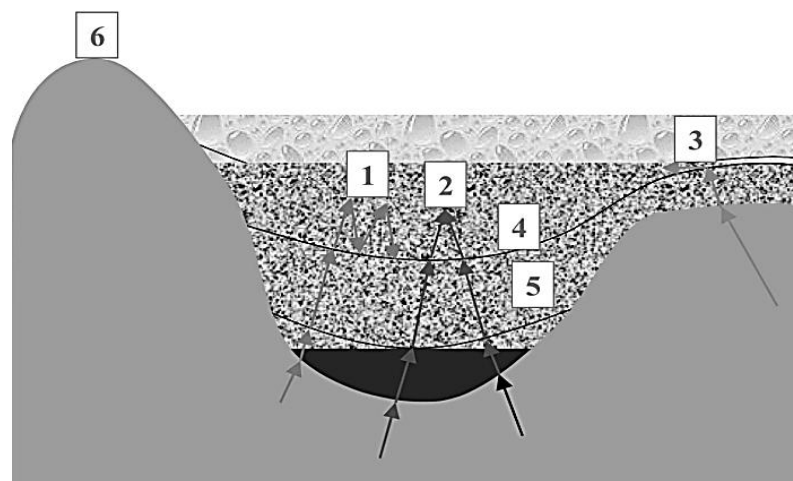


Figure 2.1: Factors affecting site amplification [36].

The main factors affecting site amplification can be listed as follows:

- 1) resonance due to impedance contrasts
- 2) underground topography
- 3) body waves converted to surface waves
- 4) underground water table
- 5) unpredictability of the medium
- 6) ground surface topography

The impedance contrasts, which are defined as density of medium multiplied by propagation velocity, affect the amplitude of seismic waves. Using the principle of energy conservation and ignoring the energy loss due to damping, we can define the seismic energy flux, $E(t)$, as constant from deeper depth to the ground surface. This method allows calculation of site amplification for a simple geological case. $E(t)$ can be defined using Equation (2.1).

$$E(t) = \frac{1}{2}(\rho V)x^2(t) \quad (2.1)$$

where the mass density, the propagation velocity and the seismic shaking velocity are denoted by ρ , V and $x(t)$, respectively. Decreasing the impedance constant increases shaking velocity while total energy remains constant. The site amplification (A) associated with the energy flux equation is given by Equation (2.2) when the impedance contrast alters from $(\rho V)_1$ to $(\rho V)_2$ [37].

$$A = \left[\frac{x_2(t)_{\max}}{x_1(t)_{\max}} \right] = \sqrt{\frac{(\rho V)_1}{(\rho V)_2}} \quad (2.2)$$

2.3. Approaches for Examination of Local Site Effects

Previous studies have suggested that local geological conditions have an effect on the amount of damage caused by earthquakes in an area. Therefore, studies focus on effect of 2D and topographic irregularities. The site amplification values can be calculated using analytical models and field tests. The most reliable results for site amplification values are obtained from analysis results of strong ground motion records.

In the field test, the ground motions or microtremor results are analyzed. In the analytical models, local site effects are obtained using 1D, 2D and 3D modeling methods [37].

2.3.1. Determination of Site Amplification

The effect of local site conditions is investigated with field tests using real, artificial earthquakes and microtremor records. In geotechnical earthquake engineering, earthquake motion records are used to predict site amplification values using following methods:

a. Using ground motion records to predict site amplification

The important issue is that the site amplification factor is independent for different earthquakes in this method. Thus, the site amplification is assumed to be linear. This method predicts an approximate site amplification value for an area. The Fourier spectrum of recorded motion is obtained in the frequency domain at the ground surface using Equation (2.3).

$$U_{ij}(f) = S_i(f) * R_i(f) * P_{i,j}(f) \quad (2.3)$$

where f represents cyclic frequency, $S_i(f)$ represents the source spectrum, $R_i(f)$ represents site amplification, and $P_{i,j}(f)$ represents path effects [37].

b. Site amplification approximation using a constant

A constant coefficient, which is average of standard spectral ratios in a given frequency band, is used to determine the effect of different local site types in practice and design codes.

c. Site amplification estimation using field tests

The Nakamura method (1989) divides the amplitude of the horizontal component by the amplitude of the vertical component. The method is generally effective for predicting the resonance site frequency, but it is not sufficient to predict amplitude.

d. Site amplification approximation using spectral ratios

The spectral ratio method was suggested by Borchardt (1970), which uses ground motion records to obtain site amplification values. The spectral ratio is calculated as the Fourier amplitude spectrum (FAS) of surface record divided by amplitude spectrum of bedrock record, using the same earthquake record at different locations. Equation (2.4) determines spectral ratio, $R(f)$.

$$R(f) = \frac{\sum_{j=1}^{2k+1} W(j) |Y(f - k - 1 + j)|}{\sum_{j=1}^{2k+1} W(j) |X(f - k - 1 + j)|} \quad (2.4)$$

The complex Fourier transforms are expressed by $X(f)$ and $Y(f)$. The symmetric smoothing window and cyclic frequency are represented by $W(j)$ and f , respectively.

Alternatively, Equation (2.4) can be calculated using the cross spectral ratio, $C(f)$. Equation (2.5) determines the cross spectral ratio, $C(f)$.

$$C(f) = \frac{\sum_{j=1}^{2k+1} W(j) |Y(f - k - 1 + j) X^*(f - k - 1 + j)|}{\sum_{j=1}^{2k+1} W(j) |X(f - k - 1 + j)|^2} \quad (2.5)$$

Site amplification can be determined using spectral ratios instead of the standard Fourier spectrum [37-41].

2.3.2. Estimation of Site Amplification Using Analysis Methods

The analysis methods are developed according to problem condition, which are 1D, 2D and 3D modeling. Local site effects can be modeled using variation analysis methods such as FDM, FEM and BEM. The analysis methods are chosen depending on their advantages and drawbacks. Literature reviews have shown that the most realistic results about local site effects were obtained using FDM to investigate seismic response of the San Bernardo basin region during earthquakes by Frankel (1993). FDM and FEM methods show flexibility for modeling topographic irregularities and investigating scattering and diffraction waves. Hybrid methods combine the advantages of different methods and reduce analysis time without affecting accuracy of results [41-42].

3. ANALYSIS METHOD

3.1. Introduction

Researchers have been studying to model the presence of underground irregularities and investigate non-linear behavior of the medium using various analytical methods. The most realistic results of the dynamic analysis are obtained using FDM. The presence of underground irregularities and non-linear behavior can be modeled using the Lagrangian finite difference method. In this study, to investigate the seismic response of underground tunnels, numerical analyses were performed utilizing FLAC3D code, which uses the Lagrangian finite difference method and nonlinear method in the time domain.

FLAC3D code, which uses the Lagrangian finite difference method, describes behavior of materials such as soil and rock undergo plastic flow using a 3D grid. The materials move and deform with the 3D grid. It is possible to perform large scale computations with minimal memory requirements. Static and dynamic analyses can be performed on the constructed model. Also, faulting mechanism can be modeled to analyze the interaction between two finite difference grids. **Figure 3.1** shows terminology for FLAC3D code program.

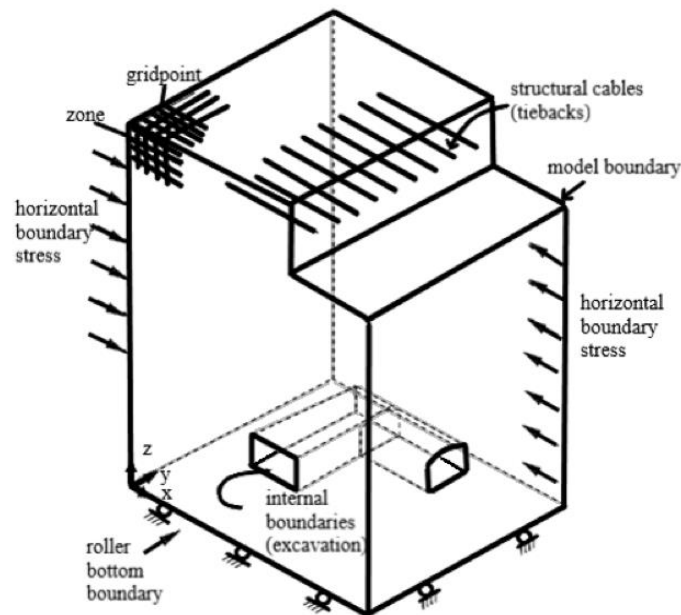


Figure 3.1: FLAC3D terminology [43].

Groundwater flow, pore pressure dissipation, liquefaction or structural elements can be simulated using FLAC3D code. FLAC3D code, which uses the Lagrangian finite difference method, can perform dynamic analysis using waves as input and applying boundary conditions to the model. Realistic modeling can be obtained by applying both static and dynamic boundary conditions to the model. Research areas including underground engineering and rock mechanics use FLAC3D code, which uses Lagrangian finite difference method [43].

3.2. Theoretical Background of the Analysis Method

The Lagrangian finite difference method investigates mechanical behavior of a continuous medium. When the medium reaches plastic flow or equilibrium, response of the mechanical behavior is derived from mathematical models and numerical implementations. The Lagrangian finite difference method relates to different analysis methods depending on the model, although the default calculation mode is static analysis. The following three approaches define the solution method for FLAC3D code, which uses the Lagrangian finite difference method. The first approach is the finite difference approach, which assumes linear trend of a parameter for a limited interval of space and time. All forces are assumed to be concentrated at the points of the mesh in the second approach, known as the discrete model approach. The final approach is the dynamic-solution approach, which obtains the equilibrium state using the equations of motion. The forms of Newton's law equations are used to solve the differential equations using above mentioned approaches over time. **Figure 3.2** shows the tetrahedron element, which defines the space interval and changes in velocity. Also, the tetrahedron element does not produce hourglass deformation [43].

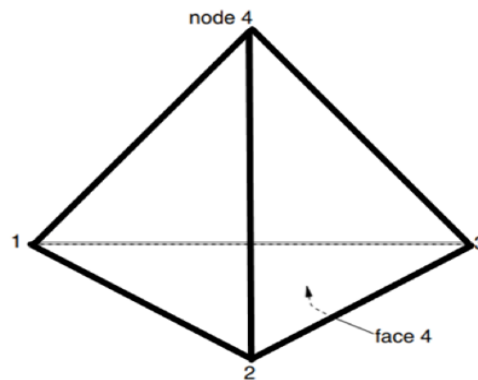


Figure 3.2: Tetrahedron element [43].

3.2.1. Initial and Boundary Conditions

A problem has initial conditions, such as body forces and initial stress conditions. To provide initial conditions, nodal velocities and stresses are first set to zero. After that, loads are added and boundary displacements are calculated. Nodal loads are applied to surface nodes and nodal velocities are used to calculate deformations at boundaries. The initial state of the numerical scheme is obtained by transforming surface tractions and body forces into statically equivalent nodal forces and other steps.

3.2.2 Steps in the Calculation

The calculation performed at each timestep for FLAC3D code, which uses the Lagrangian finite difference method, can be listed as shown in **Figure 3.3**. To obtain maximum out of balance force, stresses are obtained using nodal velocities. After that, the stresses are used to obtain new displacement and nodal velocities using the equations of motion. For each timestep, these calculation processes are repeated. The unbalanced forces will reach zero when the model system achieves an equilibrium state. The model system will not reach zero when the system shows plastic flow (steady state) of material.

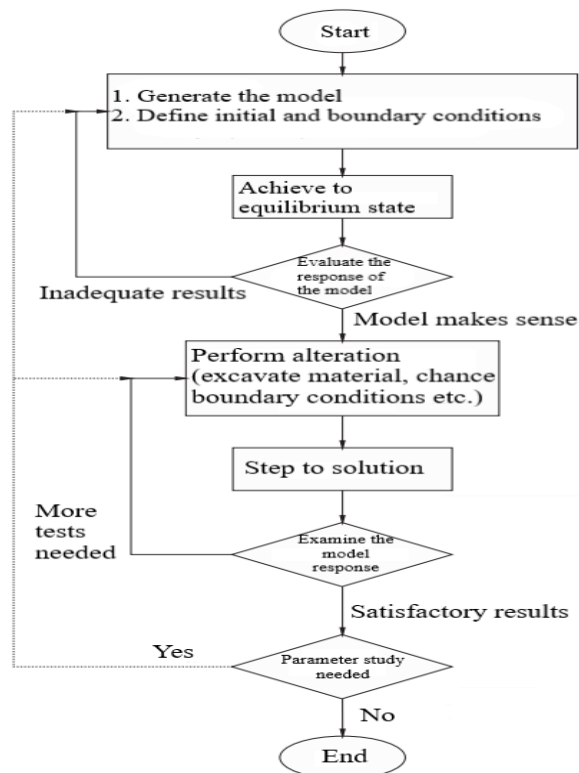


Figure 3.3: Timestep of calculation [43].

3.3. Applying Finite Difference Approximation

In this section, formulation of the strain rate tensor components of the elements is presented to explain the basic principles of the Lagrangian finite difference method. The following Equation (3.1) is derived using the Gauss divergence theorem for tetrahedron elements.

$$\int_V v_{i,j} dV = \int_S v_i n_j dS \quad (3.1)$$

where (s) is area and [n] is the external unit vector of the tetrahedron. The solution of Equation (3.1) is solved assuming a constant strain rate and Equation (3.2) is obtained.

$$V_{vi,j} = \sum_{f=1}^4 \bar{v}_i^{(f)} n_j^{(f)} S^{(f)} \quad (3.2)$$

where $\bar{v}_i$ is average velocity. If the velocity variation is linear, Equation (3.3) can be obtained.

$$\bar{v}_i^{(f)} = \frac{1}{3} \sum_{l=1, l \neq f}^4 v_i^l \quad (3.3)$$

where l is related to the value at node. Replacing 1 and v_i in Equation (3.1), Equation (3.4) is obtained.

$$\sum_{f=1}^4 n_j^{(f)} S^{(f)} = 0 \quad (3.4)$$

Equation (3.3) is divided by V and tensor of strain rate can be expressed in Equation (3.5).

$$\xi_{i,j} = -\frac{1}{6V} \sum_{l=1}^4 (v_i^{(l)} n_j^{(l)} + v_j^{(l)} n_i^{(l)}) S^{(l)} \quad (3.5)$$

3.4. Dynamic Analysis

Static analysis mode is default calculation mode in FLAC3D, which uses the Lagrangian finite difference method. On the other hand, fully dynamic analysis can be performed using the dynamic analysis mode. Dynamic analysis can be used in various fields, such as seismology and earthquake engineering, soil-structure interaction and changing pore pressure. There are some differences between the fully non-linear analysis method used by FLAC3D, which uses the Lagrangian finite difference method, and the equivalent linear method commonly used in earthquake engineering. The equivalent linear method is often preferred in geotechnical engineering, although it can be difficult to model different geometries. Because it is easy to execute and can be directly applied to laboratory results. The problem geometry can be more accurately modelled using the fully non-linear analysis method, although it is more difficult than the other method. Hysteretic damping can be analyzed using the difference between the fully non-linear and equivalent linear methods. User should consider the following three points when applying dynamic analysis to a model:

- 1) dynamic loading and boundary conditions,
- 2) mechanical damping
- 3) wave transmission through the model

3.4.1 Boundary Conditions for Dynamic Analysis

To analyze a region of space with numerical methods, it is necessary to apply suitable boundary conditions at the artificial numerical boundaries. The boundary conditions applied to models cause waves to reflect back into the models and prevent propagation of the required energy in dynamic problems. This case can be prevented using larger dimensional models, but the larger models require more effort to calculate. A number of formulations have been suggested for this case.

