Computers and Concrete, Vol. 11, No. 1 (2013) 51-61
DOI: http://dx.doi.org/10.12989/cac.2013.11.1.051

Assessment of 3D earthquake response of the Arhavi Highway Tunnel considering soil-structure interaction

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(Received May 27, 2011, Revised April 9, 2012, Accepted April 17, 2012)

Abstract. This paper describes earthquake response of the Arhavi Highway Tunnel its geometrical properties, 3D finite element model and the linear time history analyses under a huge ground motion considering soil-structure interaction. The Arhavi Highway Tunnel is one of the tallest tunnels constructed in the Black Sea region of Turkey as part of the Coast Road Project. The tunnel has two tubes and each of them is about 1000 m tall. In the study, lineartime history analyses of the tunnel are performed applying north-south, east-west and up accelerations components of 1992 Erzincan, Turkey ground motion. In the time history analyses, Rayleigh damping coefficients are calculated using main natural frequency obtained from modal analysis. Element matrices are computed using the Gauss numerical integration technique. The Newmark method is used in the solution of the equation of motion. Because of needed too much memory for the analyses, the first 10 second of the ground motions, which is the most effective duration, is taken into account in calculations. The results obtained 3D finite element model are presented. In addition, the displacement and stress results are observed to be allowable level of the concrete material during the earthquakes.

Keywords: earthquake response; linear time history analysis; highway tunnel; soil-structure interaction; 3D FEM.

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1. Introduction

Underground facilities are an integral part of the infrastructure of the modern society and they are used for a wide range of applications, including subways and railways, highways, material storage and sewage and water transport. Underground facilities built in areas subject to earthquake activity must withstand both seismic and static loading. Historically, underground facilities have experienced a lower rate of damage than surface structures. Underground structures have features that make their seismic behavior distinct from most surface structures, most notably their complete enclosure in soil or rock and their significant length (i.e., tunnels). The design of underground facilities to withstand seismic loading thus has aspects that are very different from the seismic design of surface structures. Nevertheless, some underground structures have experienced significant damage in recent large earthquakes, including the 1995 Kobe, Japan earthquake, the

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1999 Chi-Chi, Taiwan earthquake and the 1999 Kocaeli, Turkey earthquake (Hashash *et al.* 2001). So the determination of seismic behaviour of these underground structures may have an importance for the researchers (Asakura *et al.* 2000, Amberg and Russo 2001, Lanzano *et al.* 2001).

Large-diameter tunnels are linear underground structures in which the length is much larger than the cross-sectional dimension. These structures can be grouped into three broad categories, each having distinct design features and construction methods: Bored or mined tunnels, Immersed tube tunnels and Cut-and-cover tunnels (Power *et al.* 1996, Hashash *et al.* 2001). These tunnels are commonly used for metro structures, highway tunnels and large water and sewage transportation ducts (Hashash *et al.* 2001).

Bored or mined tunnels are unique because they are constructed without significantly affecting the soil or rock above the excavation. Tunnels excavated using tunnel-boring machines (TBMs) are usually circular; other tunnels maybe rectangular or horseshoe in shape. Situations where boring or mining may be preferable to cut-and-cover excavation include significant excavation depths and the existence of overlying structures (Hashash *et al.* 2001).

Immersed tube tunnels are sometimes employed to traverse a body of water. This method involves constructing sections of the structure in a dry dock, then moving these sections, sinking them into position and ballasting or anchoring the tubes in place (Hashash *et al.* 2001).

Cut-and-cover structures are those in which an open excavation is made, the structure is constructed, and fill is placed over the finished structure. This method is typically used for tunnels with rectangular cross-sections and only for relatively shallow tunnels (<15 m of overburden). Examples of these structures include subway stations, portal structures and highway tunnels (Hashash *et al.* 2001).

In the early days of FEM applications in tunnelling, computers had a very limited memory. Thus, management of data was the most important issue, whilst the choice of the appropriate constitutive equation was considered of minor importance. This attitude survived until our days and one can observe cases of numerical simulation where the used constitutive equation is not even mentioned. This is by no means justified. The (proper) use of the proper constitutive equation is of decisive importance. True, the behaviour of soil and rock is extremely complex and, therefore, realistic constitutive equations can be complex to such an extension that they cannot be used (Kolymbas 2005, Cheng *et al*. 2007, Mroueh and Shahrour 2008).

