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The Effect of Seismic Coefficients Direction on the Axial Force of Rock Bolts in Flat Ground

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Abstract- In this study, through Pseudo-static analysis with the help of finite element modeling software phase^2, effect direction of seismic coefficients on axial force of rock bolts mounted in circular tunnels and it changes in different conditions evaluated. The circular tunnels are modeled with diameter of 8 meters and in depths of 10, 25 and 35 meters in the Shale rocks. The tunnels are supported by end anchored rock bolts with length of 3 meters and spacing of 2 meters. The ground surface is flat and the earthquake magnitudes of 6.5, 7, 7.5 and 8 on the Richter scale considered in tunnels modeling. The axial force of rock bolts is measured for each of depth and magnitudes of earthquake. The results of the evaluations show that with increasing the depth of tunnel and the earthquake magnitude, the axial force of rock bolts and it variations has increased. Because in this situation, the total displacement around tunnels has been increased. Moreover, in flat surfaces, the alignment of vertical acceleration of seismic coefficient with gravitational force direction had resulted in the highest axial force of rock bolts and the direction of horizontal seismic coefficient do not make any drastic change in rock bolts' axial force values.

Keywords- *Axial force, Rock bolt, Seismic Coefficient, Tunnel, Phase2*

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 almost always 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 steep ground largely depends on the degree of surface dip and the shape and 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.

Excavating underground structures in rock mass, causes stress changes in the underground environment and this phenomenon can cause displacements in these areas. Also 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 [6].

Furthermore, applying the earthquake to the tunnel can cause compressive and tensile stresses too which can lead to the destruction of a temporary tunnel supporting system or even to a complete closure of the tunnel cross section [7].

In this research in order to study the effect of seismic coefficients direction on the axial force of rock bolts, the circular tunnels with diameter of 8 meters and in different depths are modeled and the ground surface is considered in flat mode. Fig. 1 shows the model of circular tunnel with diameter of 8 meters and in depth of 35 meters that created for analysis the tunnels behavior.

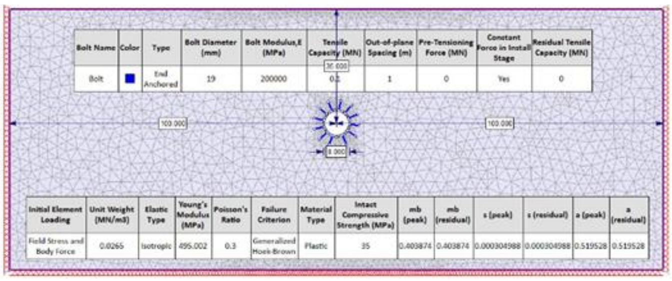

Figure 1. The model of tunnel with diameter of 8 meters and in depth of 35 meters in flat ground.

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 [8] (Table 1). This program has been developed to provide a convenient means of solving and plotting the equations presented by [8].

In RocLab program, both the rock mass strength and deformation modulus were calculated using equations of [8]. In addition, the rock mass constants were estimated using equations of Geological Strength Index (GSI) [8] together with the value of the shale material constant (mi). Also, 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 I. 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

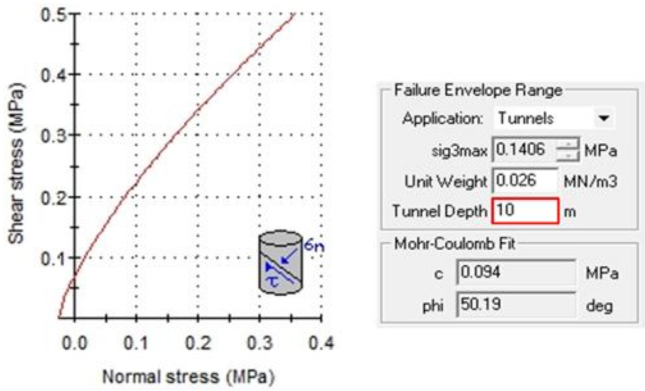

Figure 2. The Hoek-Brown failure envelope of shale rock masses in the depth of 10 meters.

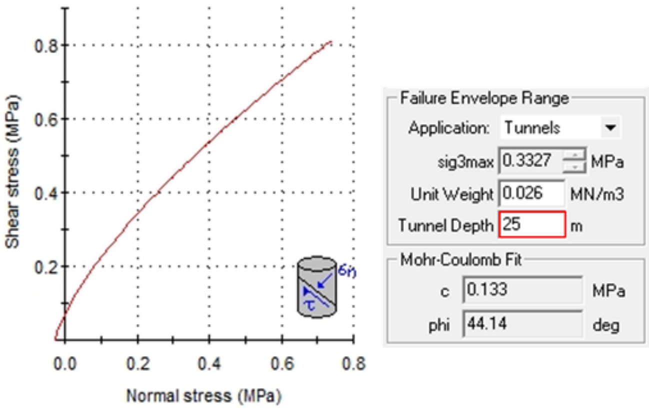

Figure 3. The Hoek-Brown failure envelope of shale rock masses in the depth of 25 meters.