In addition to typical static boundary conditions, there are two advanced dynamic boundary conditions in FLAC3D code, which uses the Lagrangian finite difference method. These boundary conditions, which are Quiet (Viscous or Absorbing) and Free-Field Boundary conditions, can be used to minimize wave reflections at model boundaries. **Figure 3.4** shows options for seismic loading and boundary conditions used in FLAC3D code. As shown in **Figure 3.4**, bottom boundary of models can be modelled with either a flexible or rigid base in dynamic analyses.

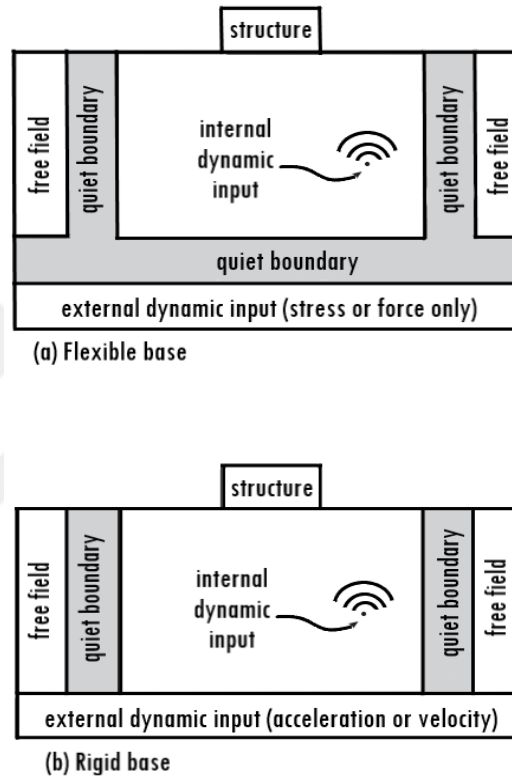


Figure 3.4: (a) and (b) show types of dynamic loading and boundary conditions in FLAC3D [43].

When there is significant impedance difference between the bedrock and upper layer of bedrock, a rigid base is necessary; when the impedance difference between the bedrock and upper layer of bedrock is less, a flexible base is necessary. Acceleration-time and velocity-time histories can be used to apply seismic loading to boundaries of model.

The Quiet Boundary condition, which includes dashpots connected to the boundaries in normal and shear directions, prevents reflection of external propagating waves back into the model, as proposed by Lysmer and Kuhlemeyer (1969) [44].

The Free Field Boundary condition is applied for modeling continuum at lateral boundaries and allows waves reaching vertical boundaries around the model to exit without reflecting from boundary. This condition is based on method of the NESSI code proposed by Cundall (1980) [45]. In addition, the method executes in parallel with the finite difference main-grid analysis in FLAC3D code. The forces applied to the main grid are defined by Equations (3.6), (3.7), and (3.8).

$$F_x = -\rho C_p (v_x^m - v_x^{ff})A + F_x^{ff} \quad (3.6)$$

$$F_y = -\rho C_p (v_y^m - v_y^{ff})A + F_y^{ff} \quad (3.7)$$

$$F_z = -\rho C_p (v_z^m - v_z^{ff})A + F_z^{ff} \quad (3.8)$$

in which ρ denotes model boundary density, influence area of the free-field gridpoint is represented by A . C_p represents compression wave velocity and C_s represents shear wave velocity at the side boundaries. x , y and z grid-point velocity in main grid at vertical boundary are represented by v_x^m, v_y^m, v_z^m , respectively. x , y and z grid-point velocity in vertical boundary are represented by $v_x^{ff}, v_y^{ff}, v_z^{ff}$, respectively. $F_x^{ff}, F_y^{ff}, F_z^{ff}$ are free-field grid-point force with contributions from $\sigma_{xx}^{ff}, \sigma_{xy}^{ff}, \sigma_{xz}^{ff}$ stresses of the free-field zones around the grid point.

The numerical accuracy of wave transmission is influenced by frequency content of the input motion and wave characteristics. To accurately represent wave transmission, the element size must be less than approximately 1/10 or 1/8 of the wavelength, as proposed by Lysmer and Kuhlemeyer (1973) [43], [44], [46].

3.4.2. Mechanical Damping

A natural dynamic system, which includes a level of damping, would not oscillate endlessly. The natural damping of materials such as soil and rock is hysteretic, and damping is independent of frequency. Rayleigh damping is often used in time domain programs to obtain a level of damping. Hysteretic Damping is an alternative damping and it is directly included in the calculation of FLAC3D code, which uses the

Lagrangian finite difference method. Hysteretic damping allows comparison of the calculations between the equivalent linear and fully non-linear methods [43].

3.5. Hysteretic Damping

Since Rayleigh damping notably increases the analysis time, Hysteretic damping was added to the FLAC3D code, which uses the Lagrangian finite difference method. Rayleigh damping or local damping can be combined with Hysteretic damping. Hysteretic damping is not a constitutive model and it should be applied in addition to non-linear models. It is known that the energy dissipation of soil and rock under dynamic loads is mostly hysteretic in nature. This means that the load/unload cycle of shear strain is independent of frequency, but it is dependent on the cycle amplitude. This behavior can be provided by an acceptable constitutive model; however, non-linear models may occur in some complex cases. Instead of this, simpler models such as the Mohr-Coulomb model can be applied.

3.5.1. Mohr Coulomb Model and Natural Damping

Shear modulus reduction and damping ratio curves are generated for standard models such as Mohr-Coulomb. Assuming an elastic/plastic model combined with a constant $G_{\max}$ and τ_m is subjected to $|\gamma|$, within yield, the secant shear modulus is equal to the constant shear modulus. The following Equation (3.9) determines the secant shear modulus, G .

$$G = \frac{\tau_m}{|\gamma|} \quad (3.9)$$

where $G_{\max}$ is constant shear modulus, τ_m is yield stress and $|\gamma|$ is cyclic shear strain of amplitude. And $G/G_{\max}$ is determined using $\gamma_m = \frac{\tau_m}{G_{\max}}$ for $|\gamma|$ greater than γ_m from Equation (3.10).

$$G/G_{\max} = \gamma_m/|\gamma| \quad (3.10)$$

Figure 3.5 shows the initial loading and unloading/reloading process.

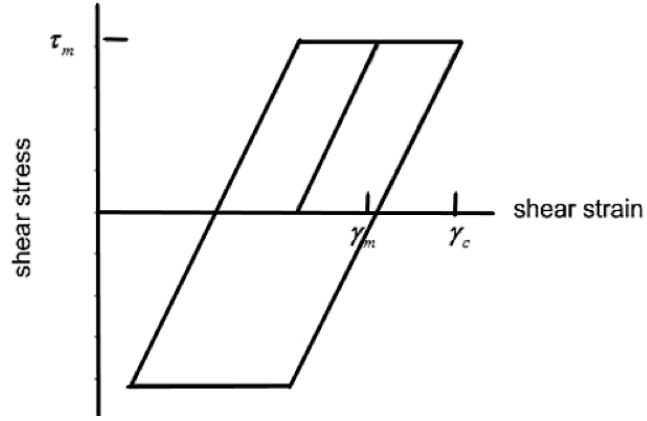


Figure 3.5: Stress-strain cycle [43].

The relationship between the maximum stored energy and dissipated energy is given in Equation (3.11).

$$\frac{\Delta W}{W} = \frac{8(\gamma_c - \gamma_m)}{\gamma_c} \quad (3.11)$$

Equation (3.12) is derived using the other equations and (D) the damping ratio.

$$D = \frac{2}{\pi} \frac{(\gamma_c - \gamma_m)}{\gamma_c} \quad (3.12)$$

Figure 3.6 shows the modulus reduction and damping ratio curves, which are obtained using Equations (3.10) and (3.12).

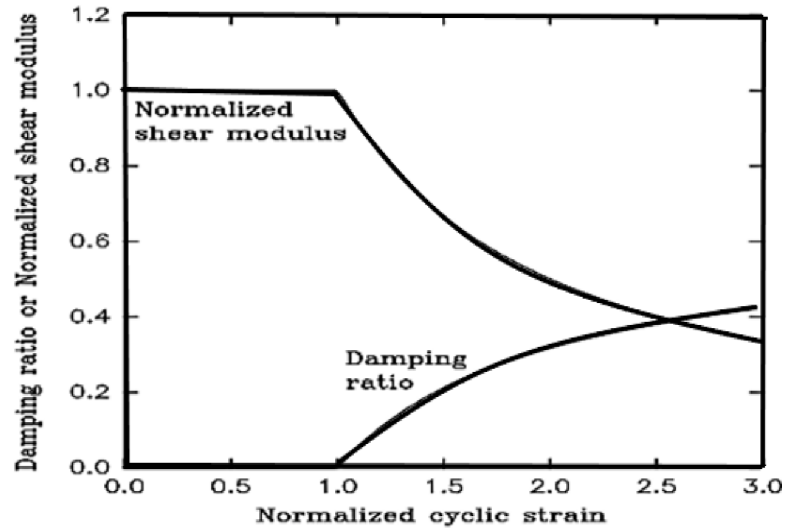


Figure 3.6: Modulus and damping ratio vs cyclic strain [43].

3.5.2. Mohr-Coulomb Model and Hysteretic Damping

For an elastic/plastic model in FLAC3D, which uses the Lagrangian finite difference method, the modulus reduction approach is used in the elastic region and damping is used in the plastic region, employing hysteric damping. Energy dissipation is generated using the Hardin/Drenevich model with the Mohr-Coulomb model for this case. Therefore, Mohr-Coulomb yield stress needs to be less than the hyperbolic law's yield level. This case is satisfied by following Equation (3.13).

$$\gamma_{\text{ref}} > \gamma_m = \frac{\tau_m}{G_{\text{max}}} \quad (3.13)$$

Figure 3.7 shows curve, which is the initial loading with Mohr-Coulomb yield and unloading/reloading process.

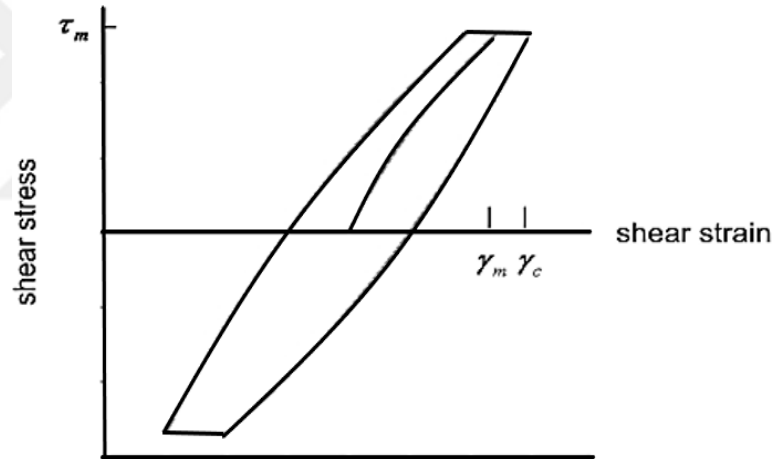


Figure 3.7: Hysteretic damping and Mohr-Coulomb model [43].

In **Figure 3.7**, $\gamma_c < \gamma_m$ defines elastic region. γ_m is obtained from following Equation (3.14).

$$\frac{\tau_{\text{max}}}{G_{\text{max}}} = \frac{\gamma_m}{1 + \frac{\gamma_m}{\gamma_{\text{ref}}}} \quad (3.14)$$

The modulus reduction factor in elastic range is obtained from following Equation (3.15).

$$\frac{G}{G_{\max}} = \frac{1}{1 + \frac{|Y|}{Y_{\text{ref}}}} \quad (3.15)$$

The region is plastic range if $\gamma_c \geq \gamma_m$. It can be defined by following Equation (3.16).

$$\frac{G}{G_{\max}} = \frac{1}{\left(1 + \frac{\gamma_m}{Y_{\text{ref}}}\right) \frac{|Y|}{Y_{\text{ref}}}} \quad (3.16)$$

The energy dissipated in the plastic region, which is the region bounded by the cycle, is presented by Equation (3.17).

$$\Delta W = \Delta W_H + \Delta W_{\text{CH}} \quad (3.17)$$

The maximum stored energy and the damping ratio equations are given by Equation (3.18) and (3.19), respectively.

$$W = \frac{1}{2} \tau_m \gamma_c \quad (3.18)$$

$$D = \frac{1}{4\pi} \frac{\Delta W_H + \Delta W_{\text{MC}}}{W} \quad (3.19)$$

where W_{MC} and W_H are hysteretic damping in the elastic range and Mohr-Coulomb damping in the plastic range, respectively. Using the above relations, the integration used in dynamic analysis is obtained by Equation (3.20).

$$D = \frac{2}{\pi} \left\{ 2 \frac{1 + \frac{\gamma_m}{Y_{\text{ref}}}}{\left(\frac{\gamma_m}{Y_{\text{ref}}}\right)^2} \left[\frac{\gamma_m}{Y_{\text{ref}}} - \ln \left(1 + \frac{\gamma_m}{Y_{\text{ref}}} \right) \right] - 1 \right\} \frac{1}{\frac{\gamma_c}{Y_{\text{ref}}}} + \frac{2}{\pi} \frac{(\gamma_c - \gamma_m)}{\gamma_c} \quad (3.20)$$

4. CHARACTERISTICS OF MODELS

4.1. Introduction

Underground irregularities cause significant site amplification. Previous studies were investigated response of underground tunnels using shaking table tests or analytical studies. These analysis methods have disadvantages due to size of model box or higher cost [34]. Therefore, the response of underground tunnels is investigated using idealized soil and geometry with numerical methods. The aim of this study is to investigate the response of tunnels to dynamic loads, considering different tunnel burial depths and tunnel cross-sections. The study also investigates the effect of single tunnels and twin tunnels on site amplification ratios. The idealized geometries were analyzed to obtain the effect of tunnels on the ground surface using FLAC3D code, which uses the Lagrangian finite difference method. The results of the dynamic analyses were compared with results of other researchers.

4.2. Choice of Analysis Method

Closed form solutions cannot be used to solve complex geometries. On the other hand, finite difference or discrete mass methods can be used to model complex geometries and investigate the response of underground irregularities or nonlinear behavior of soil. These methods are characterized as numerical methods with advanced boundary conditions. The finite difference method, which provides the most realistic results, was chosen for model analyses. The method also provides flexibility for modeling irregular geometries. FLAC3D code software, which uses the Lagrangian finite difference method, was employed because of its capability to model using advanced boundary conditions and damping formulations.

4.3. Idealized Geometry and Soil Type

Analytical and numerical methods can be used to investigate the effect of seismic loads. The analytical methods use complex mathematical equations to obtain the effect of seismic loads.

Meanwhile, considering the complex geometry of nature, it becomes evident that numerical methods are necessary for quick and accurate evaluation of scattering and diffraction of waves [35]. Local effects can be modeled with numerical methods using 1D analysis, but this is not sufficient to predict the behavior of 2D and 3D models. Therefore, more realistic results are not obtained through 1D analysis. On the other hand, 3D dynamic analysis is more costly than 2D dynamic analysis. For these reasons, 2D plane strain models were used to obtain more realistic analysis results in this study [47]. Analyzing 2D models is faster than analyzing 3D models, and 2D models help to understand the basic principles and behaviour.

The aim of this study is to investigate the effect of underground irregularities, such as tunnels, on the ground surface during seismic loading. The models were categorized into two main groups: single tunnels and twin tunnels. The effect of different burial depths and tunnel cross-sections on the ground surface for single tunnel models were investigated in the first group. The 2D single tunnel models are shown in **Figure 4.1**.