This paper investigates linear earthquake response of a particular highway tunnel, Arhavi which has two tubes. In the paper firstly the main general information's about the tunnels are presented. Then the Arhavi Highway Tunnel and its geometry are described. After that 3D FEM of the tunnel is modelled using ANSYS software considering soil-structure interaction. Finally, the linear earthquake response of the tunnel are investigated using three components of 1992 Erzincan, Turkey ground motion records. The results obtained from the analysis are presented.

2. Arhavi Highway Tunnel

The Arhavi Highway Tunnel is one of the tallest tunnels constructed in the Black Sea region of Turkey as part of the Coast Road Project. The tunnel is located in Arhavi in Artvin in Turkey. It has two tubes and each of them has about 1000 m tall. One of the photographs of the tunnel appears in Fig. 1. The tunnel has been used for the traffic since 2006. The Arhavi Highway Tunnel was constructed using New Austrian Tunnelling Method. The rock quality classification

Fig. 1 The photograph of Arhavi Tunnel

was listed based on geological data. The studies show that the rocks had been constituted 70-110 million years before in Mesozoic time (Satır 2007, Sevim 2011).

3. 3D Finite element model and linear earthquake response of the Arhavi Highway Tunnel

The linear earthquake response of the Arhavi Highway Tunnel involves its 3D finite element and its three dimensional earthquake analyses. The geometrical properties of the Arhavi Highway Tunnel appear in Fig. 2 (Cengiz Project 2006). As it is seen in Fig. 2 that, the tunnel has two tubes and each tube includes reinforced concrete and shotcrete concrete. The radius of each tunnel is 5.3 m. The constant thickness of the shotcrete concrete is 0.15 m. However, the thickness of the concrete is changeable. It has 0.4 m thickness at the top of the tunnel, but the thickness increase through the base and it has 0.7 m thickness at the road level.

3D finite element model of the tunnel is constituted using ANSYS (2012) software. 13520 SOLID45 elements are used in the 3D FEM of the tunnel. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y and z directions. The

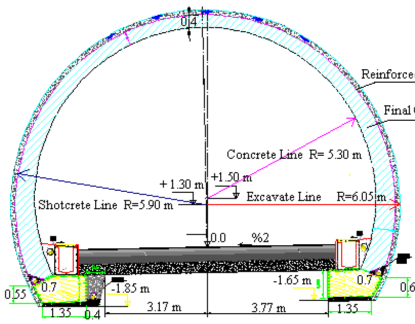


Fig. 2 Geometrical properties of the Arhavi Highway Tunnel (Cengiz Project 2006)

element has plasticity, creep, swelling, stress stiffening, large deflection and large strain capabilities. 3D finite element models of the tunnel appear in Fig. 3.

Three main materials as reinforced concrete, shotcrete concrete and rock are considered in the analyses. The material properties used in the analyses are summarized in Table 1 (GDH 2006, Satır 2007). The tunnel foundation is assumed as massless. Because of the massless foundation, the analyses considered only the effects of foundation flexibility. So, the foundation model extended to a distance beyond which its effects on deflections and natural frequencies of the dam become negligible (USACE 2003). As boundary conditions, all of the degrees of freedoms on the foundation surfaces are fixed.

Modal analysis of the tunnel is performed to obtain natural frequencies which are used to calculate Rayleigh damping coefficients. In the analyses effective first eight modes are obtained between 59-124 Hz. In addition, the modes are classed as bending modes.

The linear earthquake response of the Arhavi Highway Tunnel is investigated using 3D finite element model. Linear time history analysis of the tunnel is performed considering ERZIKAN/ERZ-NS, ERZIKAN/ERZ-EW and ERZIKAN/ERZ-UP components of 1992 Erzincan ground motion as the excitation sources. This earthquake event occurred in the North Anatolian

