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The Effect of Tunnels' Diameter on the Variations of End-Anchored Rock Bolts' Axial Forces Subjected to Seismic Waves in Steep Ground

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***Abstract*— In this study, through pseudo-static analysis using finite element modeling software phase^2, the effect of tunnels' diameter on the variations of rock bolts' axial forces Subjected to earthquake acceleration in steep ground is evaluated. The circular tunnels are modeled with the diameter of 4, 6, 8, 10 and 12 meters and in depth of 25 meters within the shale rocks. The tunnels are supported by end anchored rock bolts with the length of 3 meters and spacing of 2 meters. Moreover, the ground surface modeled with the dip of 20 degrees to the horizon and the earthquake with the magnitudes of 6.5, 7, 7.5 and 8 on the Richter scale are considered. The result of the evaluations demonstrates that the value of rock bolts' axial force increasing with increment of the tunnel depth in static mode. Furthermore, with increasing the earthquake magnitude, the axial force of rock bolts variations has increased because the total displacement around tunnels has been increased. In addition, in steep surface, the alignment of horizontal acceleration of seismic coefficient with steep direction and the same direction of the vertical seismic coefficient with gravitational force had resulted in the highest variance of rock bolts' axial force, but because of limitation of tunnel displacements in higher diameters, the variations of axial forces reduced with increasing of tunnel diameter.**

***Keywords*— FEM, Tunnel, Rock bolt, Axial force, Steep ground.**

I. INTRODUCTION

Tunnels are vital underground structures that can withstand earthquakes. Although underground structures, in comparison to surface structures are of high safety regarding seismic waves, historical evidence and earthquake reports show that these structures are vulnerable to waves, which result from earthquake, and outbreak of damage and destruction is possible.

One of the ways to stabilizing of tunnels is application of rock bolts. A rock bolt is a long anchor bolt, for stabilizing rock excavations, which may be used in tunnels or rock slopes. It transfers load from the unstable exterior to the confined interior of the rock mass. The rock bolts are usually installed in a pattern, the design of which depends on the rock quality designation and the type of excavation [1].

Rock bolts have been used for years to reinforce the surface and near surface rock of excavated or natural slopes. They are used to improve the stability and load bearing characteristics of a rock mass. When rock bolts are used to reinforce a fractured rock mass, the rock bolts will be subjected to tension, shear and compressive forces. The studies have been done by researchers [2, 3, 4] to reinforce the slopes with rock anchoring. A general rule for rock bolts is that the distance between rock bolts should be approximately equal to three times the average spacing of the planes of weakness in the rock mass, and the bolt length should be twice the bolt spacing [5].

Tunnels excavate in various rock masses and ground conditions with different modes of behavior. The way the rock masses surrounding a tunnel behave is very important. The behavior of tunnel largely depends on the surface dip and the size of underground excavation. The ground behavior can be assessed via ground conditions with various project features. The rock masses whose strength is lower than the surrounding stress can be considered as weak rocks. The behavior of weak rocks in tunnels has led to problems during the construction of a number of projects. The ratio of rock mass strength to the in situ stress value specifies that deformations induce stability problems in the tunnel. The analysis of circular tunnels excavated in weak rocks under hydrostatic stress fields has been one of the principal sources of knowledge.

Due to excavation of tunnel in weak rocks, the surface settlement of ground could be occurred. The displacements at the surface of ground and the displacement distributions around tunnels varying in the plastic zone. In this matter, the theories are investigated by [6] and [7].

Furthermore, excavating underground structures in rock mass, causes stress changes in the underground environment and this phenomenon can cause displacements in these areas. In addition, the displacements caused by excavation may cause induced stress on the support system of the tunnels and finally can end with instability of the tunnel surrounding area [8].

Moreover, applying the earthquake to the tunnel can cause compressive and tensile stresses, which can leads to the destruction of a temporary tunnel supporting system or even to a complete closure of the tunnel cross section [9].

In this research in order to study the ground surface dip and the effect of tunnels' diameter on the variations of rock bolts' axial forces, the circular tunnel with a diameter of 4, 6, 8, 10 and 12 meters and in depth of 25 meters is modeled and the ground surface dip of 25 degrees is considered.