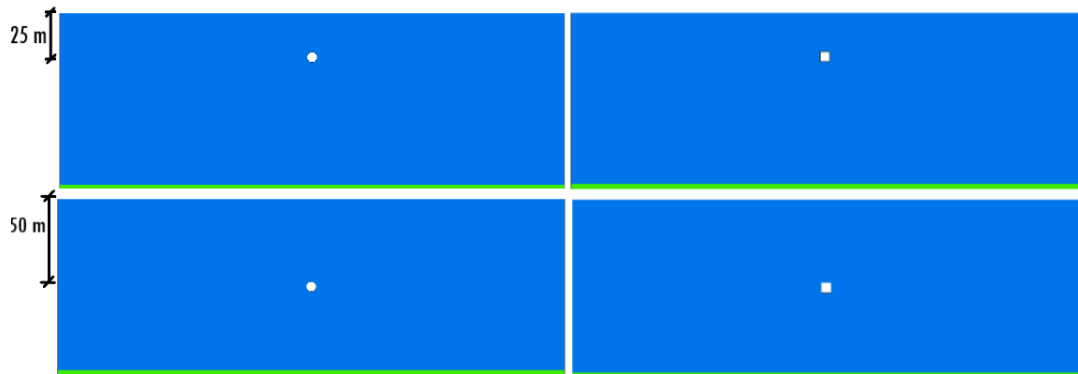


Figure 4.1: The modeled single tunnels' geometry.

FLAC3D code software, which uses the Lagrangian finite difference method, was used to generate a mesh of models, boundary conditions and initial conditions for analyses. The initial conditions of idealized models were reflected as changing with depth. The artificial boundary must be sufficiently scaled; the mesh size should represent real dimensions without significantly affecting the stress-strain field [48]. Lambrughi et al. (2012) reviewed previous studies and suggested minimum dimensions for models, which were $(H+4D)$ for mesh height, $2*(H+4D)$ for mesh length and $2*(H+4D)$ for mesh width.

D and H represent the tunnel diameter and the tunnel axis depth, respectively [49]. In the following years, Su et al. (2019) proposed minimum dimensions for numerical models, which were considered in previous studies. They proposed a half width of model between 4D and 15D, lower height of model between 1D and 10D and upper height of model between 1D and 5D, where D represents tunnel diameter. The dimensions of models are different in each study, which depend on geological conditions and the experience of the researchers [50]. In this study, the model's half width and height dimensions were chosen to be 150 and 100 meters, respectively, depending on previous studies.

Previous studies have also investigated the effect of various burial depths of tunnels on site amplification. For example, studies by Luco and De Barros (1993) and Rodríguez-Castellanos et al. (2006) concluded that location of underground irregularities, such as planar and elliptical cracks, affects seismic response. Alielahi et al. (2016) studied the effect of tunnels on site amplification exposed to P and SV waves. They concluded that when tunnels are closer to the ground surface, their amplification values are greater. According to the finding of literature review, the response of underground tunnels decreases with increasing burial depth of tunnels. In this case, the area of trapped waves increases and obtaining the site amplification becomes more complex. Previous studies have also shown that the presence of shallower underground tunnels causes notable response under seismic loads. Therefore, dynamic analyses were performed for simplified tunnels at burial depths of 25 and 50 meters to investigate the effect of underground tunnels with shallow depth in this study.

The type of tunnel cross-section affects site amplification ratios in the dynamic analysis. The amplification patterns of square cross-section tunnels are different compared to the amplification patterns of circular or horse-shoe cross-section tunnels. The waves trapped between the tunnel crest of square cross-section tunnels and the ground surface generate greater amplification values. The amplification patterns of square cross-section tunnels generate two amplification peaks due to trapped waves at shallow burial depths. Moreover, the trapped waves take some time to dissipate [28], [30], [35]. In this study, the circular and square cross-section tunnels were used to investigate the effect of different cross-sections of underground tunnels. Tunnel diameters change depending on the purpose of the tunnels.

In this study, the diameter of tunnels was chosen to be 6 meters, which is suitable for general tunnel types proposed by Bozkurt (1983) [51]. **Figure 4.2** shows dimensions of the model for single tunnel with circular cross-section.

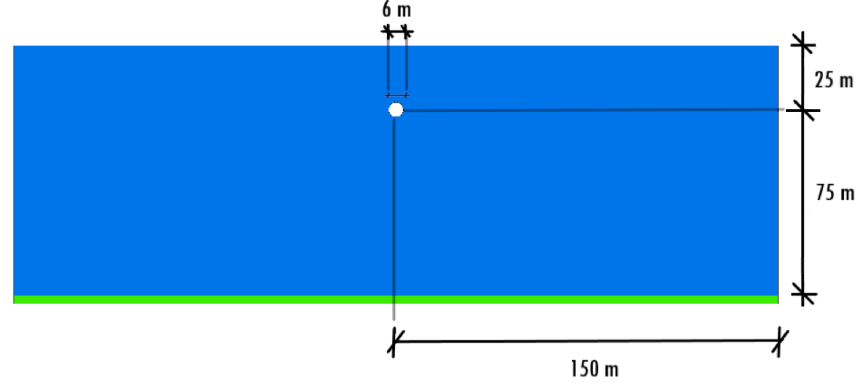


Figure 4.2: Dimensions of the single tunnel's model.

Hashash et al. (2001) carried out seismic analysis and design for underground structures. They concluded that the response of underground tunnels should be taken into account in soft soil at shallow burial depths [52]. Patil et al. (2018) carried out analyses to obtain the response of shallow tunnel in soft soil under seismic loads using different key parameters. They drew attention to the response of underground tunnel in soft soil. Other researchers also emphasized that deeper tunnels in intact rock cause less damage than shallow tunnels in soft soil [53-55]. Considering the previous studies, this study aims to investigate the effect of site amplification ratio due to the presence of underground tunnels in soft clay soil. Geotechnical properties of the used soil type are shown in **Table 4.1**.

Table 4.1: Geotechnical properties of soft clay soil.

Soil Classification	$\phi(^{\circ})$	G (MPa)	K (MPa)	c (kPa)	γ (kN/m ³)
Soft Clay	10	110	290	100	18
Bedrock	*	2200	3666	*	22
ϕ : internal friction angle, G: shear modulus, K: bulk modulus, c: cohesion, γ : unit weight					

The dynamic behavior of twin tunnels with circular and square cross-sections was analyzed as the second group. The total depth of the twin tunnels models was chosen to be same as the single tunnel models, which is 100 meters. These twin tunnels were located at burial depths of 25 and 50 meters in soft clay soil, as shown in **Figure 4.3**.

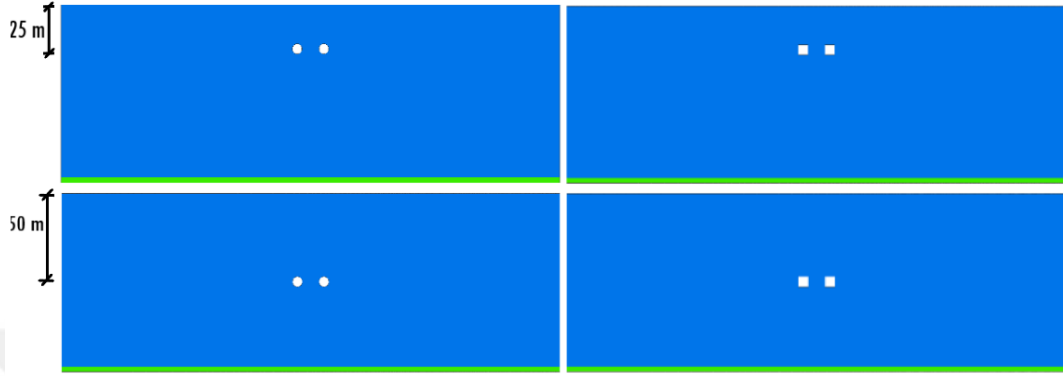


Figure 4.3: The modeled twin tunnels' geometry.

The site amplification ratios of twin tunnels are greater than the site amplification ratios of single tunnels subjected to dynamic loading and interaction between twin tunnels cannot be neglected. Twin tunnels behave similarly to single tunnels under dynamic loading when distance between twin tunnels is sufficiently greater. The distance between twin tunnels was chosen to be 16 meters, considering interaction between the twin tunnels. **Figure 4.4** shows dimensions of model for the twin tunnels with circular cross-section.

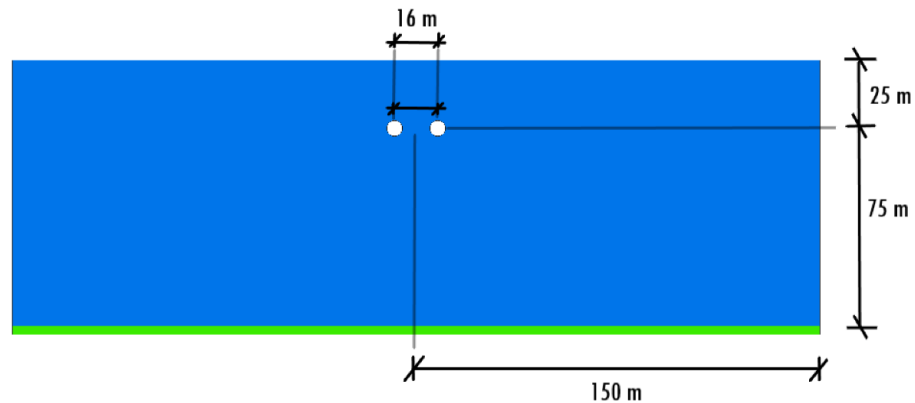


Figure 4.4: Dimensions of the twin tunnels' model.

The dynamic analyses of the models were performed using FLAC3D code, which uses the Lagrangian finite difference method. The dynamic analyses were performed between 5 and 16 hours based on frequency content, duration of the input motions and computer capability. Hysteretic damping and fully non-linear method were used to obtain non-linear behavior of the models. Bedrock was assumed to exhibit elastic behavior in the models. **Figure 4.5** shows the degradation curve of used clay materials. The curve was obtained using relationships proposed by Ishibashi and Zhang (1993) [56].

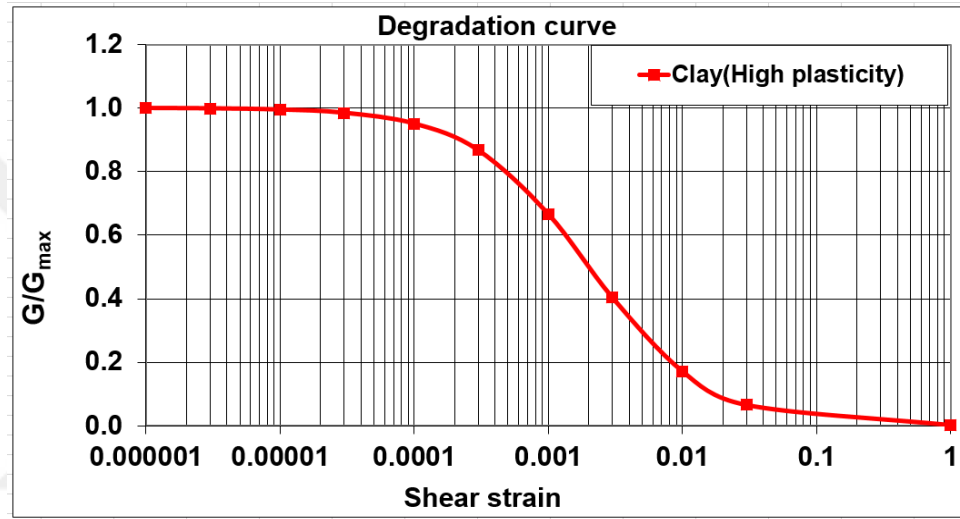


Figure 4.5: Degradation curve of the selected soft clay material.

Two advanced boundary conditions, which are Quiet and Free-Field Boundaries, were applied to the numerical models for analyses. The Quiet Boundary condition provides reflected waves to leave from the bottom of the model and Free-Field Boundary condition provides wave to exit side boundaries of the model without being wave reflection back into the model. **Figure 4.6** shows schematic coupling of the finite difference main grid to free-field grids using viscous dashpots.

Moreover, the element size was selected to be suitable for wave propagation in the models proposed by Kuhlemeyer and Lysmer (1973). The element size should not be greater than one tenth or one eighth of wavelength associated with the greatest frequency component of the dynamic loads [46].

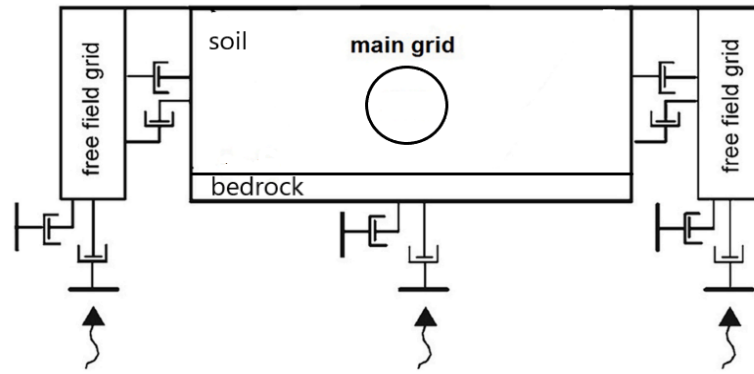


Figure 4.6: Schematic coupling of the applied dynamic boundary conditions to the main grid.

4.4. Dynamic Loading

The characteristics of input motions, such as frequency content and PGA (peak ground acceleration) level, affect site amplification ratio. Reflection and refraction of an elastic wave occur when it reaches the boundary of two layers. Body waves are categorized as compression waves (P waves) and shear waves (S waves). There are two distinct components of shear waves, which are SV and SH waves. As shown by arrows in **Figure 4.7**, SV waves are particles moving in the plane of propagation [57]. This study investigates the site amplification ratio generated by underground tunnels subjected to SV waves.

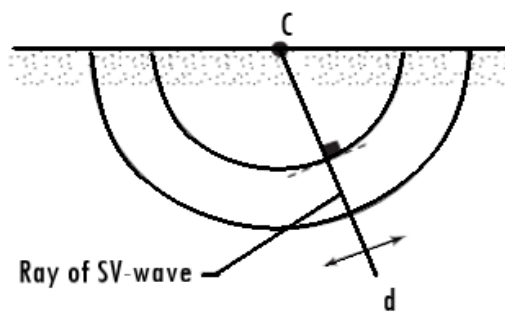


Figure 4.7: Particles moving in the plane of propagation [57].

A collection of eight real strong ground motions was chosen to investigate the effect of input motions on site amplification ratio. To avoid the effect of different soil layers in the dynamic analyses, they were filtered to correlate with bedrock motion or deconvoluted to the corresponding bedrock motion.

The recorded motions were selected to have shear wave velocity greater than 750 m/s from recorded on the bedrock layer. This collection has four peak ground acceleration levels of 0.1g, 0.2g, 0.3g and 0.4g. The motions with R_{jb} (Joyner-Boore distance) are less than 20 km to represent the specifications of the near-field motions. **Table 4.2** presents the characteristics of motions with peak ground accelerations of 0.1 and 0.2g in dynamic analyses. **Table 4.3** presents characteristics of motions with PGAs of 0.3 and 0.4g in dynamic analyses.

Table 4.2: Specifications of peak ground acceleration of 0.1g and 0.2g.

	Palm Spring (1986)	Sakarya (1999.11.11)	Düzce (1999.11.12)	Dinar (1995)
Station	Silent Valley	Sakarya Develop. Burea	Lamont-531	Dinar Station
Site class	Decomposed granite	Sandstone	Rock	Alluvium
Magnitude	$M_L=5.9$	$M_d=5.7$	$M_w=7.1$	$M_L=5.9$
Depth (km)	11.1	8.9	-	12
R_{jb} (km)	19.5	17.5	11.4	2
PGA (g)	0.1	0.2	0.2	0.2

Table 4.3: Specifications of peak ground acceleration of 0.3g and 0.4g.

	Mendocino (1992)	South Iceland (2000.06.17)	Umbria Marche (1997.10.16)	Kocaeli (1999.08.17)
Station	EEL River Valley	Thjorsarbru	Calfiorito- Casermette	Sakarya Develop. Burea.
Site class	Rock	Rock	Rock	Sandstone
Magnitude	$M_L=6.5$	$M_w=6.5$	$M_w=4.3$	$M_d=7.4$
Depth (km)	14.6	15	2	18
R_{jb} (km)	15	15	1	3.5
PGA (g)	0.3	0.4	0.4	0.4

The selected strong ground motions have been generated with right strike-slip faulting mechanism. The strong ground motions were obtained from reliable research centres.