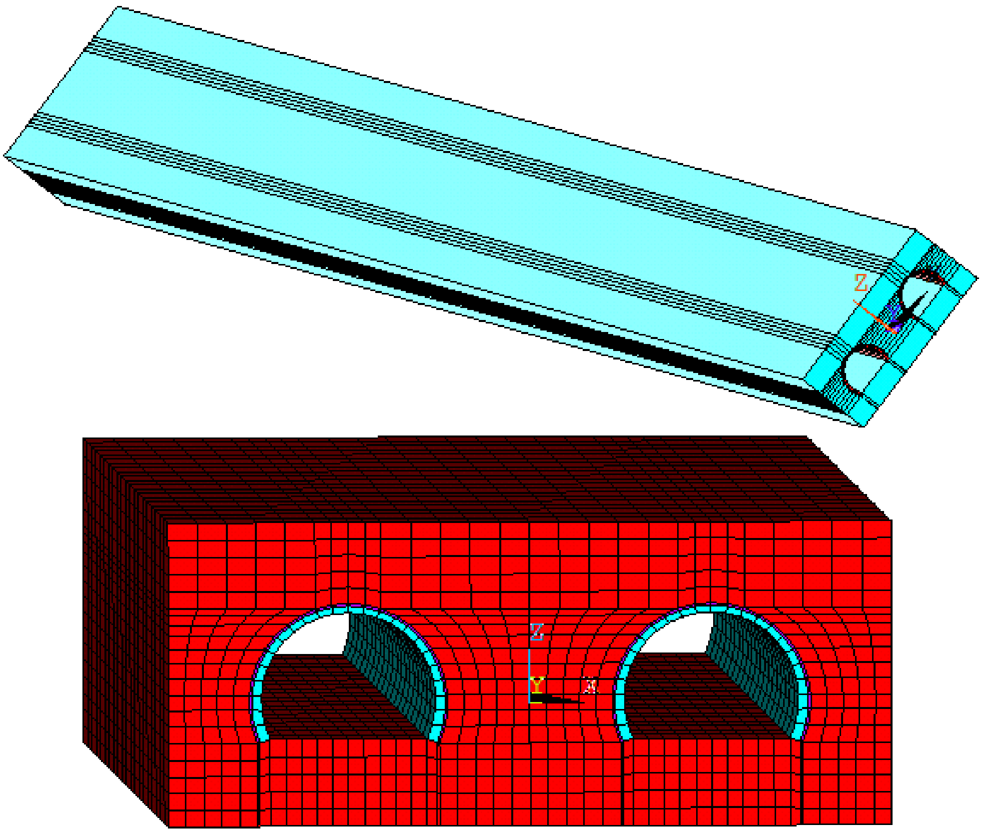
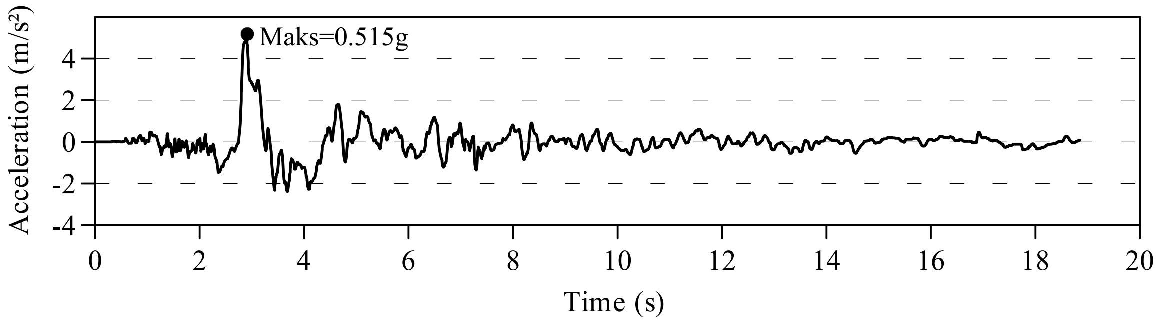