II. THE PHYSICAL AND MECHANICAL CHARACTERISTICS OF THE SHALE ROCKS

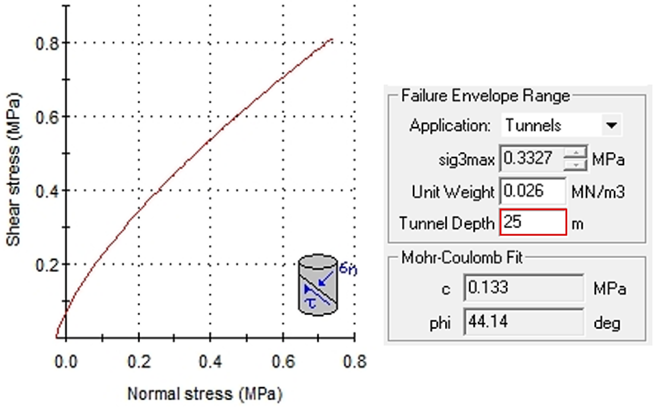
The rock mass properties such as the rock mass strength (σ_{cm}), the rock mass deformation modulus (E_m) and the rock mass constants (mb, s and a) were calculated by the RocLab program defined by [10] (Table 1). This program has been developed to provide a convenient means of solving and plotting the equations presented by [10].

In RocLab program, both the rock mass strength and deformation modulus were calculated using equations of [10]. In addition, the rock mass constants were estimated using equations of Geological Strength Index (GSI) [10] together with the value of the shale material constant (mi). In addition, the value of disturbance factor (D) that depends on the amount of disturbance in the rock mass associated with the excavation method was considered equal to 0.2 for the shale rocks in Table 1.

Table 1. Geomechanical parameters of shale rock mass obtained by using RocLab software.

Input and output of Roclab software						
Hoek-Brown classification				**Heok-Brown criterion**		
σ_{ci} (Mpa)	GSI	m_i	D	M_b	s	a
Intact Uniaxial compressive strength	Geological strength index	Constant Hoek-Brown criterion for intact rock	Disturbance Factor	Heok-Brown criterion		
35	**32**	**6**	**0.2**	**0.404**	**0.0003**	**0.520**

Parameters of the Mohr-Coulomb equivalent		Rock mass Parameters			
Mohr-Coulomb Fit		**Rock Mass Parameters**			
C (Mpa)	φ (degree)	σ_t (Mpa)	σ_c (Mpa)	σ_{cm} (Mpa)	E_{rm} (Mpa)
Cohesion	Friction angle	Tensile strength	Uniaxial compressive strength	Global strength	Deformation modulus
0.079	**54.04**	**-0.026**	**0.522**	**2.700**	**495**



Failure Envelope Range
Application: Tunnels
sig3max 0.3327 MPa
Unit Weight 0.026 MN/m3
Tunnel Depth 25 m
Mohr-Coulomb Fit
c 0.133 MPa
phi 44.14 deg

Fig. 1. The Hoek-Brown failure envelope of shale rock masses in the depth of 25 meters.

The Hoek-Brown failure envelope of shale rock masses for depth of 25 meters is obtained and presented in Fig. 1.

III. NUMERICAL ANALYSIS

Numerical analyses are done using a two-dimensional hybrid element model, called Phase^2 Finite Element Program [11]. This software is used to simulate the two-dimensional excavation of a tunnel. In this finite element simulation, based on the elasto-plastic analysis, deformations and stresses are computed. These analyses used for evaluations of the tunnel stability in the rock masses. The geomechanical properties for these analyses are extracted from Table 1. The generalized Hoek and Brown failure criterion is used to identify elements undergoing yielding and the displacements of the rock masses in the tunnel surrounding.

To simulate the excavation of tunnels in the shale rock masses, finite element models are generated for circular tunnels for different diameter and in depth of 25 meters. It should be noted that, the dip of 20 degrees to the horizon is considered as the ground surface dip. The six-nodded triangular elements are used in finite element mesh. The end anchored bolts with the length of 3 meters and spacing of 2 meters are used for stabilization of tunnels. Figs. 2 and 3 show various diameters which considered in tunnels modeling.

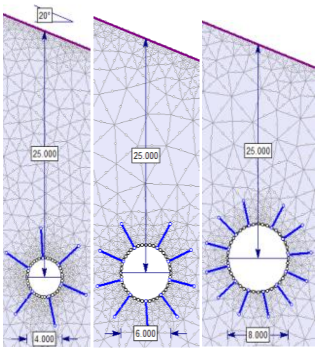


Fig. 2. The modeling of circular tunnels with the diameters of 4, 6 and 8 meters and in depth of 25 meters. The dip of ground surface is 20 degrees to the horizon.