Palm Spring, Mendocino, Kocaeli and Umbria Marche Earthquakes were obtained from PEER (Pacific Earthquake Engineering Research Center) ground motion database. The other strong ground motions were obtained from KOERI (Kandilli Observatory and Earthquake Research Institute) and IIEES (International Institute of Earthquake Engineering and Seismology) ground motion databases. The earthquake motions with different characteristics, which were baseline and filtered, were selected to analyze the response of the models [58]. **Figures 4.8 and 4.9** show acceleration-time and acceleration response spectrum histories of ground motion records.

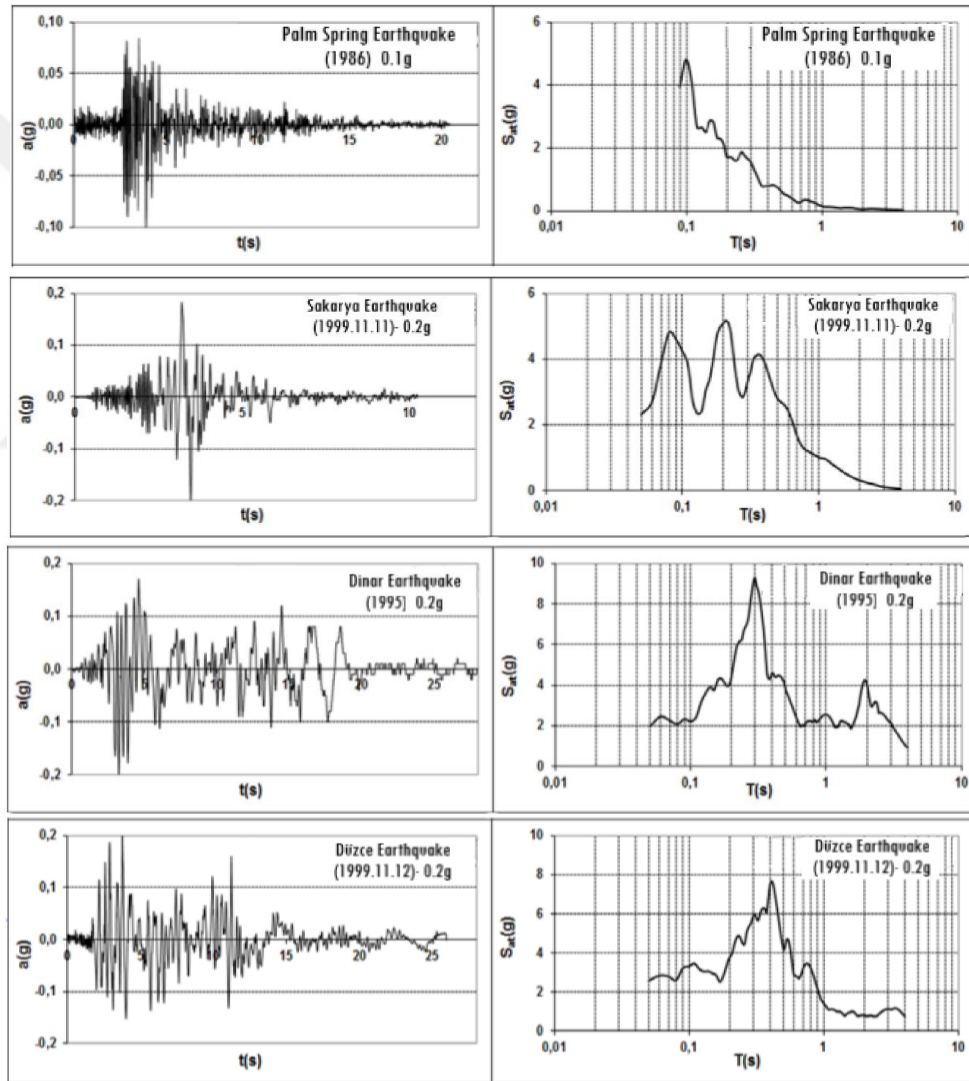


Figure 4.8: The acceleration-time and acceleration response spectrum histories with PGA of 0.1g and 0.2g, respectively.

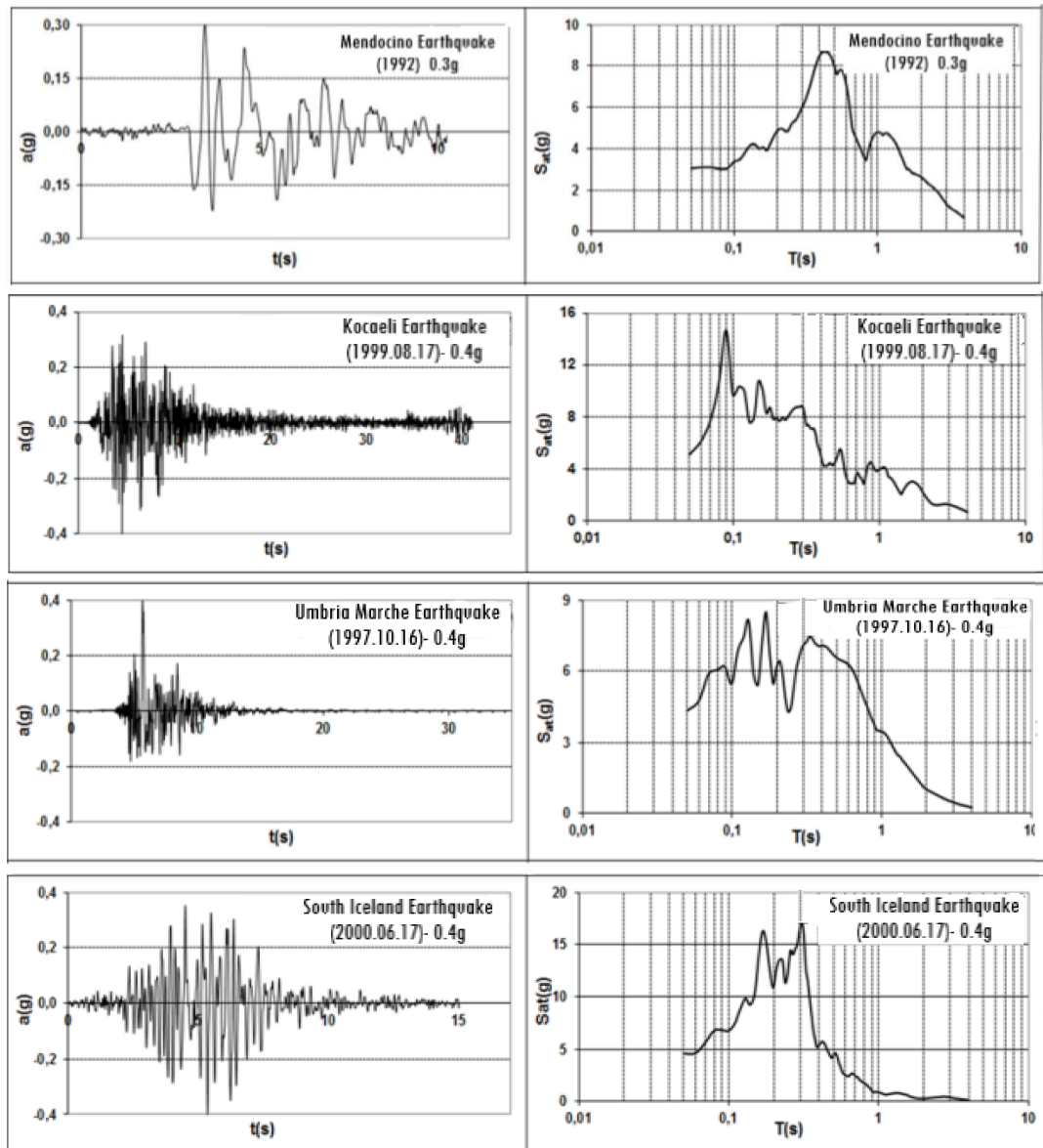


Figure 4.9: The acceleration-time and acceleration response spectrum histories with PGA of 0.3g and 0.4g, respectively.

5. VERIFICATION OF THE MODELS

A solution method, which was studied by Dravinski and Yu (2013), was used to verify the dynamic analysis results of the idealized models [22]. The solution method has been accepted by other researchers. This solution was performed dynamic analysis of an elastic inclusion, which is illustrated in **Figure 5.1**.

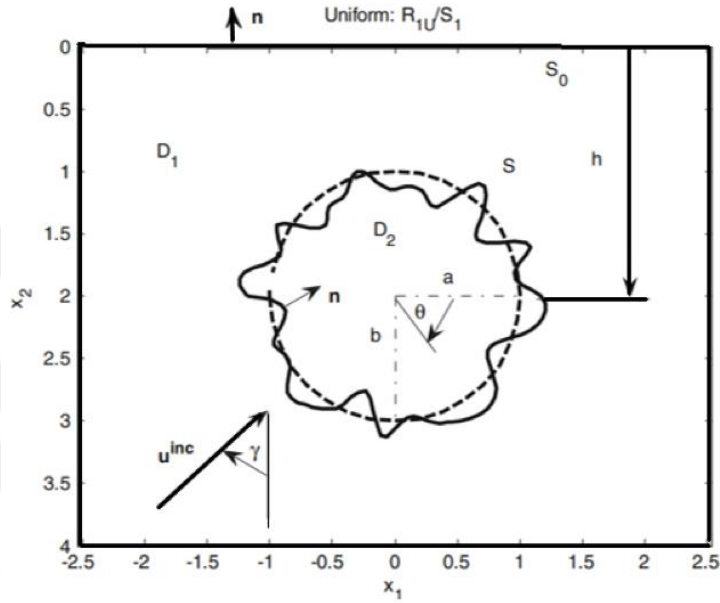


Figure 5.1: The model of randomly corrugated inclusion studied by Dravinski and Yu (2013) [22].

h , a , b , and γ denote burial depth of the randomly corrugated, principal axes and angle of the incident wave, respectively, in **Figure 5.1**. In this study, principal axes, a and b , must have same value to create a circular cross-section inclusion. D_1 and D_2 illustrate half-space domain and inclusion domain based on x_1 and x_2 , which represent dimensionless width and depth of the model, respectively. The half width and depth of model were selected to be 20 and 25 meters, respectively. Circular inclusion diameter and h/a ratio were selected to be 4 meters and 5, respectively. The displacement along the model surface points was analyzed using FLAC3D code, which uses the Lagrangian finite difference method. The validation model is presented in **Figure 5.2**. Free-field and quiet boundary conditions were applied to the validation model. In the validation model, behavior of bedrock, elastic inclusion and soil was assumed to be elastic. The geotechnical properties of the model are presented in **Table 5.1**.



Figure 5.2: Description of the validation model.

Table 5.1: Geotechnical properties of the model.

Soil Classification	V_s (m/s)	G (MPa)	K (MPa)
Soil	100	15	32,5
Bedrock	15000	33,75e5	7,3125e6
Elastic Inclusion	225	101,25e4	22e5
G: shear modulus, K: bulk modulus, V_s : shear wave velocity			

The impedance contrast (I), which is defined between elastic inclusion and half space, was assumed to be 300 for the validation model. I is defined in Equation (5.1).

$$I = \frac{\rho_1 * \beta_1}{\rho_2 * \beta_2} \quad (5.1)$$

where ρ and β represent mass density and wave velocity, respectively. The Ricker wavelets were applied to the validation model to obtain displacement values.

The Equation (5.2), which represents SV waves, defines propagating wave equation, and angle of incident wave is assumed to be zero.

$$f(t) = A_{\max} [1 - 2 * (\pi * f_p * (t - t_0))^2] e^{-(\pi * f_p * (t - t_0))^2} \quad (5.2)$$

where predominant frequency (f_p), total time, time shift parameter (t_0) and maximum amplitude of time history ($A_{\max}$) parameters were assumed to be 12.5 Hz, 1 s, 0.2 s and 1 mm, respectively. **Figure 5.3** denotes input motion for the verification model.

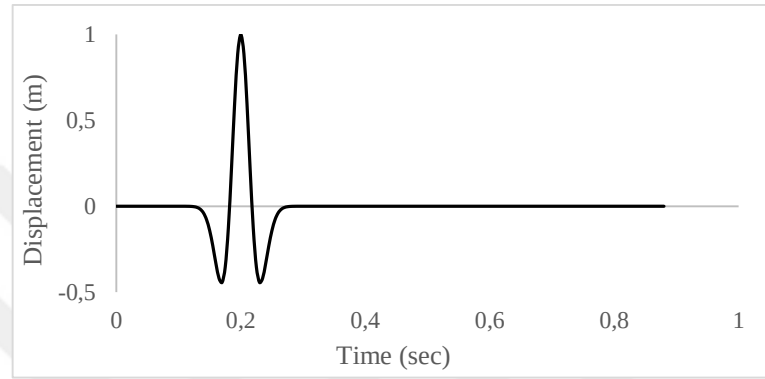


Figure 5.3: Input motion for verification model.

The model was performed under same conditions as the research by Dravinski and Yu (2013), in which the elastic inclusion was located at 5 (h/a). The changing displacement values away from the inclusion axis are presented in **Figure 5.4**.

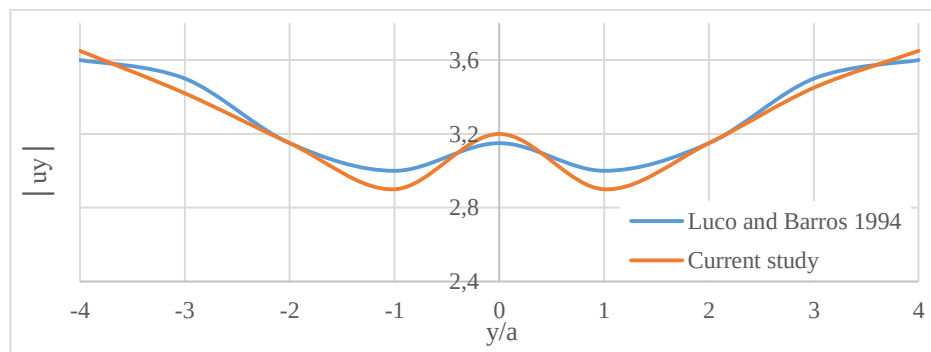


Figure 5.4: Comparison of the results.

It was found that the results are similar to each other, although a few differences are observed. The results suggest that differences arise due to the solution method employed by Dravinski and Yu (2013). It was observed that there is a displacement peak at the axis of elastic inclusion and minimum displacement around the elastic inclusion wall ($y/a=1$). It was also observed that displacement values increase away from the elastic inclusion axis.



6. EFFECT OF THE TUNNELS ON SITE AMPLIFICATION RATIO

6.1. Introduction

In the first step of this study, the effect of 2D single tunnels on site amplification ratio was investigated at shallow depth in soft clay soil. Idealized models were analyzed to investigate effect of the presence of single underground square and circular tunnels on the ground surface. Tunnels were located at burial depths of 25 and 50 meters to evaluate effect of the tunnel burial depth. Different burial depths and cross-sections were employed to compare the differences between idealized single tunnels. Eight strong ground motions were used as seismic loads to obtain the response of the tunnels. Parameters such as properties of soil and characteristics of input motion are important to obtain real response from models during seismic loading. Artificial wave records generate excessive energy when number of cyclic increases in input motion [59]. The response of underground tunnels was obtained from six surface points for each real strong ground motion. **Figure 6.1** shows the location of record points on dimensionless model.