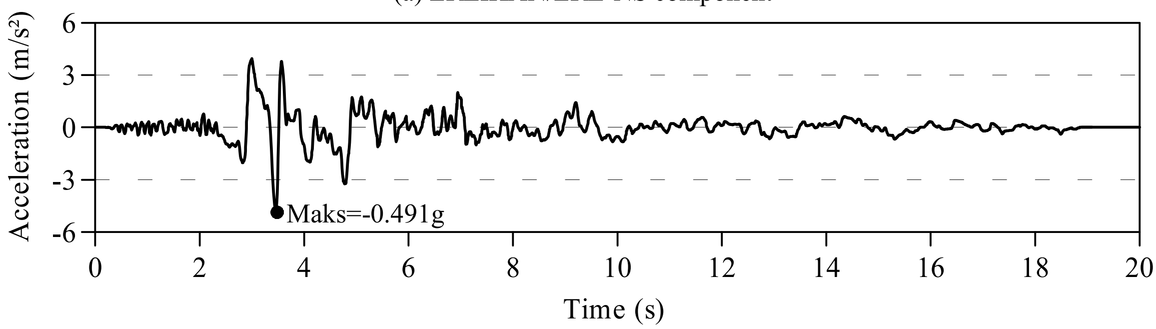
Fig. 3 3D FEMs of the Arhavi Highway Tunnel

Table 1 Material properties of the Arhavi Highway Tunnel

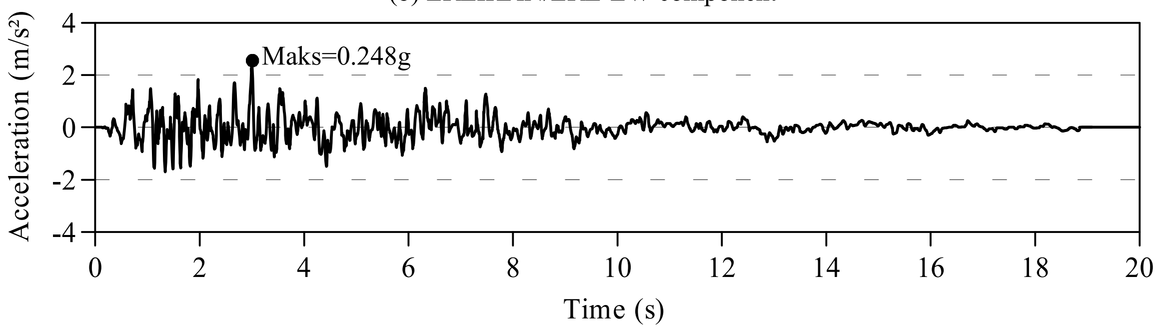
Material	Element (3D)	Properties		
		Elasticity modulus (N/m^2)	Poisson ratio (-)	Mass density (kg/m^3)
Reinforced concrete	SOLID45	3.00E10	0.2	2500
Shotcrete concrete	SOLID45	2.75E10	0.2	2400
Rock	SOLID45	3.00E10	0.2	-



(a) ERZIKAN/ERZ-NS component



(b) ERZIKAN/ERZ-EW component



(c) ERZIKAN/ERZ-UP component

Fig. 4 The time histories of ground motion accelerations of 1992 Erzincan earthquake

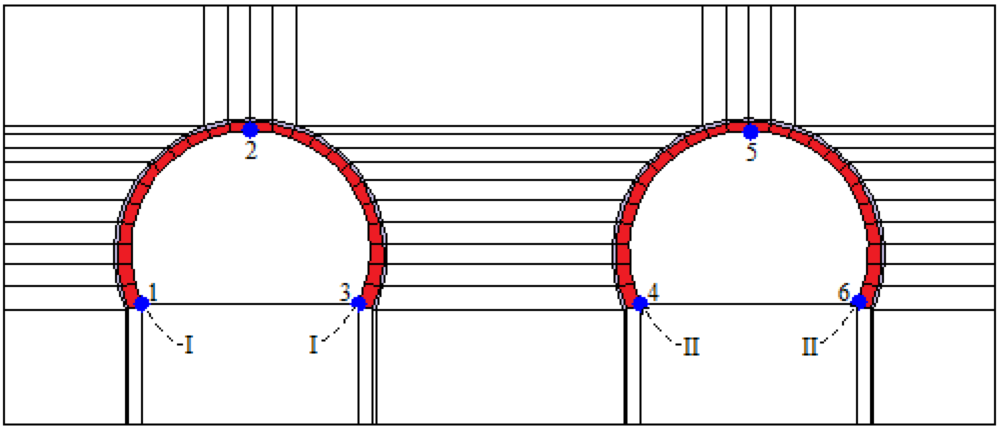


Fig. 5 Location of presented nodes, I-I and II-II sections on the Arhavi Highway Tunnel

Fault, which is the nearest fault to the tunnel. The components of the earthquakes appear in Fig. 4 (PEER 2012). The components of the ground motion are applied to model in global X, Y, Z directions, respectively. (Fig. 3). The reason of using these three components is to simulate the realistic response of the earthquake.