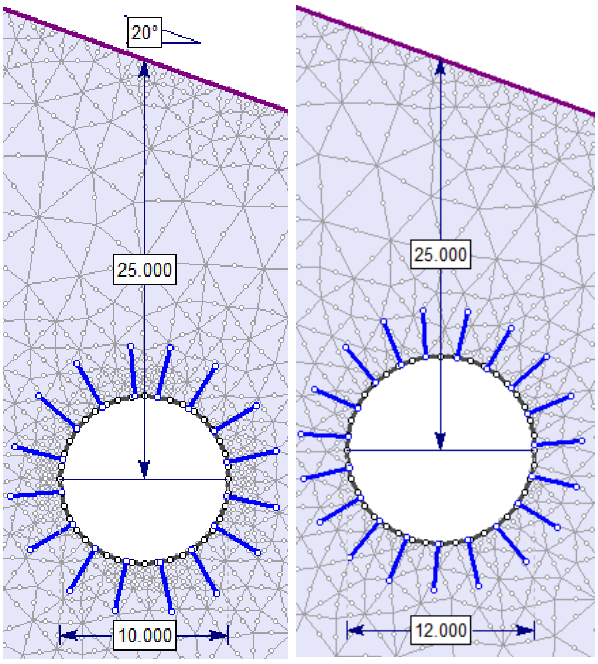


Fig. 3. The modeling of circular tunnels with the diameters of 10 and 12 meters and in depth of 25 meters. The dip of ground surface is 20 degrees to the horizon.

Figs. 4 to 9 show the results of rock bolts' axial forces maximum values and stress trajectories for various diameters of tunnels in static mode.

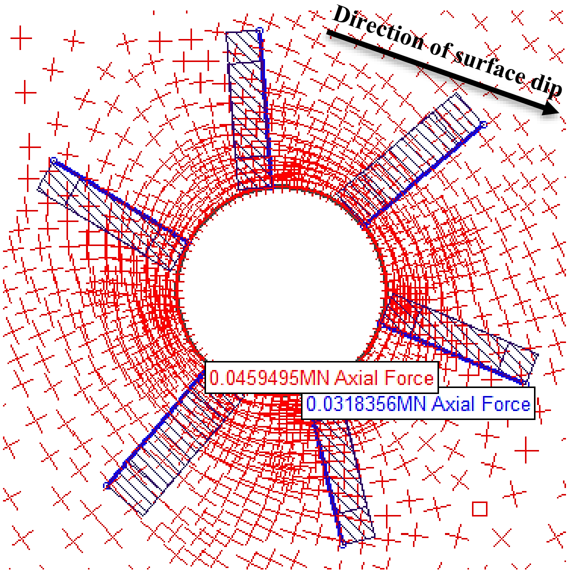

Maximum value of axial forces = 0.04595 MN

Fig. 4. The axial force of rock bolts and tunnel displacements for diameter of 4 meters in static mode.

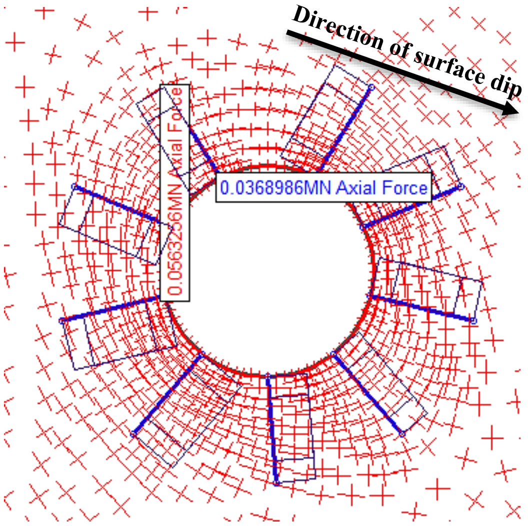

Maximum value of axial forces = 0.05633 MN

Fig. 5. The axial force of rock bolts and tunnel displacements for diameter of 6 meters in static mode.