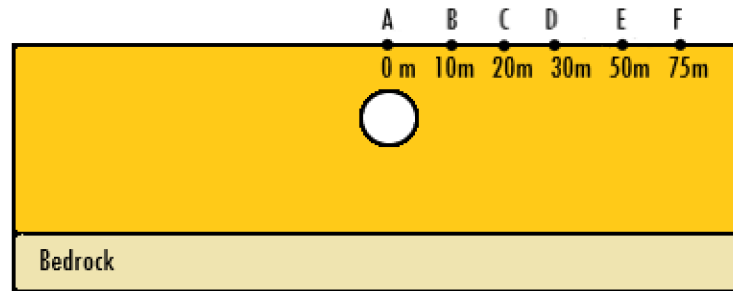


Figure 6.1: The recording points along the dimensionless model.

The acceleration response spectra were obtained to make more useful of the tunnels response for each surface point. The term site amplification ratio refers to the ratio of acceleration response spectrum in the presence of tunnels to the acceleration response spectrum in the absence of tunnels. The acceleration response spectrum in the absence of tunnels, also known as free-field, can be obtained when there are no structural elements in the ground.

Using same earthquake records for both free-field and the presence of underground tunnel models, the acceleration response spectra were obtained. For each frequency, the site amplification ratios were calculated using the acceleration response spectrum ratios obtained from a surface point. For each frequency, the process was repeated to determine the maximum site amplification ratios. The purpose of this process is to investigate the effect of different parameters, including cross-section of tunnels, burial depth of tunnels and input motion characteristics, on site amplification ratios. In the second step of this study, the effect of interaction between underground twin tunnels on site amplification ratios was investigated. The maximum site amplification ratios were obtained using the acceleration response spectra for each surface point.

6.2. Effect of the Single Tunnels on Site Amplification Ratio

Increasing the amplitude of earthquake waves is known as site amplification; local site conditions and wave characteristics, such as incident wave angle, frequency content of input motion, geological conditions, burial depth and geometry of the underground irregularities, affect this term. 1D dynamic analysis is the simplest way to investigate complex local site effect of nonlinear soil behaviour caused by changing stiffness and damping ratios. This analysis is sufficient to study the propagation of body waves in both upward and downward directions. However, 1D analysis is inadequate to study body waves converted to surface waves in the presence of underground irregularities. 2D and 3D analyses are used to examine diffraction and scattering waves [60-61]. In this part of the study, 2D analyses were performed to investigate the effect of burial depth, cross-section of underground single tunnels and input motion characteristics. In idealized models, circular and square cross-section tunnels were chosen to investigate the effect of different cross-section single tunnels on site amplification ratios. The eight strong ground motions were applied to the numerical models using FLAC3D code, which uses Lagrangian finite difference method. **Figures 6.2 and 6.3** show idealized single tunnel models. The model width is 300 meters and the model depth is 100 meters. **Figure 6.4** shows dimensions of the model for single tunnel with circular cross-section.

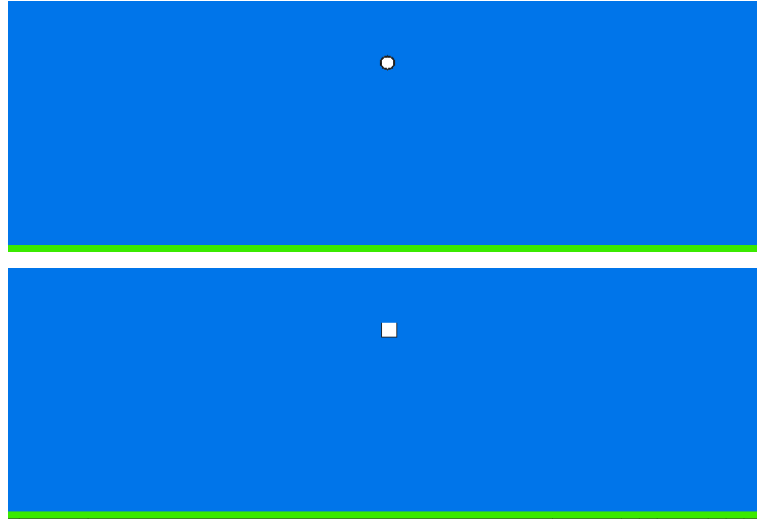


Figure 6.2: The single tunnels with circular and square cross-sections at burial depth of 25 meters.

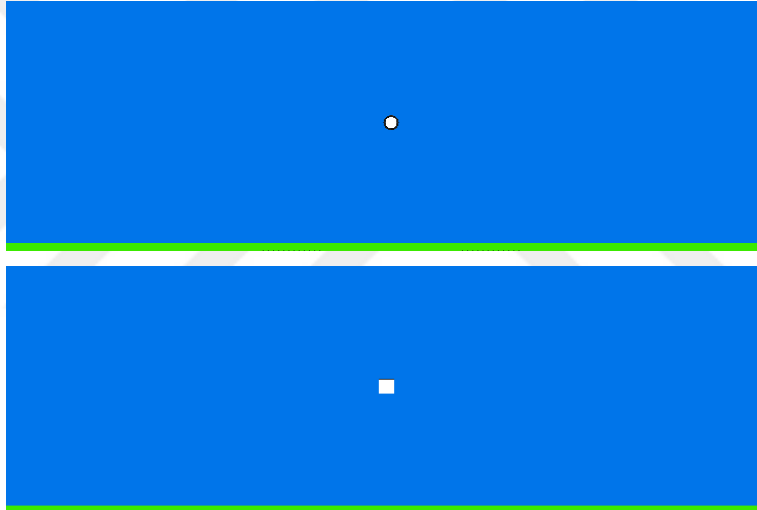


Figure 6.3: The single tunnels with circular and square cross-sections at burial depth of 50 meters.

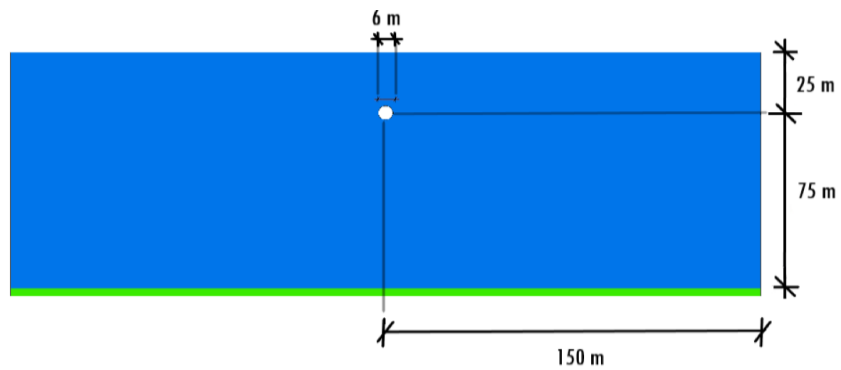


Figure 6.4: The dimensions of the single tunnel's model.

Geotechnical properties of the used soft clay soil are presented in **Table 6.1**.

Table 6.1: Geotechnical properties of soft clay soil.

Soil Classification	$\phi(^{\circ})$	G (MPa)	K (MPa)	c (kPa)	γ (kN/m ³)
Soft Clay	10	110	290	100	18
Bedrock	*	2200	3666	*	22
ϕ : internal friction angle, G: shear modulus, K: bulk modulus, c: cohesion, γ : unit weight					

6.2.1. Effect of the Single Tunnel with Circular Cross-Section on Site Amplification Ratio

In this part, dynamic analyses were performed to obtain the seismic response of single tunnels with circular cross-section, located at burial depths of 25 and 50 meters below the ground surface. **Figure 6.5** shows variation of acceleration-time histories with distance from the tunnel axis for single circular cross-section tunnel at burial depth of 25 meters under the effect of Düzce Earthquake (1999) with PGA of 0.2g.

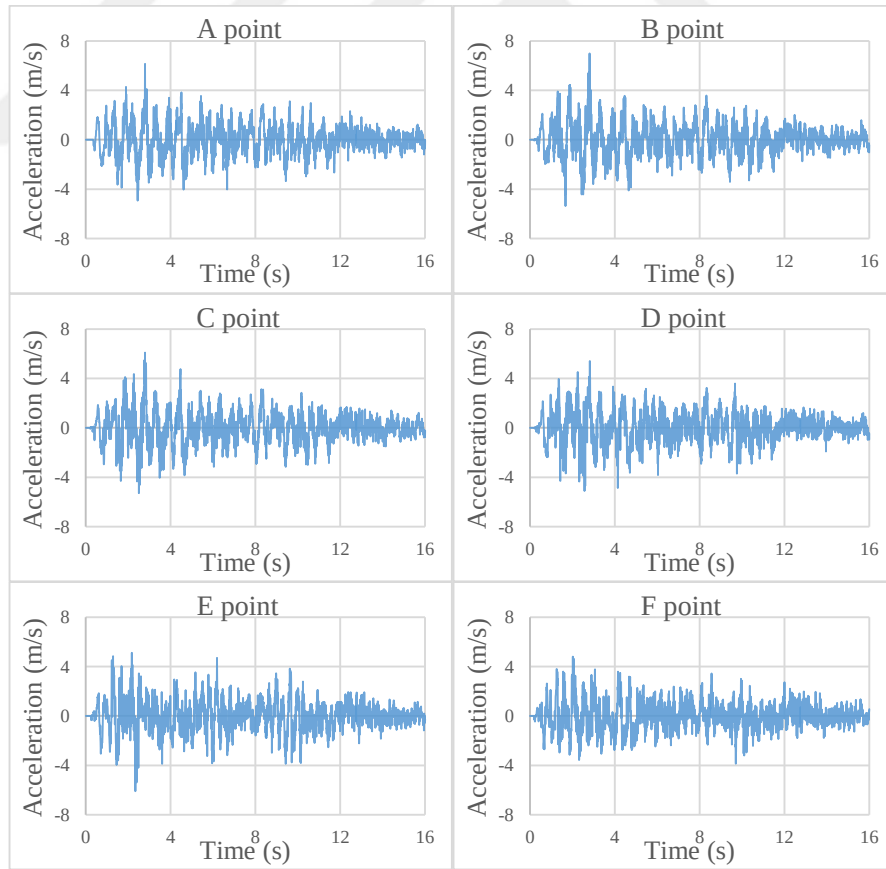
**Figure 6.5:** Variation of acceleration under the effect of Düzce Earthquake.

Figure 6.6 shows acceleration response spectrum histories under the effect of Düzce Earthquake (1999). The site amplification ratios were calculated by dividing the response spectra obtained from model with the tunnel by those obtained from the model without the tunnel. **Figure 6.7** presents variation of site amplification ratios for single tunnels with circular cross-section. The site amplification ratios are greater than one value for both burial depths.

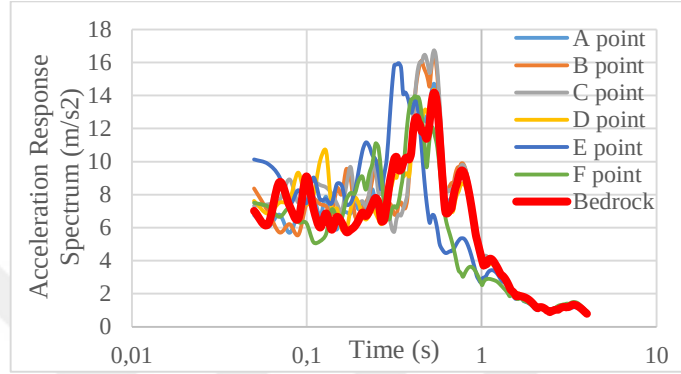


Figure 6.6: Acceleration response spectrum histories under the effect of Düzce Earthquake.

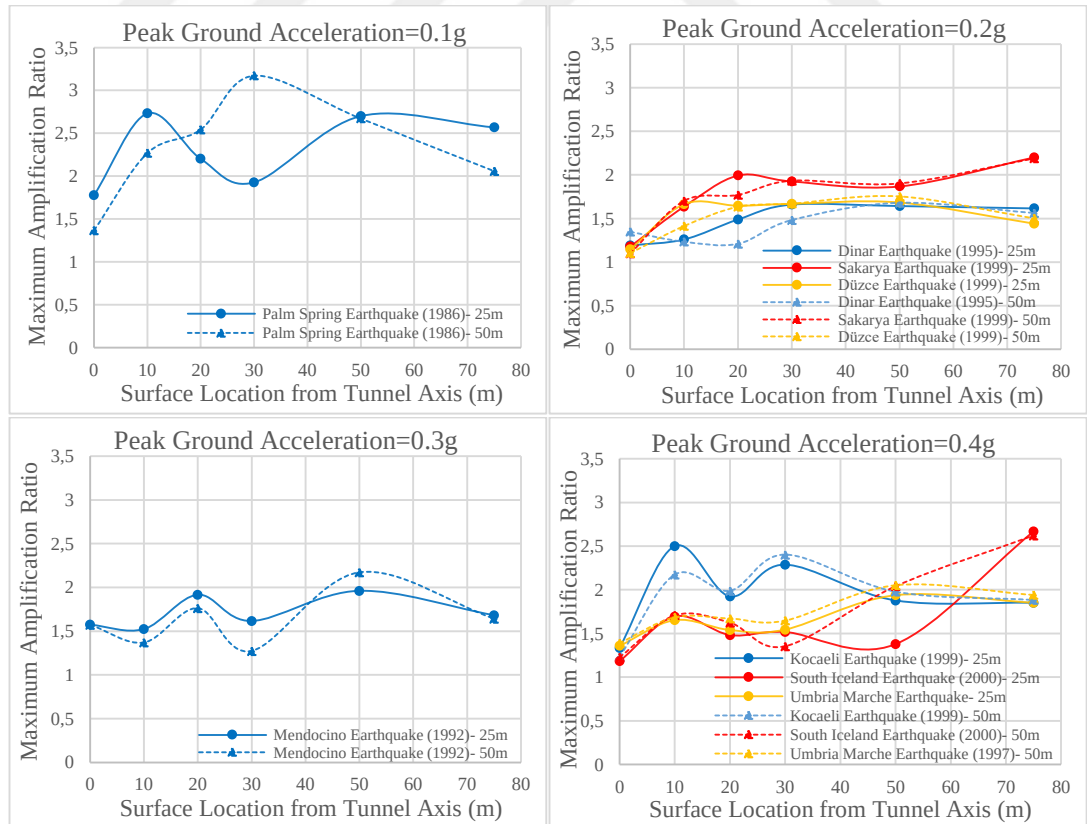


Figure 6.7: Variation of maximum site amplification ratio for single tunnels with circular cross-section at burial depths of 25 and 50 meters.

The results show that site amplification ratios are less under the effect of stronger motions compared to the effect of weaker motion with PGA of 0.1g. This result can be explained by fact that the effect of weaker motion with PGA of 0.1g causes non-linear behavior in the soil, and earthquake energy is more effective under conditions of the model. The patterns of site amplification ratios are similar between shallower and deeper tunnels under the effect of stronger motions, but they are not similar under the effect of motion with PGA of 0.1g. Two peak points are obtained at 10 and 50 meters from tunnel axis and one deamplification point is obtained at 30 meters from tunnel axis for shallower tunnel. When a deamplification point occurs for the shallower tunnel, an amplification point is observed for the deeper tunnel at 30 meters from tunnel axis. Minimum site amplification ratios are observed at the tunnel axis for both burial depths and soil amplification ratios increase away from the tunnel axis. The site amplification ratio of shallower tunnel, which reaches 1.78 at the tunnel axis, increases to 2.57 at the furthest surface point from the tunnel axis. The site amplification ratio of the deeper tunnel, which reaches 1.37 at the tunnel axis, reaches 2.06 at the furthest surface point from the tunnel axis. At the furthest surface point from the tunnel axis, it was observed that the site amplification ratio is greater value for the shallower tunnel. Moreover, it was noticed that maximum site amplification ratios reach almost 2.7 for both burial depths at 50 meters from the tunnel axis under the effect of motion with PGA of 0.1g. The location of maximum site amplification ratio for the shallower tunnel is closer to the tunnel axis compared to the deeper tunnel. The maximum site amplification ratio for the deeper tunnel is greater than ratio of the shallower tunnel, although location of maximum ratio is further from the tunnel axis.