The element matrices are computed using the Gauss numerical integration technique (Bathe 1996) in the analyses. The Newmark method is used in the solution of the equation of motion. Because of the computational demand of this method, only the first 10 seconds of the ground motions are considered during calculations. As the first few seconds of the Erzincan Earthquake are of greater magnitude (Fig. 4). Because the damping ratios are unknown the authors estimate the Rayleigh damping coefficients for an assumed 5% damping ratio and Rayleigh damping coefficients are calculated using main natural frequency obtained from modal analysis.

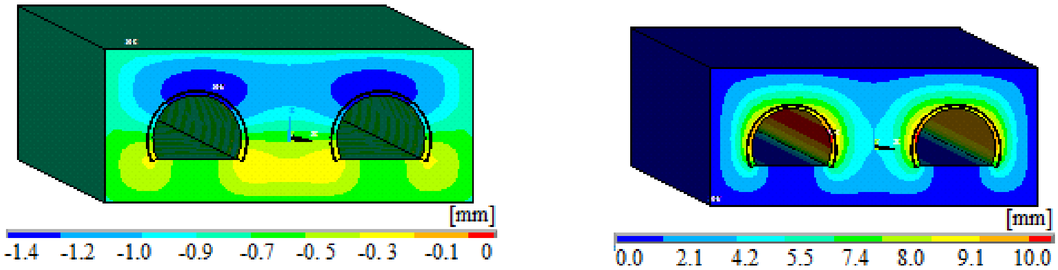
The time histories of displacements and principal stresses on nodes such as 1, 2, 3, 4, 5 and 6 (Fig. 5) are the results of the linear timer history analysis of the Arhavi Highway Tunnel, additionally, the variations in X, Y and Z direction displacements along to I-I and II-II sections (Fig. 5), the displacements, and the stresses contour diagrams are obtained.

3.1 Displacements

The maximum horizontal and vertical displacement contours of the tunnel are presented in Figs. 6(a) and (b), respectively. These contours represent the distribution of the peak values reached by the maximum displacement at each point within the section. It can be seen in Fig. 6 that the maximum displacements occur at the top of the tunnel for Y direction; however they occur at the nearly half height of the tunnel for Z direction. On the other hand, vertical displacements are almost 7-8 times bigger than those of horizontal displacements. Horizontal displacements in X direction are obtained too small, so they are not included in this part of the study.

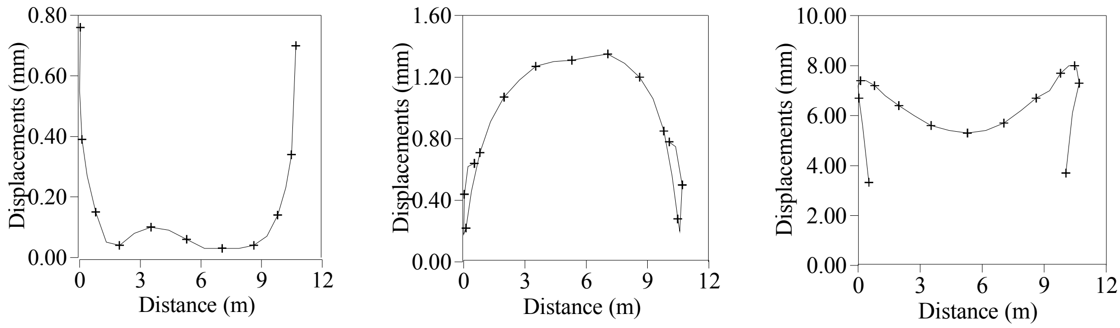
Figs. 7(a-c) show the variation of maximum displacements (X, Y, Z directions-Fig. 3) on I-I section (Tube 1) and II-II section (Tube 2) of the Arhavi Highway Tunnel, respectively. As it can be seen from Fig. 7, there is not a regular distribution along I-I and II-II sections, however, the

maximum displacements in X direction occur in left and right bottom side of the tunnel, the maximum displacements in Y direction occur on the top of the tunnel and the maximum