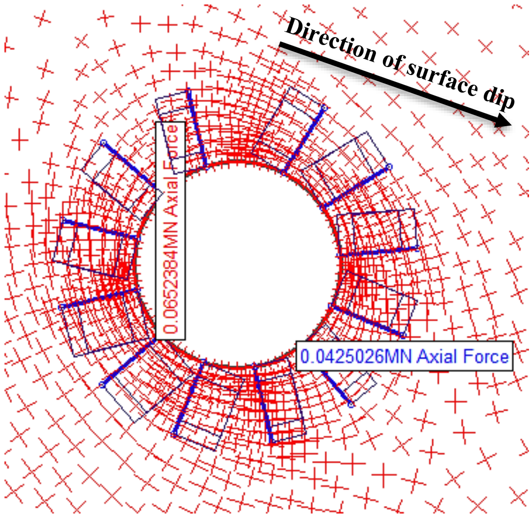

Maximum value of axial forces = 0.06524 MN

Fig. 6. The axial force of rock bolts and tunnel displacements for diameter of 8 meters in static mode.

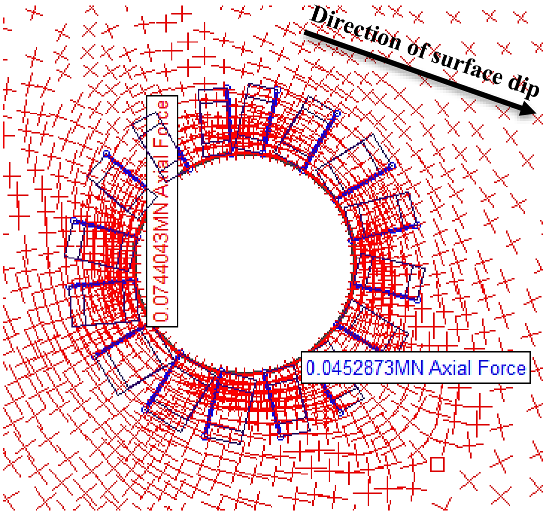

Maximum value of axial forces = 0.07440 MN

Fig. 7. The axial force of rock bolts and tunnel displacements for diameter of 10 meters in static mode.

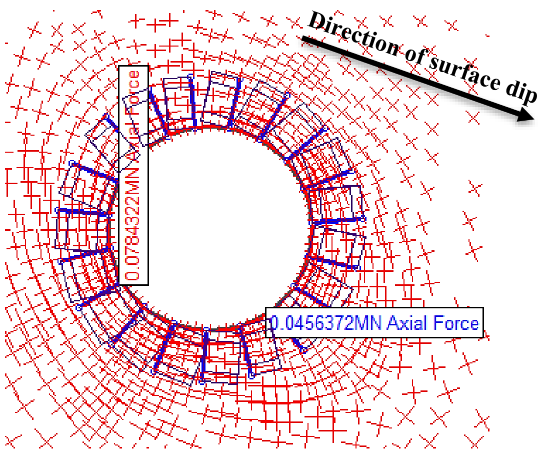


Fig. 8. The axial force of rock bolts and tunnel displacements for diameter of 12 meters in static mode.

As the above figs. show, with augment of the tunnels' diameter in static mode, the axial force of rock bolts increased as well. Because the declivity of ground surface, forces the tunnel to have more displacement and in this condition, rock bolts are under higher tensile stresses which shown as increment of the axial forces and the stress trajectories also indicate this act.

Furthermore, a set of numerical analysis case studies were carried out to investigate the effect of horizontal and vertical seismic coefficient in steep ground, using the pseudo-static seismic loading procedure. Four seismic loading scenarios, as shown in below are applied to the models.

It should be noted that, when horizontal seismic coefficient (K_h) is positive, it applies to right side and when it is negative, applies to left side. For vertical seismic coefficient (K_v), positive value means upward and negative value means downward.

1) K_h = **+** value and K_v = **zero**. In this case, the effect of vertical seismic coefficient ignored and equal to zero considered.

2) K_h = **+** value and K_v = **+** value too. This seismic loading scenario considers a positive horizontal and vertical seismic coefficient. In this case, the vertical seismic coefficient is adding an inertial force and in the opposite direction as the downward force due to gravity.

3) K_h = **+** value and K_v = **-** value. This loading case the sign of the vertical seismic coefficient is negative. Thus, the inertial force, simulating seismic loading, is in the same direction with gravitational force and therefore is added to the self-weight.