Earthquake waves are notably affected by various parameters. Depending on the wave characteristics parameters or impedance ratio, waves can be more easily absorbed, propagated or reflected in soft clay soil. Therefore, the effect of Sakaraya Earthquake with PGA of 0.2g and South Iceland Earthquake with PGA of 0.4g causes greater site amplification ratio away from the tunnel axis. The site amplification ratios exhibit as a linear trend between 40 and 50 meters from the tunnel axis for shallower tunnels, under the effect of motions with PGA of 0.2g. The patterns of site amplification ratios are similar for both burial depths, and the ratios are greater for shallower tunnel. In general, the site amplification ratio for shallower tunnel decreases by 11% with increasing burial depth at 20 meters away from tunnel axis.

Under the effect of motions with PGA of 0.2g, for Dinar Earthquake (1995), the maximum amplification ratios reach 1.66 at 30 meters for the shallower tunnel and 1.68 for the deeper tunnel at 50 meters. For Sakarya Earthquake (1999), it reaches almost 2.20 for both burial depths at 75 meters. For Düzce Earthquake (1999), the maximum site amplification ratios reach 1.7 for both burial depths at 50 meters from tunnel axis. In general, under the effect of motions with PGA of 0.2g, the site amplification ratios for the shallower tunnels are greater than those of the deeper tunnels.

Under the effect of motion with PGA of 0.3g, two amplification peak points are observed at two surface points, which occur at 20 and 50 meters away from the tunnel axis. Additionally, the deamplification point occurs at 30 meters from the tunnel axis for both burial depths. In general, the ratios of the shallower tunnel are greater than the deeper tunnel.

Under the effect of motion with PGA of 0.4g, for Kocaeli Earthquake (1999), the maximum amplification ratios reach 2.5 for both burial depths at different surface points. It was observed that the deamplification points move closer to tunnel axis with increasing burial depth for South Iceland Earthquake (2000), and the ratios reach around 1.35. In general, the ratios of deeper tunnels is greater than ratios of shallower tunnel. The difference of tunnel burial depth is more noticeable at 30 meters from the tunnel axis; the site amplification ratio increases by about 10% for deeper tunnels.

Figure 6.8 shows spectral amplification ratios of surface points for single tunnels with circular cross-section in the time domain. The maximum site amplification ratio curves have no information about their corresponding periods. To determine the periods of site amplification ratio, the site amplification ratios should be analyzed in the time domain at each surface point. Six different surface points, marked as A, B, C, D, E and F, were defined to obtain the maximum site amplification ratio periods in the time domain. Under the effect of motions with all PGA levels, it can be observed that the site amplification ratios for the surface point A curve are significantly less than those for the other surface point curves. This observation can be explained by the fact that the tunnels prevent the propagation of seismic waves and generate a safe area at the tunnel axis. Furthermore, seismic response of the tunnels increases around the tunnel axis [32].

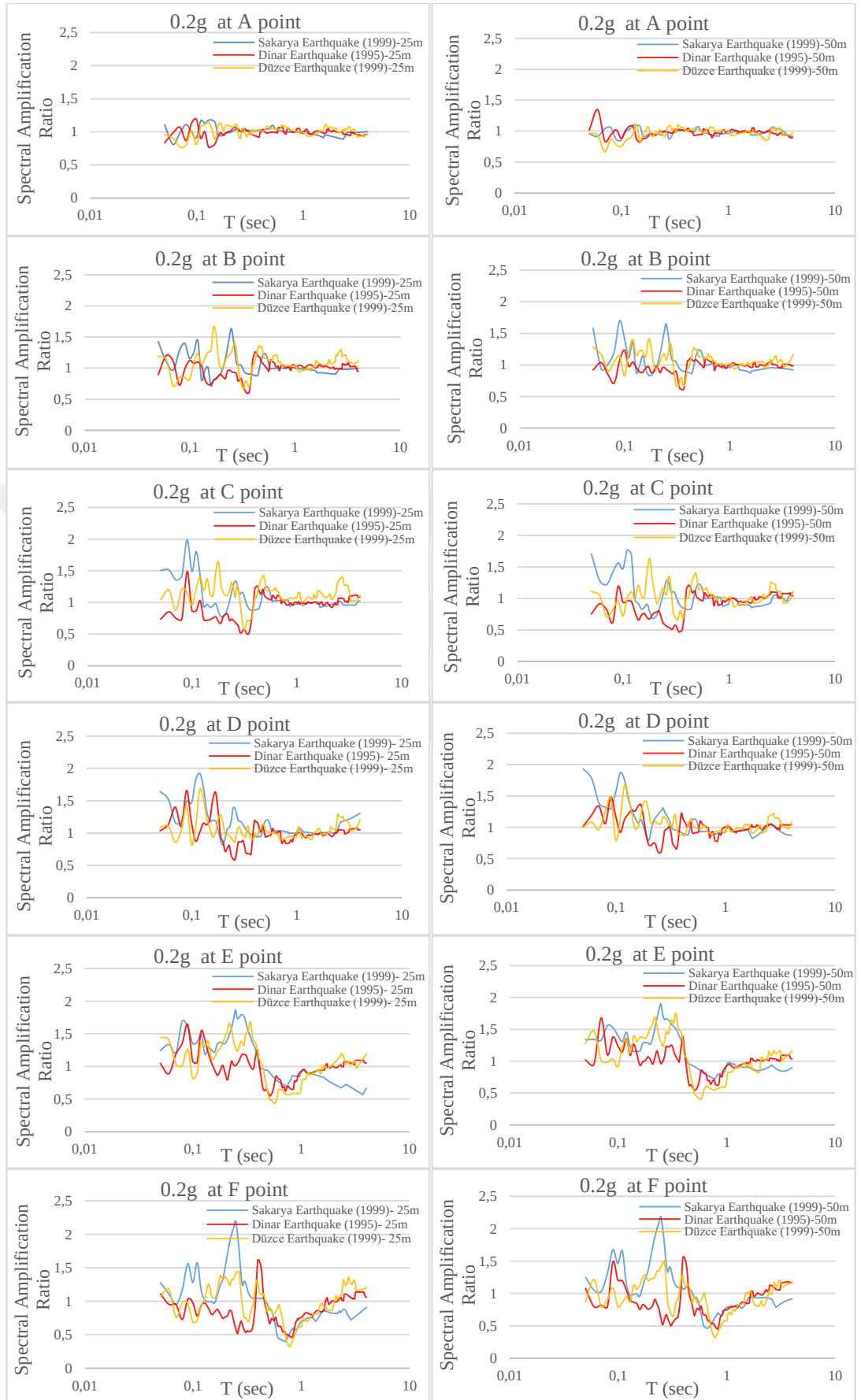


Figure 6.8: Spectral amplification ratio of the surface points for single tunnels with circular cross-section.

The results showed that different surface points are sensitive to lower periods. Under the effect of motions with PGA of 0.2g, the maximum site amplification ratios for the shallower tunnel occur at periods of 0.09 s, 0.277 s, 0.089 s, 0.12 s, around 0.25 s and 0.27 s for surface points A, B, C, D, E and F, respectively. For the deeper tunnels, the ratios occur at periods of 0.05 s, 0.247 s, 0.15 s, 0.12 s, 0.237 s, around 0.4 s for surface points A, B, C, D, E and F, respectively. Under the effect of motions with PGA of 0.4g, the site amplification ratios for the shallower tunnel occur at periods of 0.237 s, 0.257 s, 0.237 s, 0.227 s and 0.208 s for surface points B, C, D, E and F, respectively. For the deeper tunnel, the ratios occur at periods of 0.217 s, 0.227 s, 0.237 s, 0.217 s, 0.217 s for surface points B, C, D, E and F, respectively.

6.2.2. Effect of the Single Tunnel with Square Cross-Section on Site Amplification Ratio

Tunnel cross-section plays a significant role for site amplification ratios. To investigate the effect of tunnel cross-section, tunnel with square cross-section was investigated using distance from the tunnel axis and time domain curves. **Figure 6.9** shows variation of maximum site amplification ratio curves for the single tunnel with square cross-section, which are fixed at burial depths of 25 and 50 meters below the ground surface.

Under the effect of motion with PGA of 0.1g, the site amplification ratios of the square tunnel are greater than those of the circular tunnel values at 0 meters for both burial depths. There are two peak points for shallower circular and square tunnels. The first point reaches 2.73 for shallower circular tunnel at 10 meters and 2.35 for shallower square tunnel at 20 meters. The second point reaches 2.7 for shallower circular tunnel and 2.78 for shallower square tunnel at 50 meters from tunnel axis. In general, the maximum site amplification ratios of the deeper tunnels are greater than the ratios of shallower tunnel.

Under the effect of motions with PGA of 0.2g, the ratios of square tunnel are greater than the circular tunnel for both burial depths. In general, there are two peak points for shallower square tunnel. The points reach almost 2 for Sakarya Earthquake and reach 1.67 and 1.90 for Düzce Earthquake at 10 and 30 meters from tunnel axis. The points reach 1.53 at 20 meters and 1.82 at 50 meters for Dinar Earthquake.

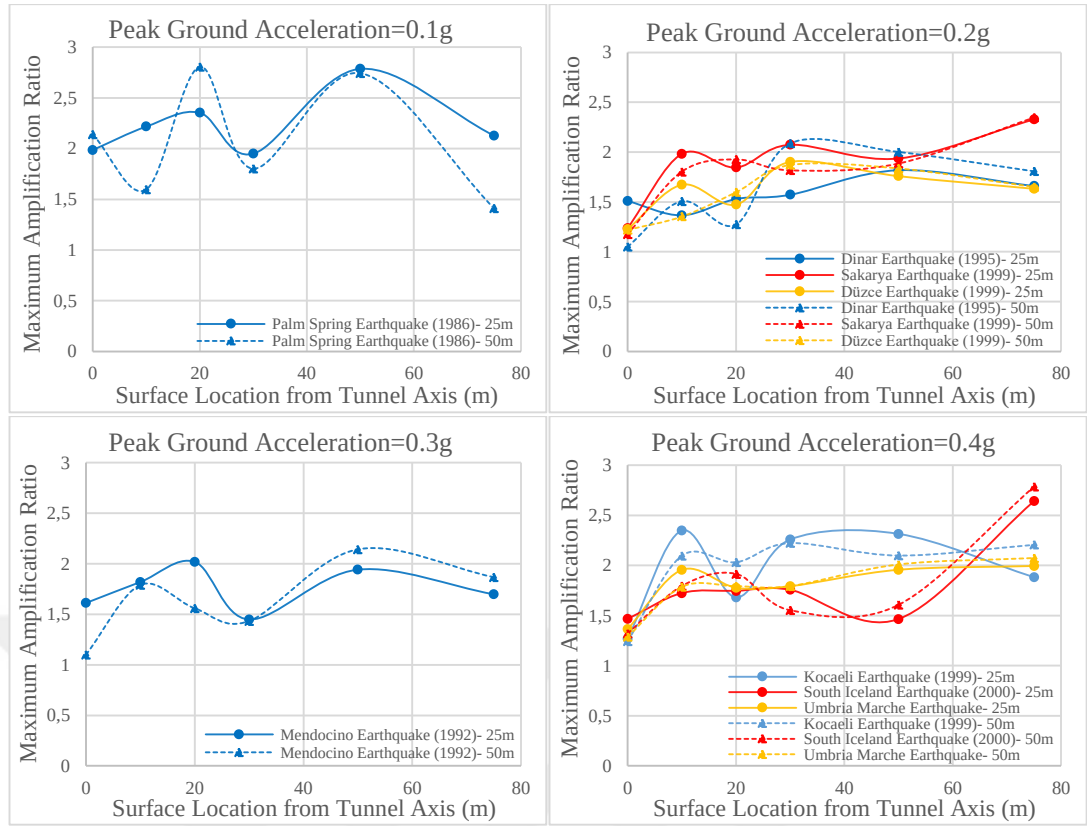


Figure 6.9: Variation of maximum site amplification ratio for single tunnels with square cross-section at burial depths of 25 and 50 meters.

Sakarya Earthquake curve has a peak point for the shallower circular tunnel which reaches 1.99, while deamplification point for the shallower square tunnel reaches 1.84 at 20 meters from tunnel axis. For the square tunnel, the maximum amplification ratios decrease at 10 and 30 meters from tunnel axis, while the deamplification ratios increase with increasing tunnel depth for both Sakarya and Düzce Earthquakes. In general, the effect of the deeper tunnels are dominant after 40 meters away from the tunnel axis for both cross-sections. In general, the difference for the burial depth becomes noticeable at 10 meters away from the tunnel axis for both cross-sections. After 20 meters from the tunnel axis, the effect of square cross-section tunnel are greater than the effect of circular cross-section tunnel for both burial depths. The site amplification ratios of the deeper square tunnels are generally 10% less than ratios of the shallower square tunnels.

Under the effect of motion with PGA of 0.3g, for the shallower square tunnel, two amplification peaks occur at 20 and 50 meters. This case occurs at 10 and 50 meters for the deeper square tunnels. Additionally, the ratios of deeper square tunnels are greater after 30 meters from the tunnel axis.

Under the effect of motion with PGA of 0.4g, for the shallower square tunnel, a deamplification point is observed at 50 meters from the tunnel axis. However, this case is observed at 30 meters from the tunnel axis as the tunnel depth increases for South Iceland Earthquake. For both burial depths, the ratios reach 1.76 at between 20 and 30 meters from the tunnel axis for Umbria Marche Earthquake. The site amplification ratio peaks occur at 10 and 30 meters away from the tunnel axis for shallower square and circular tunnels, the ratios of shallower circular peaks are greater than shallower square tunnels for Kocaeli Earthquake. In **Figure 6.9**, two site amplification ratio peaks are observed for almost all of curves based on frequency content. The site amplification ratio is greater for tunnels with square cross-section due to trapped waves between tunnel crest and the ground surface. Additionally, the effects of the waves take longer time to dissipation. This scenario can be observed with two peaks and one bottom point (deamplification) [35].

To determine the periods of maximum site amplification ratio, the site amplification ratios were analyzed in the time domain at each surface point. The **Figure 6.10** illustrates spectral amplification ratios under the effect of motions with PGA of 0.2g. Six different surface points, marked as A to F, were defined to obtain the maximum site amplification ratio periods in the time domain. Under the effect of motions with PGA of 0.2g, the maximum site amplification ratio for the shallower square tunnel occur at periods of 0.247 s, 0.09 s, 0.12 s, around 0.25 s and 0.3 s for surface points B, C, D, E and F, respectively. Ratios for the deeper square tunnel occur at periods of 0.12 s, 0.138 s, 0.09 s, around 0.25 s, around 0.4 s for surface points B, C, D, E and F, respectively. Under the effect of motions with PGA of 0.4g, the maximum site amplification ratios for the shallower tunnel occur at periods of 0.237 s, 0.247 s, 0.237 s, 0.217 s and 0.217 s for surface points B, C, D, E and F, respectively. Ratios for the deeper tunnel occur at periods of 0.227 s, 0.227 s, 0.237 s, around 0.3, 0.217 s for surface points B, C, D, E and F, respectively. It was observed that there are two peaks for spectral amplification ratio curves of Sakarya Earthquake at points B and E, under the effect of motion with 0.2g. The first peak occurs at period of around 0.12 s and the other one occurs at period of around 0.26 s for shallower tunnel. For deeper tunnel, the first peak occurs at period of about 0.1 s and the other one occurs at period of around 2.5 s.

