Comparison on the Use of Steel Fiber Reinforced and Geopolymer Concrete as a Tunnel Lining under Seismic Conditions

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Abstract

In recent decades, different alternatives towards construction materials have been offered for such implementations as retrofitting and strengthening of existing buildings. These applications have also become widespread in outstanding structures. Reinforcement via fiber reinforced polymers has been used in tunnel structures. Furthermore, geopolymer concrete which has low CO_2 emissions during manufacture, and has been user friendly in terms of alkaline reagents with some additives, is an alternative way during the construction. The aim of this research presented in this paper is to show the effectiveness of such innovative applications to be used as the primary materials for outstanding structures. Static and dynamic analyses of these materials on the case study located in East Black Sea surroundings called T3 Gubuket Tunnel are carried out by using ANSYS software for tunnel linings constructed with steel fiber reinforced concrete and geopolymer concrete. The final evaluation is taken into account as far as earthquake performance of tunnel structures based on each tunnel linings was concerned.

Keywords: Steel fiber reinforced concrete; Geopolymer concrete; Tunnel lining; Earthquake performance; Soil-Structure interaction

1. Introduction

Tunnels are known as a sort of outstanding structures, which are built for the purpose of transportation, defending, and storing. Nowadays, it is required much more construction of these structures because of broadening of cities, stabilization of road standards, increasing of defense and shelter needs, being uneven or/and valuable of land. In Turkey, transportation tunnels are built widely. These facilities built in earthquake prone areas must withstand both seismic and static loading. Until now, it was observed that tunnel structures experienced a lower incidence of damage than such surface structures as buildings and bridges. This implies that their seismic behavior is different from most surface structures. This is because tunnel structures completely engulf in soil and rock. Nonetheless, some tunnel structures have experienced significant damage in such recent and large earthquakes as the 1995 Kobe, Japan earthquake, the 1999 Chi-Chi, Taiwan earthquake and the 1999 Kocaeli, Turkey earthquake (Hashash et al. 2001). In this sense, the importance of soil-structure interaction comes into consideration when tunnels are designed as earthquake resistant (Amberg, and Russo 2001; Asakura et al. 2000; Lanzano et al. 2001).

Large-diameter tunnels are linear underground facilities in which the length through soil or rock is larger than those given dimension in the cross section of structure. They divide into three broad categories that vary in terms of construction process. These are bored or mined tunnels, immersed tube tunnels and cut-and-cover tunnels (Hashash et al. 2001). Such structures are used for metro structures, highway tunnels, and large water and sewage transportation (Hashash et al. 2001).

Bored or mined tunnels are constructed by excavating via tunnel boring machines (TBMs) which are usually circular while others are maybe rectangular or horseshoe in shape. This is a significant point that such tunnels do not severely affect the soil or rock above the excavation.

Immersed tube tunnels are structures that are used for traversing a body of water. The construction process includes building sections in a dry rock, then moving these sections, sinking them into position and ballasting or anchoring the tubes in place (Hashash et al. 2001).

Cut-and-cover tunnels encompass a process by which an open excavation is made, the structure is constructed, and finally fill is placed over the finished structure. In this construction, the structure is known as precast concrete segments with normal or high strength, which one tube consists of roughly 4 or 5 precast concretes with completed steam curing at 55 ^{0}C. This method is generally used for tunnels with rectangular cross-sections in which highway tunnels, portal structures and subway stations are regarded as some examples (Hashash et al. 2001).

Use of tunnel linings which are also known as tunnel segments is vital for the initial support for the stabilization of soil or rock with a thickness of ranging from 0.15 cm to 0.30 cm. The process involves step-by-step construction by increasing the thickness of the lining. Generally, reinforced concrete is used as tunnel linings, however some research illustrates that the use of steel fiber reinforced dissipates the energy originated from a seismic vibration with higher ductility rather than reinforced concrete (Sevim 2011). Tunnel linings constructed from steel fiber reinforced concrete and mesh steel reinforcement in the technical literature were compared. According to these studies, steel fiber reinforced concrete linings have higher shear strength and flexural strength while it is stated that it reaches that of concrete linings using mesh steel reinforcement. The results show that the steel fibers added to the concrete have high tensile strength (Vanderwalle 2005). On the other hand, geopolymer concretes are those obtained from the mix of stone aggregates, alumina-silicates, user-friendly alkaline reagents, which refers to irritant materials in terms of classification and material safety rules of alkaline products and water (Davidovits 2013). Another significant point is that the duration of curing of these materials is rapid rather than the concrete with using Portland cement (Davidovits 2013). Furthermore, according to the Australian concrete scholar B.V.J. Rangan, geopolymer concrete has an opportunity for the construction sector with lower tally of carbon dioxide CO_2 as a result of a reduction of 80% the CO_2 emission during manufacture of rock-based geopolymer cement in comparison with Portland cement and there is no difference of the strength at 28 days with an average of 40 MPa (Rangan 2008). There are two types of geopolymer concretes based on its cement, (i.e., Rock-based Geopolymer concretes and Fly ash-based geopolymer concretes). In this research, only geopolymer concrete with rock-based geopolymer cement has been investigated under earthquake excitation.