4) K_h = **-** value and K_v = **-** value too. In this case, the direction of horizontal seismic coefficient is in negative direction. This case was established to investigate the influence of direction of horizontal seismic coefficient on the axial force of rock bolts.

All the horizontal and vertical seismic coefficients are calculated for the earthquakes with the magnitudes of 6.5, 7, 7.5 and 8 on the Richter scale, by equations presented in [12].

Figs. 10 to 15 show variations of axial force in terms of earthquake magnitudes for different diameters of tunnels. The variations of axial force are difference between static and pseudo-static axial force values. In addition, the dip of 20 degrees and depth of 25 meters considered for tunnels in all cases.

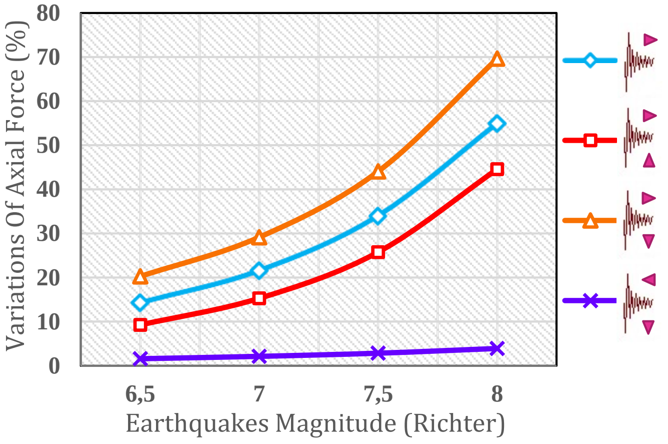


Fig. 10. Variations of axial force in terms of earthquake magnitudes for diameter of 4 meters.

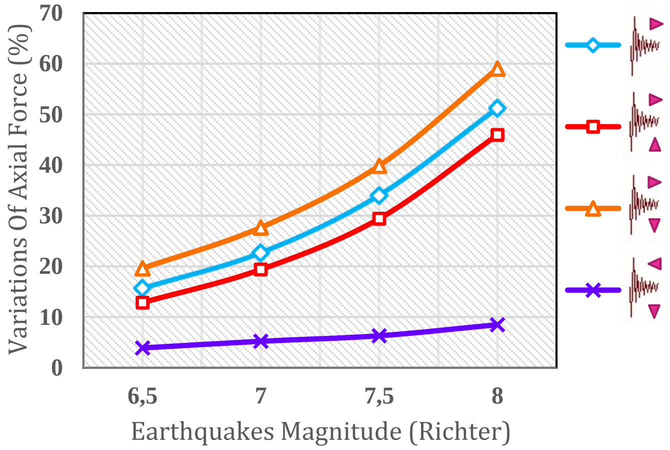


Fig. 11. Variations of axial force in terms of earthquake magnitudes for diameter of 6 meters.

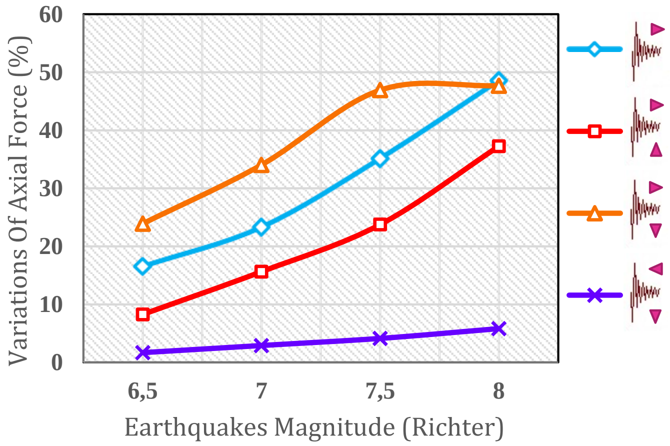


Fig. 12. Variations of axial force in terms of earthquake magnitudes for diameter of 8 meters.