(a) Displacement contour for Y direction (b) Displacement contour for Z direction

Fig. 6 The maximum horizontal displacement contours in: (a) Y direction and (b) Z direction of the Arhavi Highway Tunnel



(a) X displacements (b) Y displacements (c) Z displacements

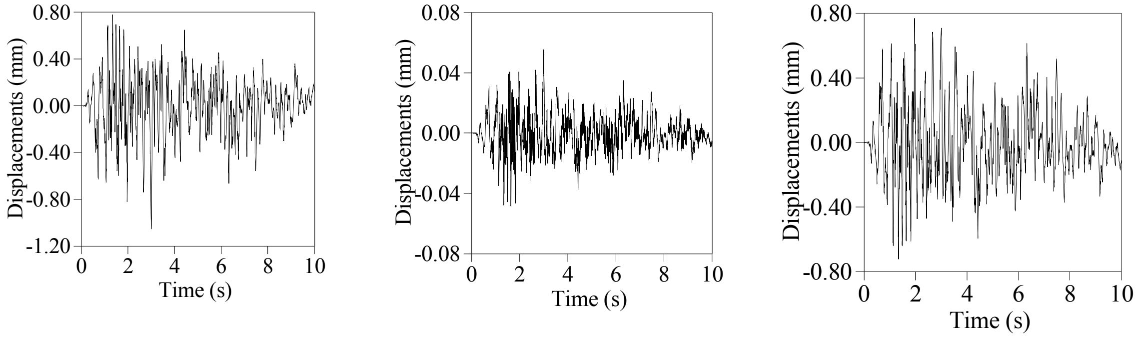
Fig. 7 The variation of maximum displacements on I-I and II-II sections of the Arhavi Highway Tunnel for: (a) X direction, (b)Y direction and (c) Z direction

displacements in Z direction occur in left and right bottom side of the tunnel. Also, The Z displacements are bigger than Y displacements and Y displacements are bigger than X displacements.

The time histories of X, Y and Z displacements at the nodal points 1, 2 and 3 of the tunnel (Fig. 3), where the maximum displacements occurred, are plotted in Figs. 8-10(a-c), respectively. As it is seen in Figs. 8-10 that the Z displacements are bigger than those X and Y displacements. However, the value of the displacement are small to not damage the tunnel. Due to symmetry of the system the time histories of X, Y and Z displacements at the nodal points 4, 5 and 6 of the tunnel (Fig. 3) are same as those of nodal points 1, 2 and 3.

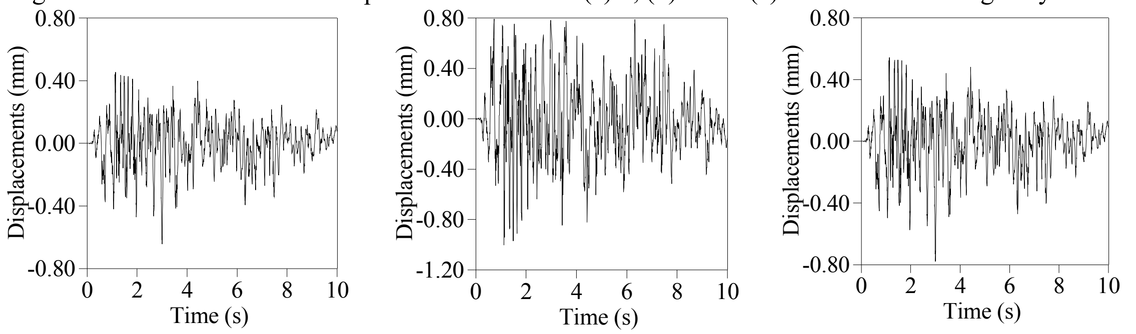
3.2 Principal stresses

The maximum and minimum principal stress contours of the tunnel are presented in Figs. 11(a) and (b), respectively. These represent the distribution of the peak values reached by the maximum stresses at each point within the section. As it is seen in Fig. 11 the maximum and minimum principal stresses occur at the bases of the tunnel. In addition the stresses have a symmetrical distribution along to Z axis of the tunnel section. Also, the highest absolute values of maximum and minimum stresses are about 4 MPa. The principal stress values in the tunnel can be the acceptable strength of the concrete during the earthquakes.