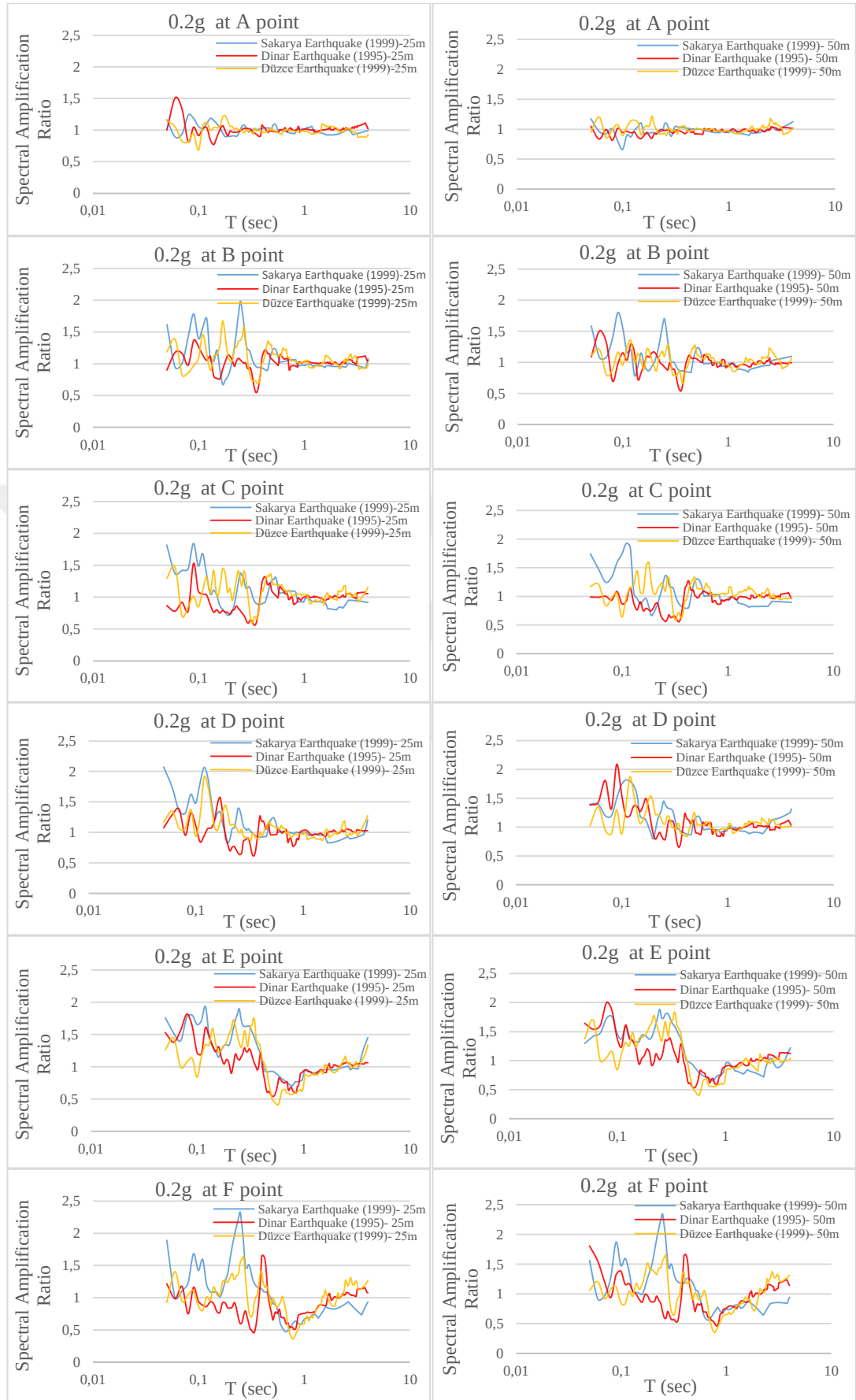


Figure 6.10: Spectral amplification ratio of the surface points for single tunnels with square cross-section.

These points show second resonance mode, the behaviour of points B and E is similar to a transient point. Since different periods are important for the features of structural design, both the spectral amplification ratio and the position of resonance period should be taken into account together.

6.3. Effect of the Twin Tunnels on Site Amplification Ratio

In this part of the study, the effect of interaction between twin tunnels, burial depth and cross-section of twin tunnels was investigated in 2D dynamic analyses of twin tunnels. The idealized twin tunnels models width is 300 meters and the model depth is 100 meters. The eight strong ground motions were applied to models using FLAC3D code, which uses Lagrangian finite difference methods. **Figure 6.11** and **6.12** show the idealized twin tunnels at burial depths of 25 meters and 50 meters below the ground surface, respectively. To estimate the behavior of twin tunnels under the effect of motions with different PGAs, acceleration response spectra for each surface point were used. **Figure 6.13** shows the dimensions of the model for twin tunnels with circular cross-section. Geotechnical properties of the used soft clay in the idealized models are presented in **Table 6.2**.

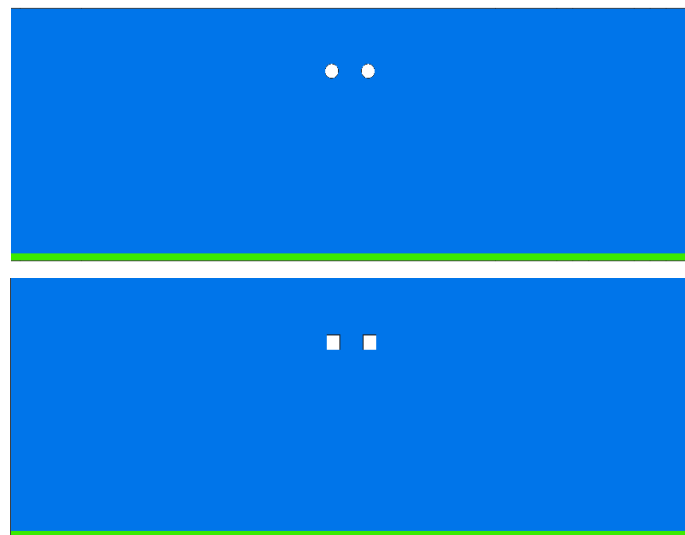


Figure 6.11: The twin tunnels with circular and square cross-sections at burial depth of 25 meters.

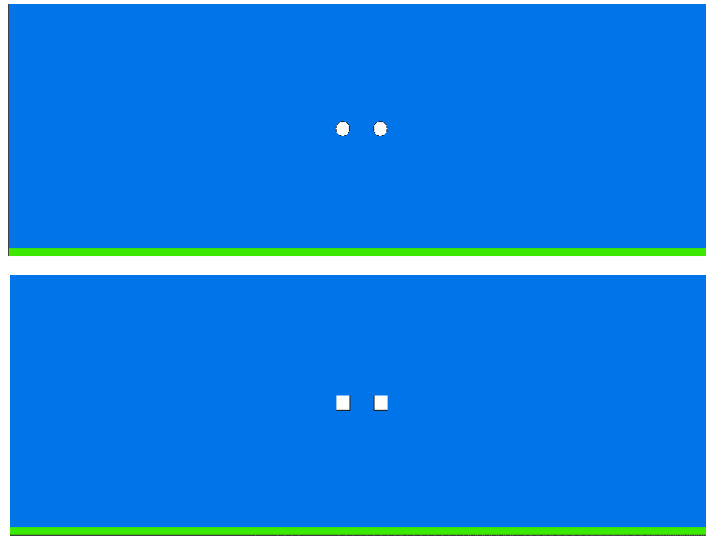


Figure 6.12: The twin tunnels with circular and square cross-sections at burial depth of 50 meters.

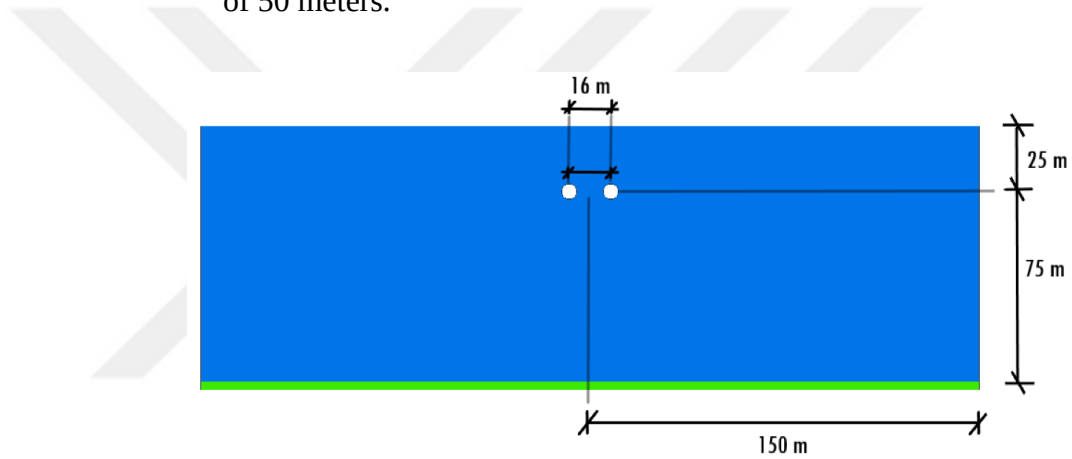


Figure 6.13: Dimensions of the twin tunnels' model.

Table 6.2: Geotechnical properties of soft clay soil.

Soil Classification	$\phi(^{\circ})$	G (MPa)	K (MPa)	c (kPa)	γ (kN/m ³)
Soft Clay	10	110	290	100	18
Bedrock	*	2200	3666	*	22
ϕ : internal friction angle, G: shear modulus, K: bulk modulus, c: cohesion, γ : unit weight					

6.3.1. Effect of the Twin Tunnels with Circular Cross-Section on Site Amplification Ratio

Figure 6.14 illustrates variation of maximum site amplification ratio curves for the twin tunnels with circular cross-section at various burial depths. Under the effect of motion with PGA of 0.1g, the maximum site amplification ratios occur at 10 meters from the midpoint of the twin tunnels for the deeper twin tunnels and at 20 meters from the midpoint of the twin tunnels for the shallower twin tunnels.

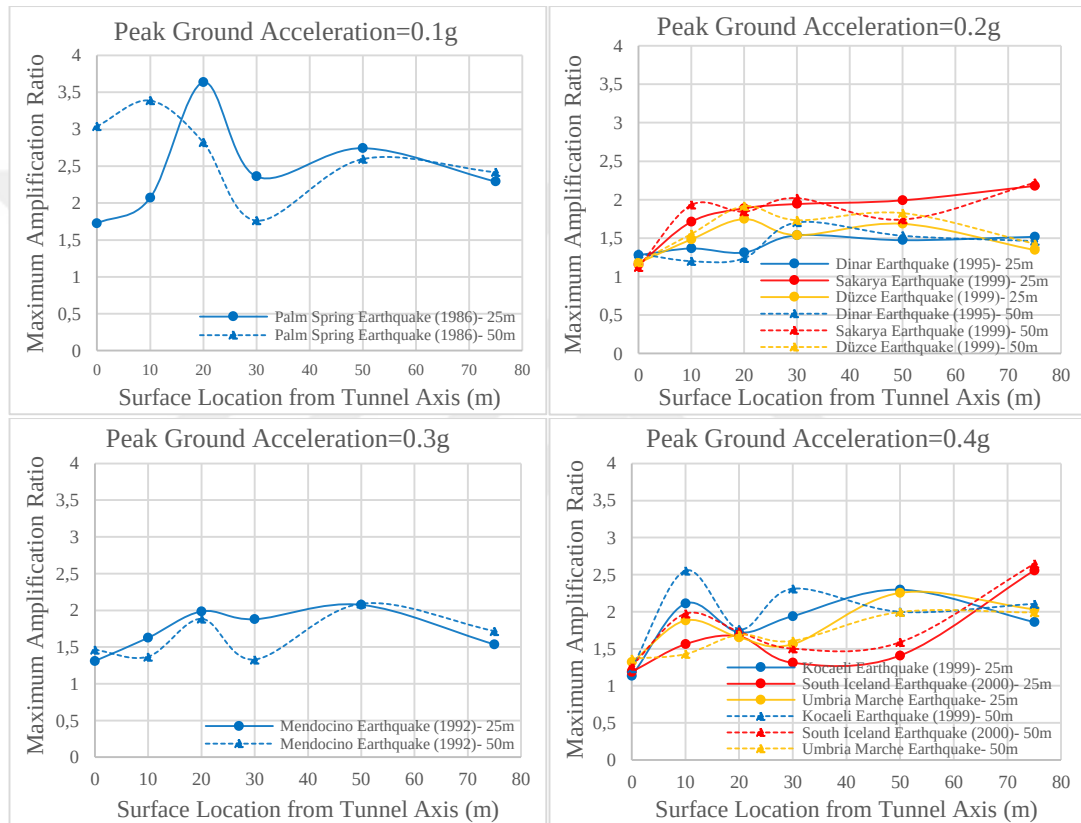


Figure 6.14: Variation of maximum site amplification ratio for twin tunnels with circular cross-section at burial depths of 25 and 50 meters.

The site amplification ratio of the shallower twin tunnels is 75% greater than that of the shallower single tunnel. The maximum site amplification ratios are almost same at the midpoint of twin tunnels under the effect of stronger motions for both burial depths, except for motion with PGA of 0.1g. It was found that the ratios of deeper twin tunnels are greater than those of the shallower twin tunnels at midpoint of the twin tunnels.

Under the effect of motions with PGA of 0.2g, site amplification ratios of the deeper twin tunnels are more dominant than those of the shallower twin tunnels after 20 meters away from the midpoint of twin tunnels for Dinar Earthquake. It was observed that the patterns for Dinar and Düzce Earthquakes are similar for both burial depths but the patterns for Sakarya Earthquake are not similar. It should also be noted that the deeper twin tunnels exhibit greater ratios along the ground surface for Düzce Earthquake. The burial depth difference is essentially insignificant at 0 meters. In general, at 30 meters from the midpoint, the site amplification ratios of the deeper twin tunnels are greater than those of the shallower twin tunnels by more than 11%.

Under the effect of motion with PGA of 0.3g, two amplification points and one deamplification point are clearly observed for the deeper twin tunnels. In general, the shallower twin tunnels are dominant along the model surface. When the ratios of square and circular cross-section twin tunnels are compared, it is observed that the site amplification ratios are greater for both the shallower circular cross-section twin tunnels and the deeper square cross-section twin tunnels.

Under the effect of motions with PGA of 0.4g, the maximum site amplification ratios are obtained around 1.78 at 20 meters from the midpoint between the twin tunnels for both burial depths. The locations of maximum site amplification ratios are obtained at the same surface points for both burial depths, although the trends of site amplification ratios are generally different. In general, under the effect of motion with PGA of 0.4g, the site amplification ratios of shallower twin tunnels are greater, and under the effect of motion with PGA of 0.2g, the ratios of deeper twin tunnels are greater.

To determine the periods of maximum site amplification ratios, the site amplification ratios were analyzed in the time domain at each surface point. **Figure 6.15** shows the spectral amplification ratio curves for twin circular cross-section tunnels, under the effect of motions with PGA of 0.2g. Important periods were recorded at surface points A to F along the model surface. Under the effect of motions with PGA of 0.2g, the spectral amplification ratios for the shallower circular twin tunnels occur at periods of 0.247 s, 0.138 s, 0.1 s, around 0.257 s and 0.4 s for surface points B, C, D, E and F, respectively. Ratios for the deeper circular twin tunnels occur at periods of 0.257 s, 0.168 s, 0.1 s, 0.346 s, around 0.247 s for surface points B, C, D, E and F, respectively.