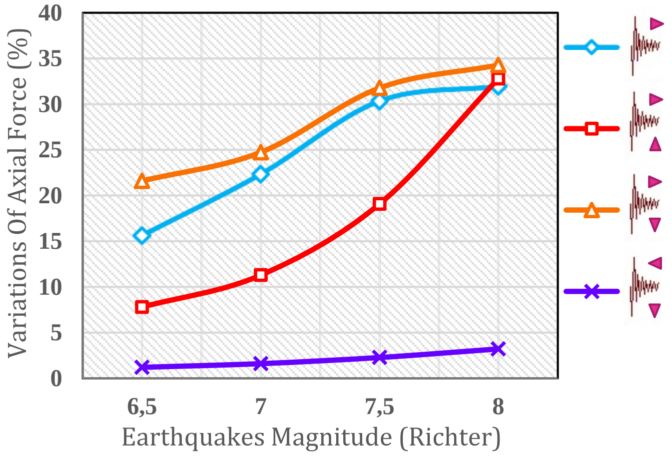


Fig. 13. Variations of axial force in terms of earthquake magnitudes for diameter of 10 meters.

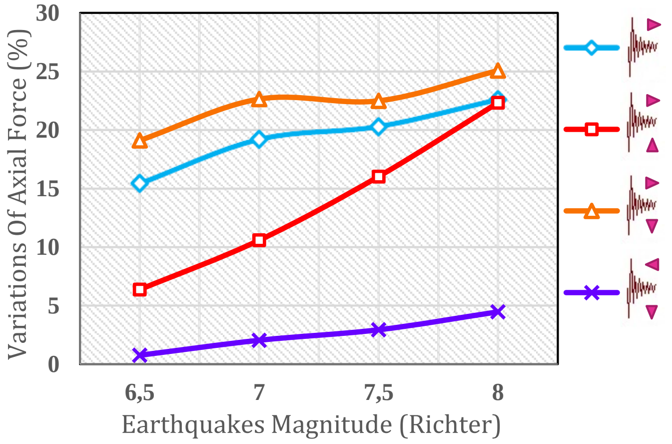


Fig. 14. Variations of axial force in terms of earthquake magnitudes for diameter of 12 meters.

As the results show, we see the lowest variations of axial forces for purple curves and the highest results related to the orange curves. In fact, in these cases, the alignment of horizontal acceleration of seismic coefficient (K_h) with steep direction and the same direction of the vertical seismic coefficient (K_v) with gravitational force had resulted in the highest axial force of rock bolts and it variations that shown with orange curves in Figs. 10 to 14. However, when the horizontal seismic coefficient (K_h) is in opposite direction of ground surface dip, the lowest results, compared to the other modes have been obtained. Because it reduces the displacements of tunnel.

Furthermore, based on the above figs. we can see about 70 percent of variations as the maximum axial forces variations for the diameter of 4 meters (fig. 10). Nevertheless, with increasing the diameter of tunnels, the maximum variations of axial forces reduced. Because augment of tunnel size leading to diminution of its movements. So, in this condition, rock bolts put under lower tensions that indicates by decreasing the growth rate of axial force variations as well.

IV. CONCLUSIONS

The results of the evaluations show that, with increasing the diameter of tunnel in static mode, the axial force of rock bolts increased. Because the declivity of ground surface, forces the tunnel to have more displacement and in this condition, rock bolts are under higher tensile stresses, which emerge as increasing of the axial forces and position of stress trajectories, also indicate it.

Moreover, with increasing the earthquake magnitude, the variations of axial forces have increased for all seismic loading scenarios. The highest variations of axial forces are related to the orange curves in all diagrams, because the alignment of horizontal acceleration of seismic coefficient (K_h) with the direction of ground surface dip and the same direction of vertical seismic coefficient (K_v) with the gravitational force, had resulted in the highest axial force of rock bolts variations and the opposite direction of horizontal seismic coefficient (K_h) with ground surface dip leads to obtaining the lowest rate of variations.

Furthermore, augment of the tunnels' diameter, resulted reducing rate of the maximum axial forces variations. Because increment of tunnel size leading to reduction of its movements. Therefore, in this condition, rock bolts stand lower tensions that indicates by decreasing the growth rate of axial force variations.

This study expresses the importance of axial force factor. As we know, in excessive tensile stresses, there is a possibility of yielding in rock bolts, which can leads to the destruction of a temporary tunnel supporting system or even to a complete closure of the tunnel cross. Therefore, design engineers have to pay special attention in variations of rock bolts' axial forces and tensile stresses, which affect the tunnel and it supporting system, to prevent structural damages and casualties in underground structures during the earthquake.

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