In recent decades, Finite element modelling (FEM) applications have been used for understanding structural, soil or any member behavior of the given system. Especially for the case of soil-structure interaction, numerical simulation with using Finite Element modelling must be performed to recognize the effects of soil on the structure such as tunnel and pipeline structures. Within the scope of this study, it is also known that the behavior of soil and rock is sophisticated and, therefore, realistic constitutive equations can be complex (Cheng et al. 2007; Kolymbas 2005; Mroueh and Shahrour 2008).

This research points out that linear seismic behavior of highway tunnel, T3 Gubuket, which has only one tube, is evaluated by considering soil-structure interaction. The earthquake performance is also assessed based on the different lining materials (e.g., reinforced concrete, steel fiber reinforced concrete and geopolymer concrete.). In this paper, the main general information regarding the case tunnel is presented. Then the T3 Gubuket Tunnel and its geometry is described. After that 3D FEM of the tunnel engulfed with soil structure is modelled using ANSYS software. Finally, 8 modal response results, which show the predictable behavior of soil-structure system, and linear seismic response of the tunnel are investigated by using

1992 Erzincan Earthquake ground motion records. The results from the analysis based on the materials are also presented and evaluated.

2. T3 Gubuket Tunnel

The T3 Gubuket Tunnel is constructed in the Black Sea region of Turkey located between Artvin and Çoruh River, which is also near the Artvin Dam and remains to the left lane of the Çoruh River according to the flow of the river. The T3 Gubuket Tunnel was constructed using New Austrian Tunnelling Method (NATM). According to the rock quality classification (i.e., RMR and Q), the rock totally corresponds to B2 rock class, which means the severe brittle failures might occur without B2 support system (e.g., rock bolts.). The tunnel has only one tube and it is about 1450 m tall which is categorized as entrance portal (22 m tall), tunnel axis (1360 m tall) and exit portal (35 m tall). Fig. 1 shows the location of T3 Gubuket tunnel route (Dogus Project 2013).

Figure 1. The location of Tunnel Route (Dogus Project 2013)

3. 3D Finite element model and linear earthquake response of T3 Gubuket Tunnel

The static and linear earthquake response of Gubuket Tunnel are performed by using its 3D finite element in ANSYS software. The geometrical properties of the tunnel appear in Fig. 2 (Dogus Project, 2013). As it is seen in Fig. 2, the tunnel has only one tube and the tube include reinforced concrete and the constant thickness of shotcrete concrete is 0.15 m, while the constant thickness of lining is 0.40 m. In this study, three distinct permanent concrete segments are investigated. These are reinforced concrete, steel fiber reinforced concrete and geopolymer concrete.