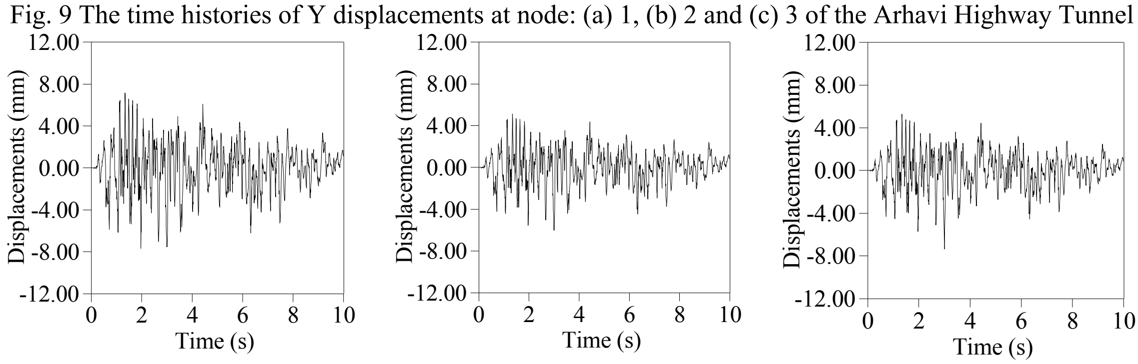
(a) X displacements on 1 point (b) X displacements on 2 point (c) X displacements on 3 point

Fig. 8 The time histories of X displacements at node: (a) 1, (b) 2 and (c) 3 of the Arhavi Highway Tunnel



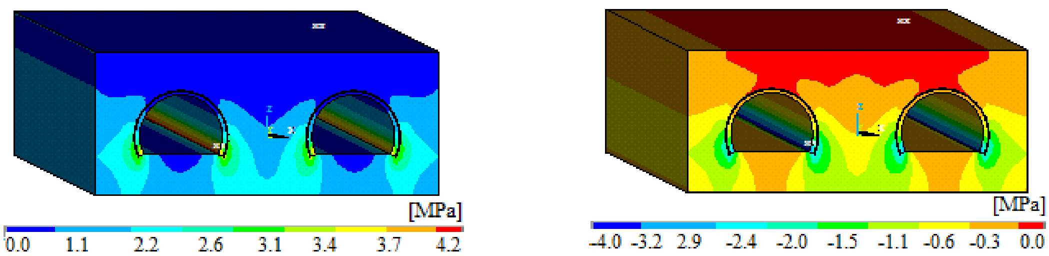
(a) Y displacements on 1 point (b) Y displacements on 2 point (c) Y displacements on 3 point

Fig. 9 The time histories of Y displacements at node: (a) 1, (b) 2 and (c) 3 of the Arhavi Highway Tunnel



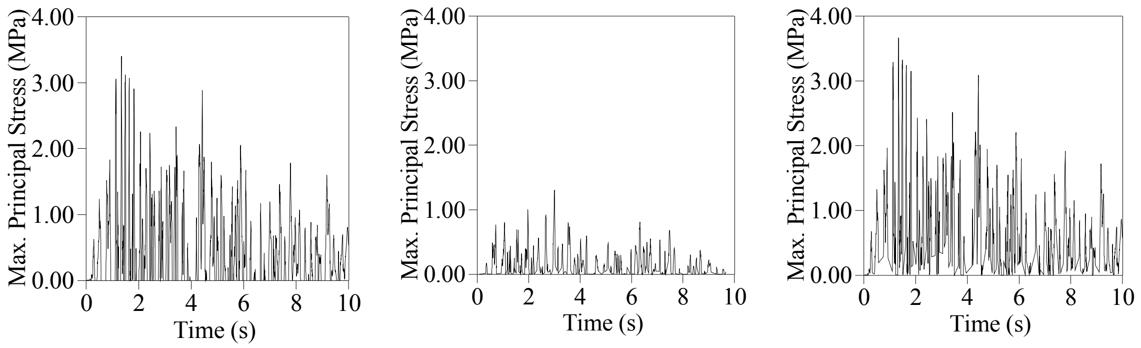
(a) Z displacements on 1 point (b) Z displacements on 2 point (c) Z displacements on 3 point