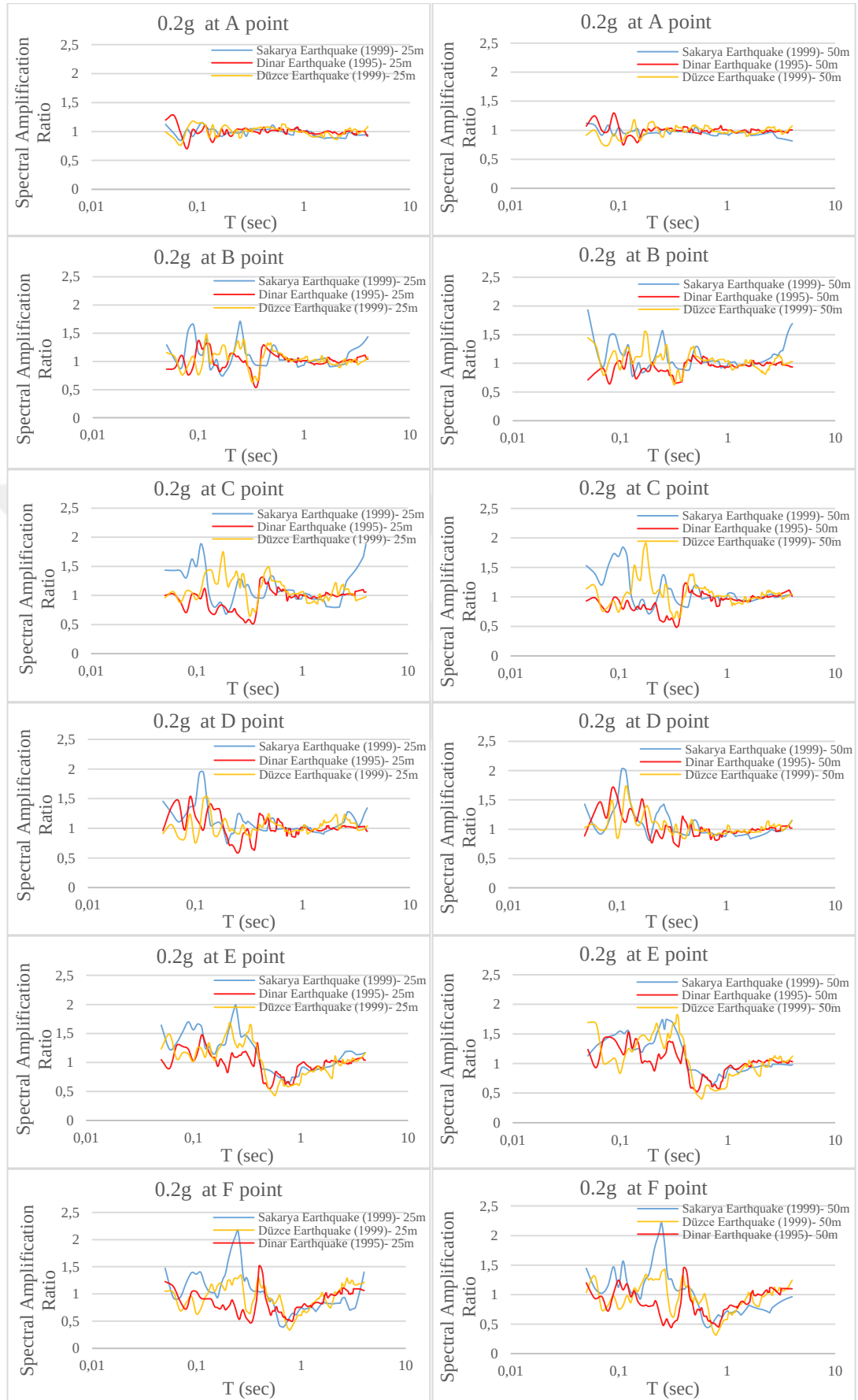


Figure 6.15: Spectral amplification ratio of the surface points for twin tunnels with circular cross-section.

Under the effect of motions with PGA of 0.4g, the spectral amplification ratios for the shallower circular twin tunnels occur at periods of around 0.22 s for surface points B, C, D, E and F. Ratios for the deeper circular twin tunnels occur at periods of 0.23 s for surface points B, C, D and F and at periods of around 0.39 s for surface point E. The results showed that different surface points are sensitive to lower periods.

6.3.2. Effect of the Twin Tunnels with Square Cross-Section on Site Amplification Ratio

Figure 6.16 shows variation of maximum site amplification ratios in the presence of twin tunnels with square cross-section under the effect of strong motions.

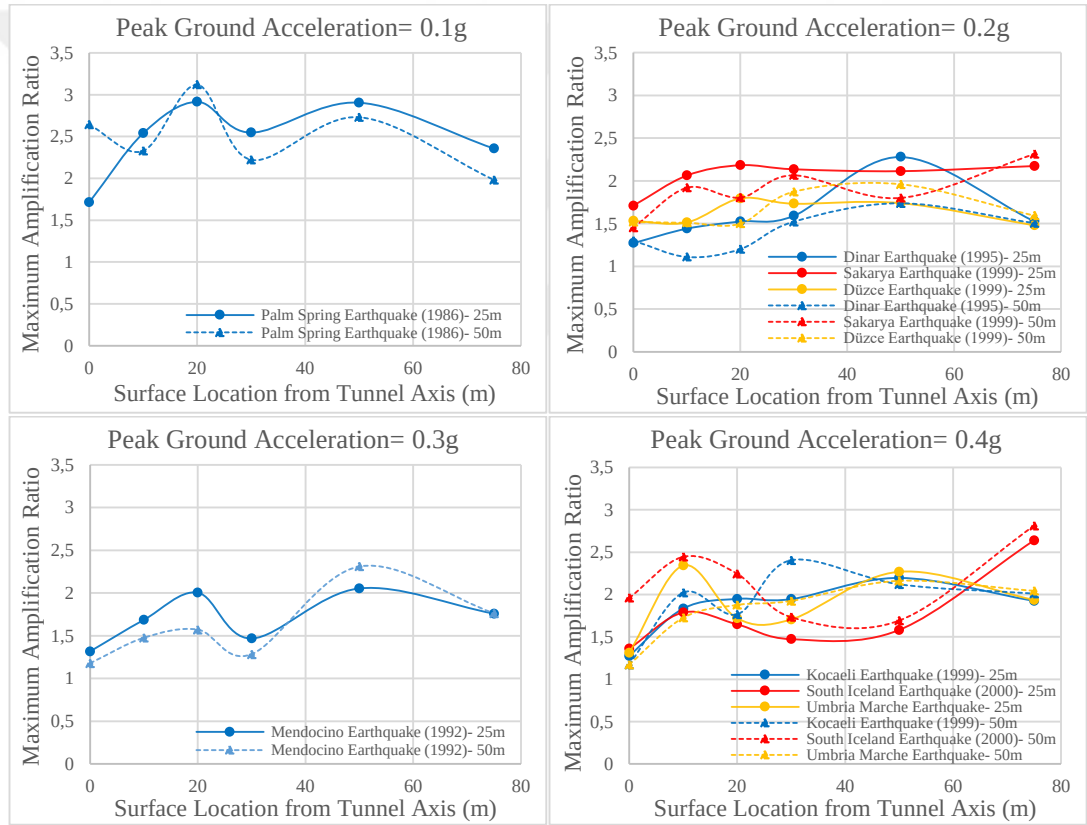


Figure 6.16: Variation of maximum site amplification ratio for twin tunnels with square cross-section at burial depths of 25 and 50 meters.

Under the effect of motion with PGA of 0.1g, the site amplification ratios of twin square tunnels are less than twin circular tunnels. Under the effect of motion with PGA of 0.2g, the patterns of both the shallower and the deeper twin tunnels exhibit distinct patterns under the effect of Sakarya Earthquake.

Two amplification points were observed for the deeper square twin tunnels. The deeper square tunnels are dominant after 30 meters from the midpoint of the twin tunnels for Düzce Earthquake. It was observed that site amplification ratio is 1.5 up to 10 meters from the tunnel axis for shallower tunnels and up to 20 meters from the tunnel axis for deeper tunnels under the effect of Düzce Earthquake. Under the effect of motion with PGA of 0.3g, there are two amplification peak points for both burial depths. The site amplification ratio of the deeper twin tunnels is greater than the shallower twin tunnels at 50 meters from the tunnel axis. Under the effect of motions with PGA of 0.4g, the deeper twin tunnels are generally more dominant than the shallower twin tunnels.

Figure 6.17 illustrates the spectral amplification ratio in the time domain for square twin tunnels under the effect of motions with PGA of 0.2g. The maximum site amplification ratios occur at different periods depending on frequency content of the strong ground motions. The results showed that different surface points are sensitive to lower periods. Under the effect of motions with PGA of 0.2g, the spectral amplification ratios for the shallower square twin tunnels occur at periods of 0.168 s, 0.178 s, 0.12 s, 0.129 s and 0.247 s for surface points B, C, D, E and F, respectively. Ratios for the deeper square twin tunnels occur at periods of 0.12 s, 0.168 s, 0.12 s, 0.346 s, around 0.25 s for surface points B, C, D, E and F, respectively. Under the effect of motions with PGA of 0.4g, the spectral amplification ratio for the shallower and the deeper square twin tunnels occur at periods of around 0.2 s for surface points B, C, D, E and F.

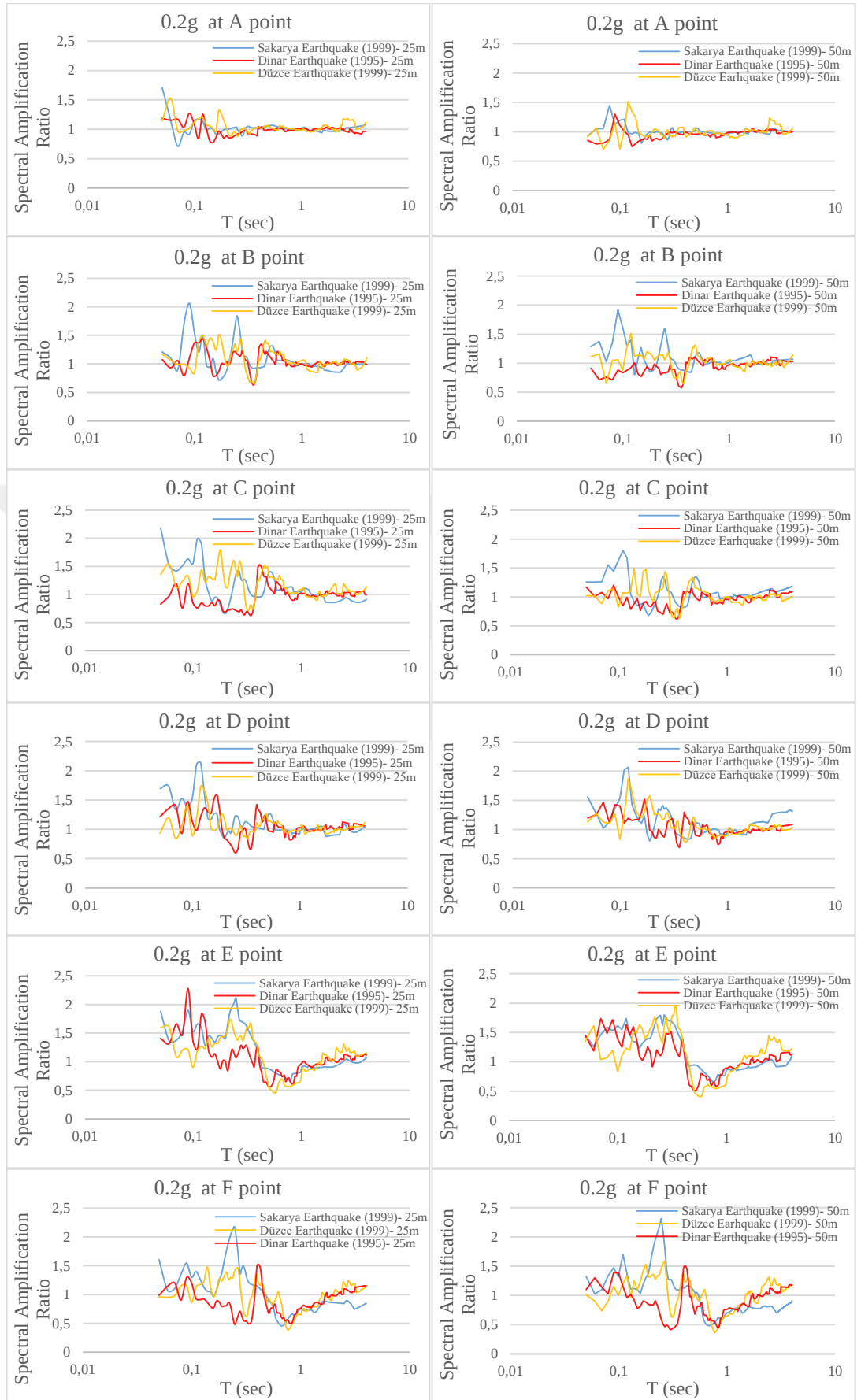


Figure 6.17: Spectral amplification ratio of the surface points for twin tunnels with square cross-section.

7. CONCLUSIONS

Local site conditions affect characteristics of earthquake waves propagating from bedrock to the ground surface. 1D dynamic analyses are not sufficient for detailed geotechnical investigations. The detailed investigations are also complex and expensive. For these reasons, idealized models are used to investigate the effect of local site conditions. In this study, the effect of the underground tunnels on site amplification ratio is investigated using numerical methods. Using the idealized models, 2D dynamic analyses were performed to investigate the effect of burial depth, tunnel cross-section and earthquake intensity. Dynamic analyses were performed using acceleration records of strong ground motions, which have different duration, PGA and frequency contents.

For single tunnels with circular cross-section under the effect of motions with PGAs of 0.1g and 0.3g, the site amplification ratios increase by 10% with increasing burial depth. Under the effect of motions with PGAs of 0.2g and 0.4g, single tunnels with circular cross-section exhibit different trends with increasing burial depth, although the location of maximum site amplification ratios generally remains constant. In addition, the maximum site amplification ratios change by up to 4% with increasing burial depth. The results of dynamic analyses showed that the maximum site amplification ratios increase with increasing PGA, except for the site amplification ratios obtained from motion with PGA of 0.1g.

For twin tunnels with circular cross-section under the effect of motions with PGA of 0.4g, the maximum site amplification ratios of the deeper twin tunnels with circular cross-section are greater than those of the shallower twin tunnels with circular cross-section. Under the effect of motions with PGA of 0.2g, the site amplification ratios become more effective with increasing tunnel burial depth as the distance from 0 meters increases. The results showed that the maximum site amplification ratios of twin tunnels with circular cross-section are greater than those of the single tunnels with circular cross-section. When twin tunnels and single tunnels with circular cross-section are compared, the location of the maximum site amplification ratios for twin tunnels with circular cross-section occurs closer to the tunnel axis. The maximum site amplification ratios of twin tunnels increase with increasing PGA.

For single tunnel with square cross-section under the effect of strong ground motions, increasing burial depth does not significantly change the ratios at the tunnel axis. The locations of maximum ratios remain constant with increasing burial depth, despite trends change. It was observed that the maximum site amplification ratios increase with increasing earthquake intensity.

For twin tunnels with square cross-section under the effect of strong ground motions, the maximum site amplification ratios increase with increasing burial depth and earthquake intensity. As burial depth increases, the location of maximum site amplification ratios moves away from 0 meters. Generally, the amplification ratios of twin tunnels with square cross-section are greater than those of the single tunnels with square cross-section.

Under the effect of strong ground motions, the maximum site amplification ratios are greater than 1.5. The sensitivity of underground tunnels to different periods under the effect of strong ground motions is investigated in this study. For both burial depths, it was observed that the maximum amplification ratios occur at lower periods, and the periods of site amplification ratios increase with increasing earthquake intensities.

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BIOGRAPHY

Aslı Nur KARAHAN graduated from Nigde Omer Halisdemir University, Faculty of Engineering, Department of Civil Engineering in 2021. Then, she started the Civil Engineering Master's Program at Gebze Technical University.



PUBLICATIONS AND PRESENTATIONS FROM THE THESIS

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