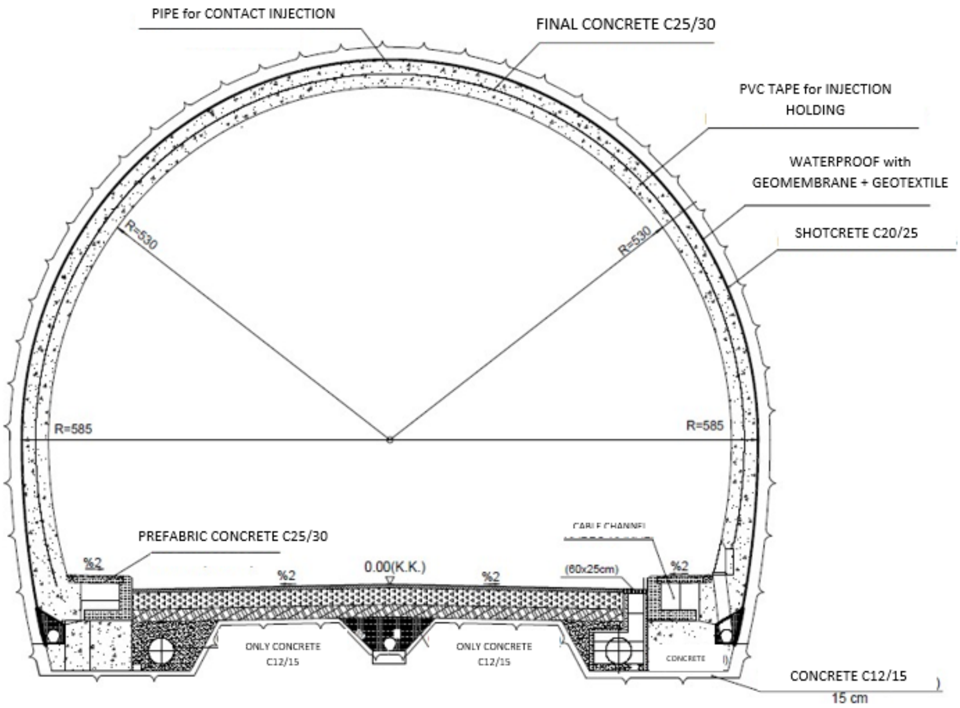
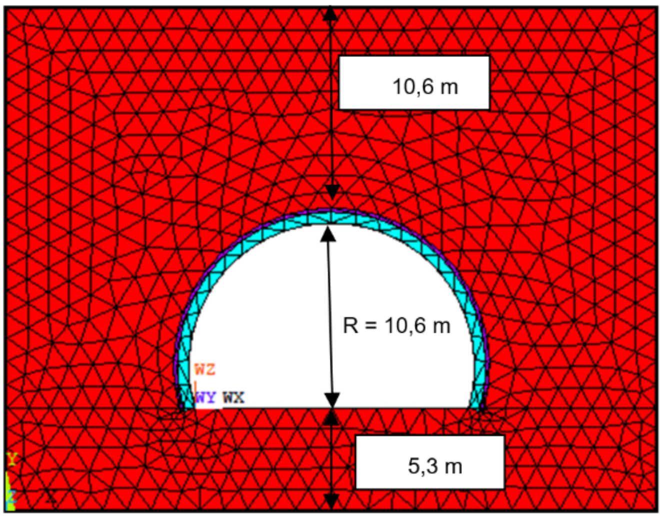
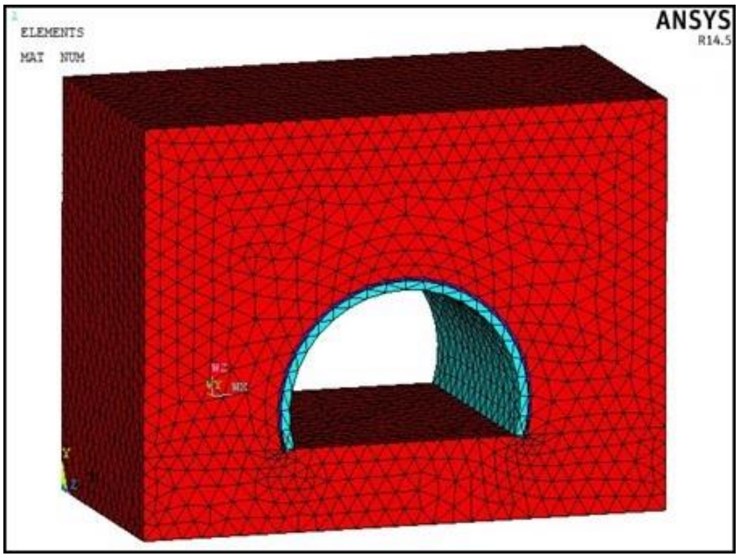


Figure 2. Geometrical Properties of T3 Gubuket Tunnel

3D finite element model of the tunnel is performed by ANSYS (2012) software. 30760 SOLID45 elements are used in 3D FEM of the tunnel. SOLID45 material is assigned for both soil and tunnel structure, which corresponds that only one element has eight nodes, and each node has three degrees of freedom referring to translations in the nodal x, y and z directions. The element has plasticity, creep, stress stiffening, large deflection, and large strain capabilities. Cross section of Soil-Structure system and 3D finite element models of the tunnel are illustrated in Fig.3.



(a)



(b)

Figure 3. 2D and 3D Modelling of T3 Gubuket Tunnel

The main materials in this study are reinforced concrete/steel fiber reinforced concrete/geopolymer concrete, shotcrete, and rock. The material properties are listed in Table 1 based on references Fernandez-Jimenez et al. (2006), Ponikiewski and Katzer (2017), Satır (2007) and Sevim (2011). The foundation of tunnel takes into account as flexible, implying that the foundation is considered massless. As boundary conditions, all the degrees of freedoms on the foundation surfaces are fixed. The soil profile is also fixed from all directions.