Fig. 10 The time histories of Z displacements at node: (a) 1, (b) 2 and (c) 3 of the Arhavi Highway Tunnel



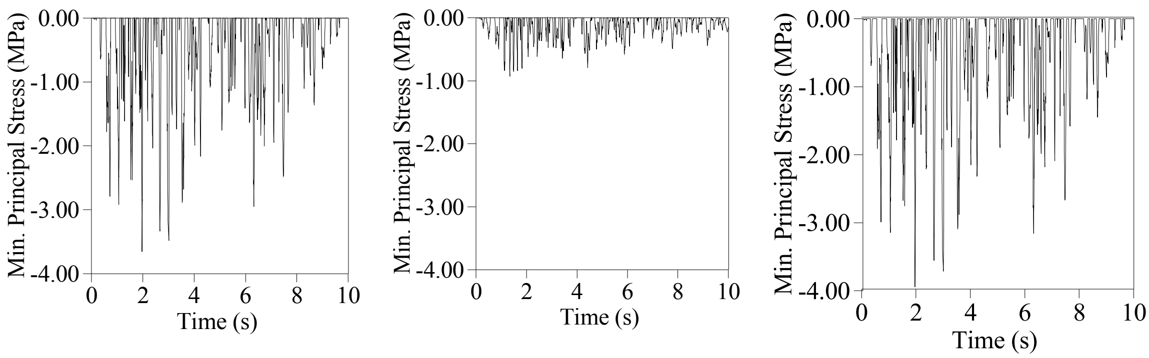
(a) Maximum principal stress contour (b) Minimum principal stress contour

Fig. 11 (a) The maximum and (b) the minimum principal stress contours of the Arhavi Highway Tunnel



(a) Principal stresses on 1 point (b) Principal stresses on 2 point (c) Principal stresses on 3 point

Fig. 12 The time histories of maximum principal stresses at node: (a) 1, (b) 2 and (c) 3 of the Arhavi Highway Tunnel



(a) Principal stresses on 1 point (b) Principal stresses on 2 point (c) Principal stresses on 3 point

Fig. 13 The time histories of minimum principal stresses at node: (a) 1, (b) 2 and (c) 3 of the Arhavi Highway Tunnel

The time histories of maximum principal stresses at the nodal points 1, 2 and 3 of the tunnel (Fig. 3), where the maximum stresses occurred, is plotted in Figs. 12(a-c), respectively. The time histories of minimum principal stresses at the nodal points 1, 2 and 3 of the tunnel (Fig. 3), where the minimum stresses occurred, is plotted in Figs. 13(a-c), respectively. As it is seen in Figs. 12 and 13 that the maximum and minimum principal stresses obtained for nodal point 1 and 3 are bigger than those of nodal point 2. Due to symmetry of the system the time histories of principal stresses at the nodal points 4, 5 and 6 of the tunnel (Fig. 3) are same as those of nodal points 1, 2 and 3.

4. Conclusions

This paper investigates 3D linear earthquake response of the Arhavi Highway Tunnel considering foundation-structure interaction. 3D finite element model of the tunnel is modelled using ANSYS software and the earthquake response of the tunnel is assessed using 1992 Erzincan, Turkey ground motion records. In this study, the author noted the following observations:

·Effective first eight modes are obtained between 59-124 Hz. The modes are classed as bending modes.

·The maximum displacements occur at the top of the tunnel for Y (road) direction; they occur at the nearly half height of the tunnel for Z (vertical) direction. Vertical displacements are almost 7-8 times bigger than those of horizontal displacements. On the other hand, Horizontal displacements in X direction are obtained too small to make a deformation on the tunnel. .

·The maximum and minimum principal stresses generally occur at the bases of the tunnel. The stresses have a symmetrical distribution along to Z axis of the tunnel section. Also, the highest absolute values of maximum and minimum stresses are about 4 MPa. The principal stress values in the tunnel can be the acceptable strength of the concrete during the earthquakes.

Acknowledgments

The author extends his thanks to Ömer FETTAHOĞLU, who is an engineer in the Cengiz Project, for his logistical assistance.

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