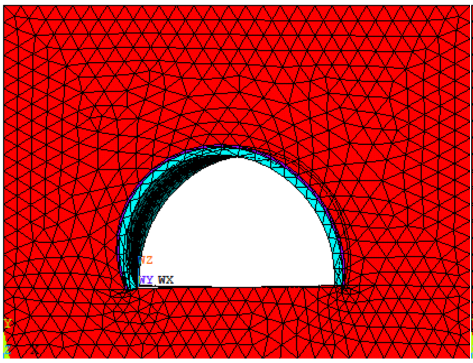
Table 1. Material Properties of T3 Gubuket Tunnel

Material	Element (3D)	Poisson ratio (-)	Elasticity modulus (N/m^2)	Mass density (kg/m^3)
Reinforced Concrete	SOLID45	0.20	3.00E10	2500
Steel Fiber Reinforced Concrete	SOLID45	0.20	3.29E10	2363
Geopolymer Concrete	SOLID45	0.20	1.70E10	2466
Shotcrete	SOLID45	0.25	2.85E10	2400
Rock	SOLID45	0.20	4.00E10	2600

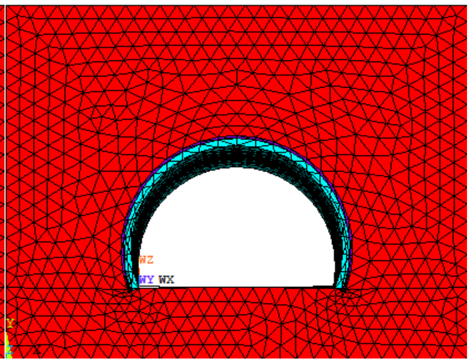
Modal analysis of the tunnel is performed to define modal characteristics of the tunnel structure. It is deduced from the analysis that mode shapes are related to the main concrete of the tunnel. Figure 4 shows natural frequencies and the mode shapes of T3 Gubuket Tunnel, which Rayleigh damping coefficients are used, and effective eight modes respectively listed are ranging from 79-110 Hz.

1992 Erzincan Earthquake Ground motion as excitation sources with three components obtained from PEER (2022) as shown in Figure 5. The event occurred in the North Anatolian Fault, which is the nearest fault to the tunnel. The Newmark method is used in the solution of the equation of motion. Only the first 10 seconds of the ground motions are used for the linear earthquake response of the idealized structure.

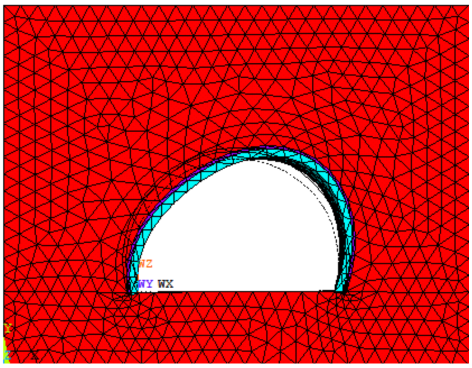
The time histories of displacements and principal stresses on nodes 1,2 and 3 (Figure 6) are the results of the linear time history analysis of the T3 Gubuket Tunnel. The displacements, and contour diagrams are obtained.



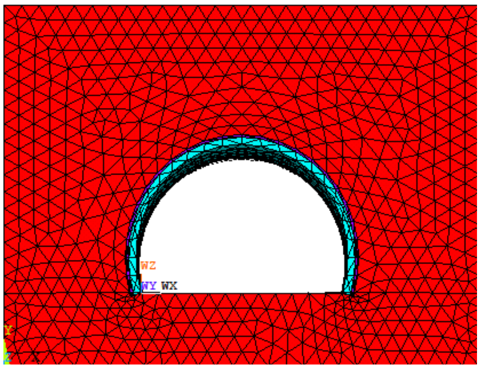
f_1 = 79 Hz



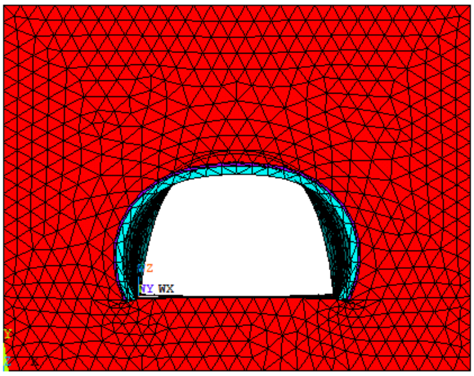
f_2 = 81 Hz



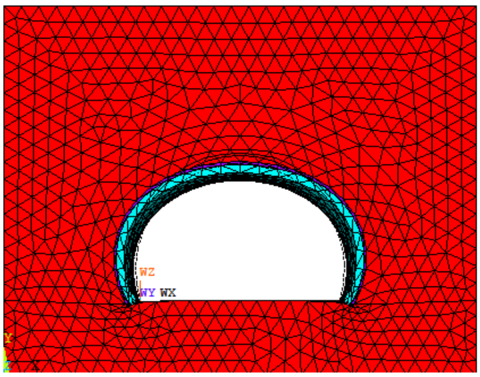
f_3 = 83 Hz



f_4 = 84 Hz



f_5 = 90 Hz



f_6 = 96 Hz

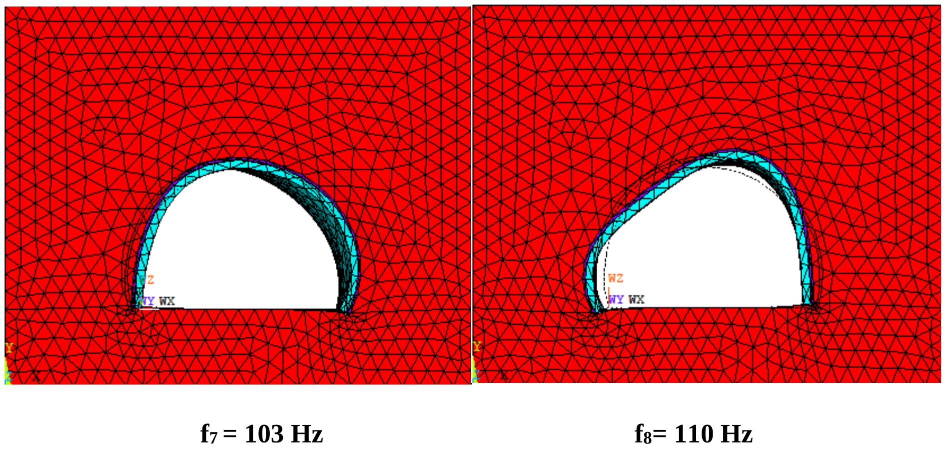


Figure 4. Mode shapes and natural frequencies of T3 Gubuket Tunnel

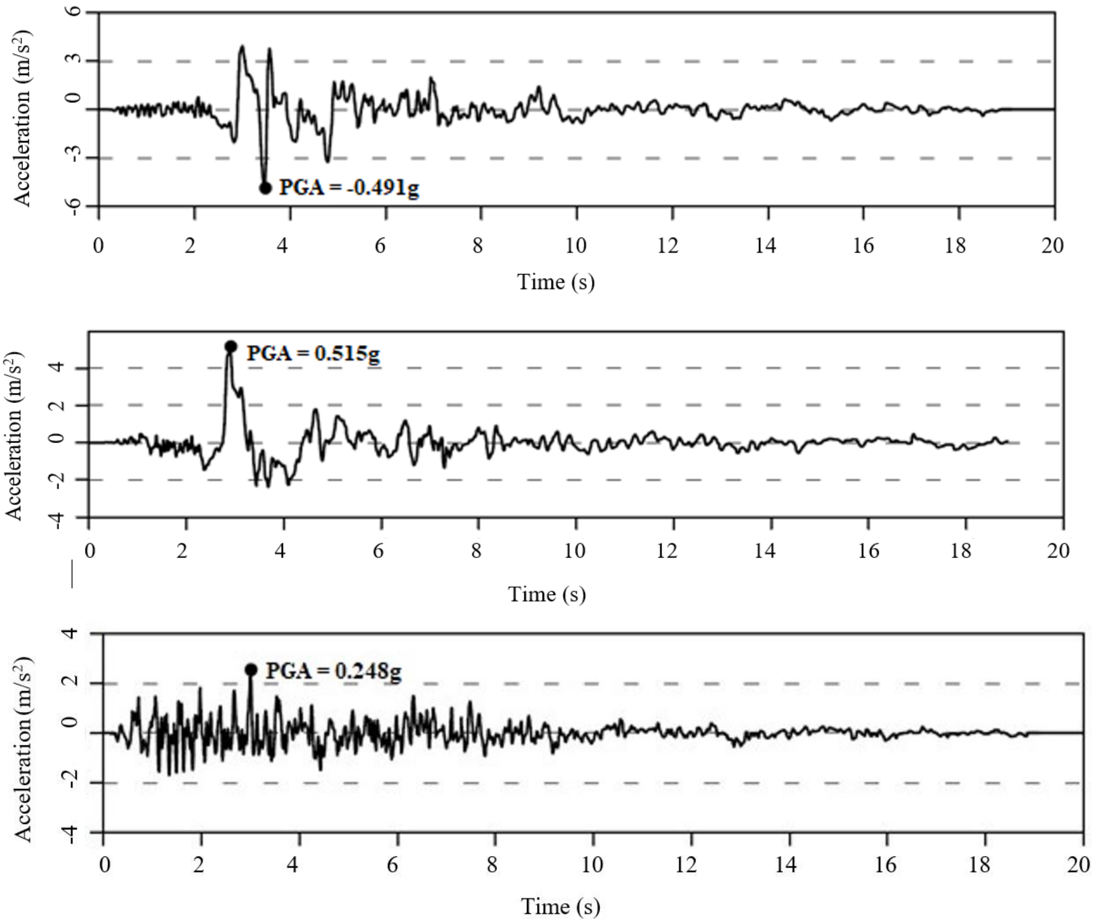


Figure 5. 1992 Erzincan Earthquake ground motion listed as EW, NS and UD components respectively.

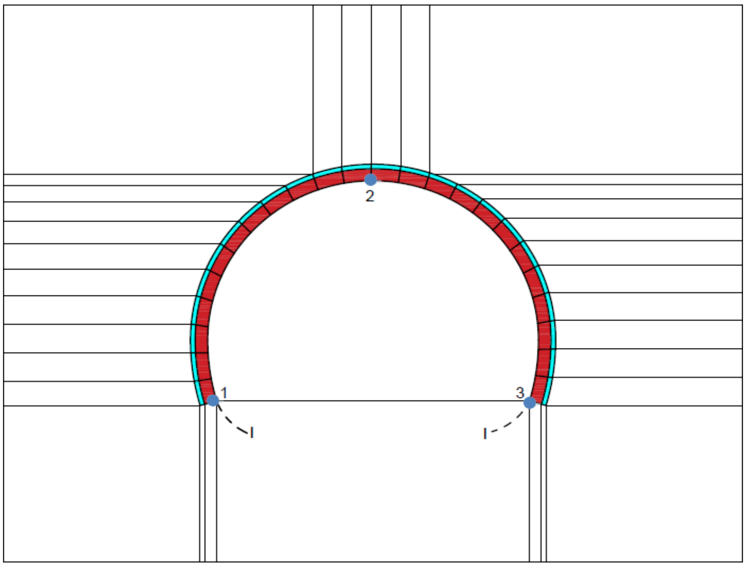


Figure 6. I-I Section on T3 Gubuket Tunnel and nodes monitored in this study.

4. Results

The displacement contour diagram because of the boundary conditions is shown in Figure 7. These contours illustrate the distribution of the peak values of each node defined through FEM. According to Figure 7, the damage highly occurred at the arch, which refers to Node 2 described in Figure 6. Nodes 1 and 3 have a tendency to larger cracks in y axis as a result of time history analysis. Due to the page limitation, only one axis is considered, which results in higher damage, for tunnel linings with reinforced concrete, steel fiber reinforced concrete and geopolymer concrete. It is expected that low elasticity modulus leads to an increase in the deformation strain at the material assigned in this study. In other words, geopolymer concrete has higher deformation strain than the rest of materials as lining. Figure 8 demonstrates the displacement contour diagrams of assigned three different materials in which axis with high deformations was selected for each one.

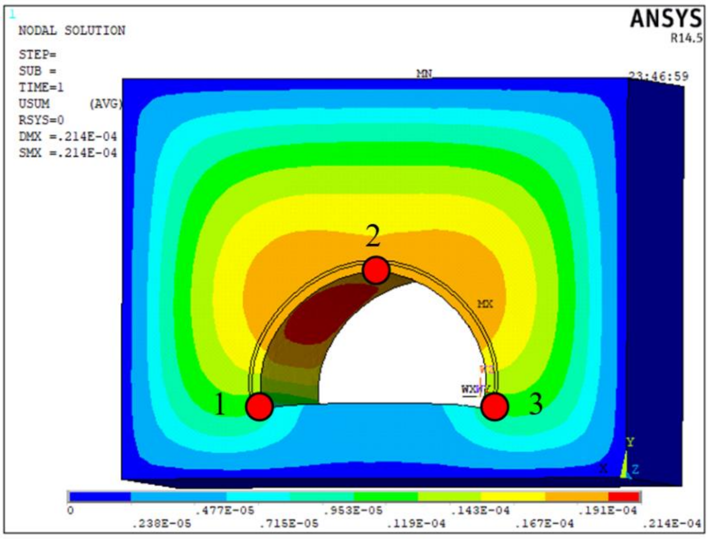


Figure 7. Displacement contour diagram based on boundary conditions.

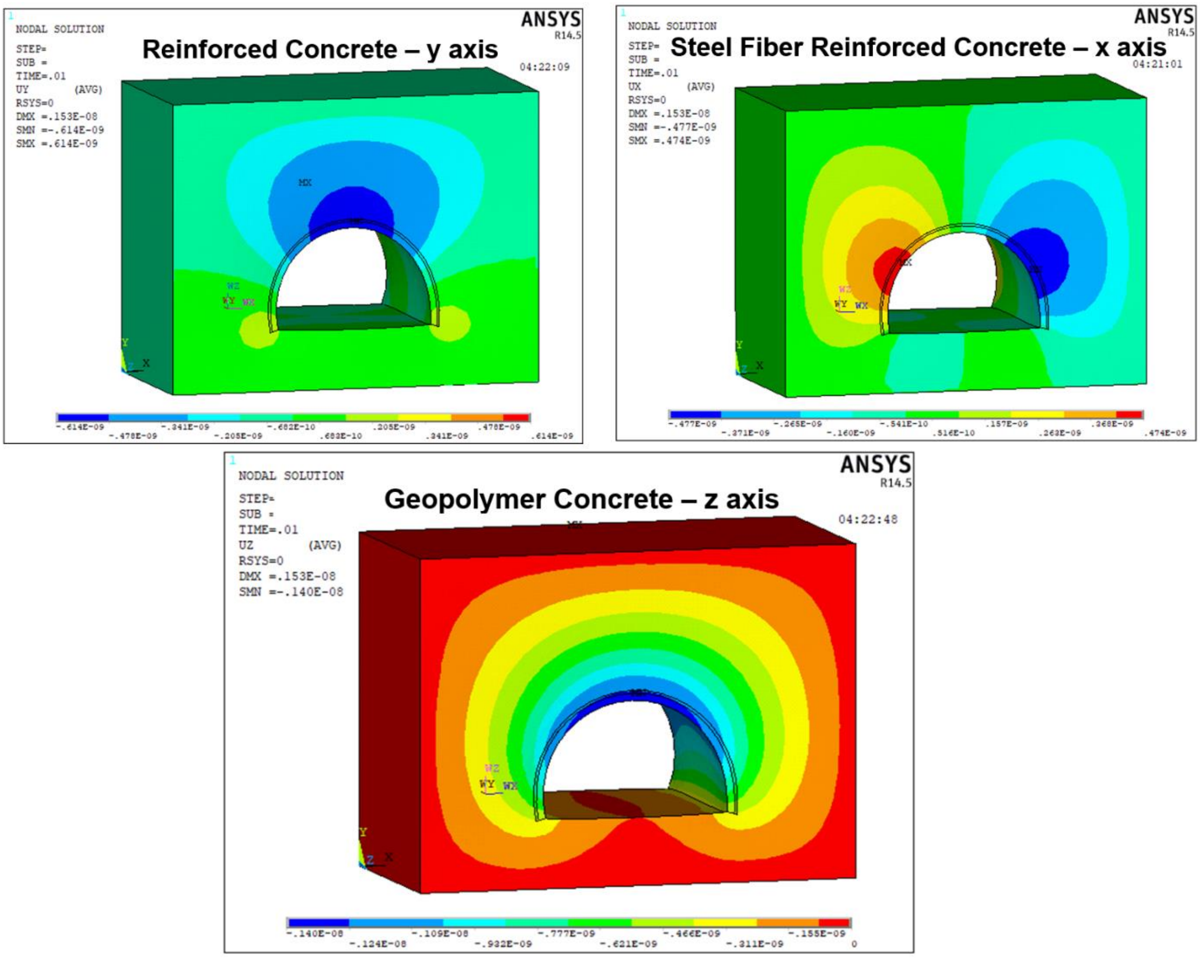
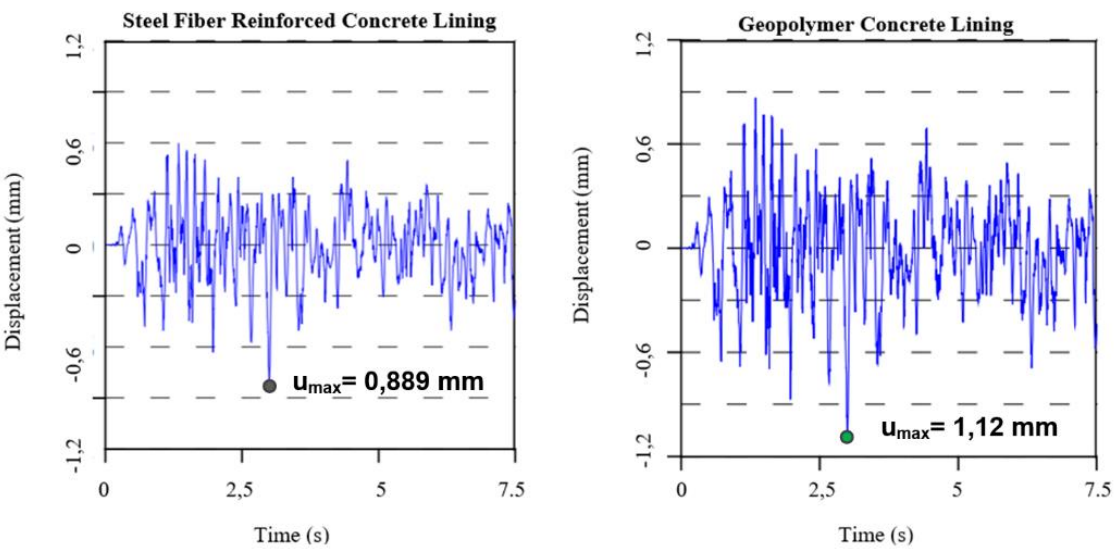


Figure 8 Displacement distributions for three distinct tunnel lining.

Figure 9 shows the ultimate displacement plots of each material used. Results illustrate that geopolymer concrete allows large deformations with the range of between 0.9 mm and 1.12 mm while steel fiber reinforced concrete has high modulus of elasticity, which does not allow high deformation strain.



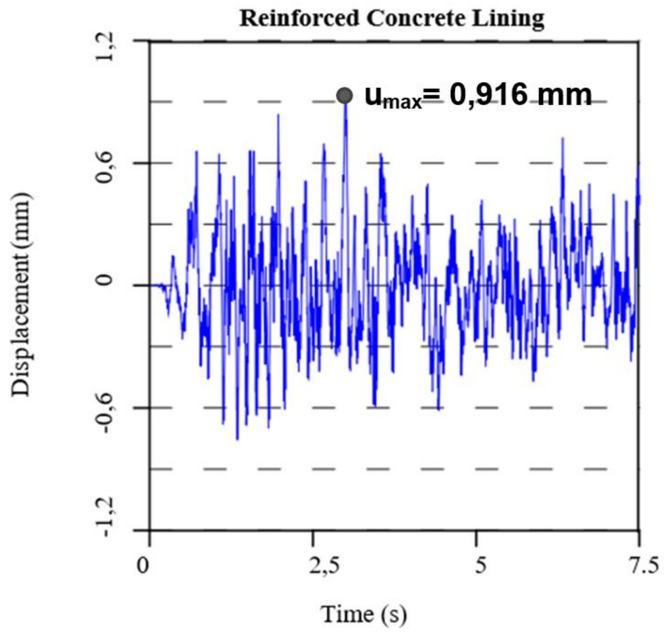


Figure 9. Displacement graphs of three different linings

5. Conclusions

This paper examines linear earthquake response of the tunnel structure called T3 Gubuket Tunnel, considering soil-structure interaction. In this context, the effect of the use of different lining materials on the seismic performance of tunnel structure is investigated and evaluated. Steel fiber reinforced and geopolymer concretes are assessed in terms of the linear earthquake behavior of the system. 3D finite element model of tunnel is created using ANSYS software, and to get an earthquake response of the system 1992 Erzincan Earthquake ground motion is used in this study. Following points can be drawn for this study:

- Effective first eight modes range from 79 Hz to 110 Hz which are classified as bending modes.
- Three distinct materials are compared in order to show the deformation capacity of linings under earthquake excitation. Steel fiber reinforced concrete is the best choice as a tunnel lining because of allowing lower damage to the case structure, while geopolymer concrete should not be used to earthquake prone areas because of low elasticity.
- According to displacement contours, the linear seismic damage is locally concentrated at the middle height nodes of the tunnel.
- The horizontal displacements are highest at the base nodes and the vertical displacements are the middle height nodes of the tunnel.
- Geopolymer concrete is more brittle than a fiber reinforced concrete under higher seismicity, implying that steel fibers provide ductility. Results show that the use of geopolymer concrete is acceptable for the PGA values between 0.1g and 0.25g at the vertical component of ground motion, however, it can be applicable to utilize geopolymer concrete only if such

strengthening material as fiber reinforced cementitious matrix (FRCM) could be used, which such implementations provide increase in the ductility for the material.

- In earthquake prone zones, steel fiber reinforced concrete may be preferred against high magnitudes of earthquakes and near-fault effects (i.e., forward, and backward rupture directivities and pulse like velocities).

Statements & Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

The author contributed to the study conception and design. Material preparation, data collection and analysis were performed by Orhun Kalyoncu. The first draft of the manuscript was written by Orhun Kalyoncu. The author read and approved the manuscript.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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