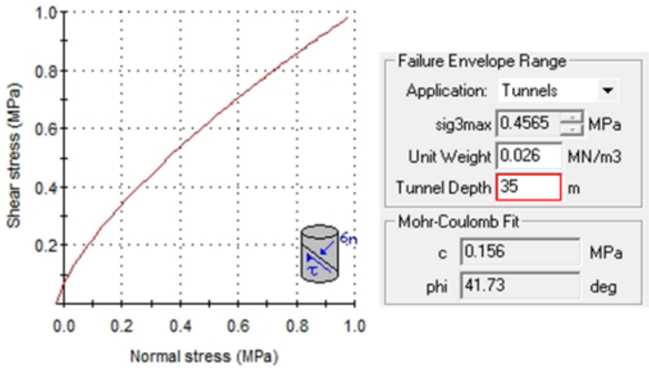

Figure 4. The Hoek-Brown failure envelope of shale rock masses in the depth of 35 meters.

The Hoek-Brown failure envelope of shale rock masses for different depths is obtained and presented in Figs. 2 to 4.

In order to achieve more accurate results, material properties defined for each depth of tunnels separately and individually applied to different models with different depths.

III. NUMERICAL ANALYSIS

Numerical analyses are done using a two-dimensional hybrid element model, called Phase^2 Finite Element Program [9]. 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, a finite element models is generated for circular tunnels with diameter of 8 meters and in depths of 10, 25 and 35 meters. Also the dip of 0 degrees to the horizon is considered for the ground surface. The six-nodded triangular elements are used in the finite element mesh. The end anchored bolts with length of 3 meters and spacing of 2 meters is used for reinforcement of tunnels. Fig. 5 shows different depths of tunnels modeling.

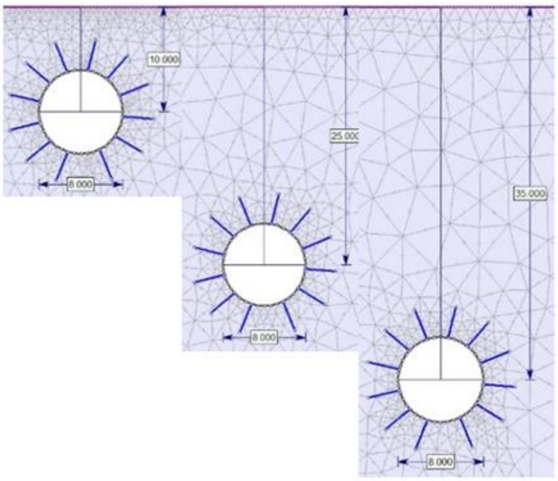

Figure 5. The modeling of the circular tunnel with a diameter of 8 meters, in depths of 10, 25 and 35 meters. The ground surface is flat.

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.

At first, it's necessary to mention that when horizontal seismic coefficient (K_h) is positive, it applies to right side and when it's 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 = 0. 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 magnitudes of 6.5, 7, 7.5 and 8 on the Richter scale, by equations presented in [10].

$$K_h=\frac{A^h_{max}}{g} \tag{1}$$

According to [10], the ratio of peak ground acceleration to the acceleration of gravity suggested to evaluate the horizontal seismic coefficient "(1)". Also for the vertical seismic coefficient suggested using "(2)".

$$K_v=0.5\ K_h \tag{2}$$

Moreover, fig. 6. helps to calculate the peak acceleration with knowing of earthquakes magnitude that presented by [11].

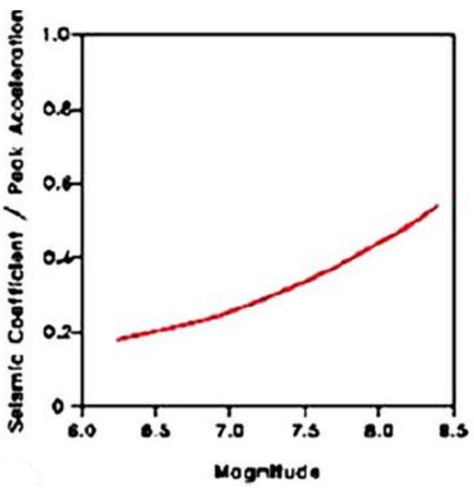

Figure 6. Obtaining peak acceleration by earthquake magnitude [11].

Reference [12] presents depth reduction factor for tunnels that shown in table 2. This factor helps to obtaining the seismic coefficients in scale of tunnel depth.

TABLE II. RATIOS OF GROUND MOTION AT DEPTH TO MOTION AT GROUND SURFACE [12].

Tunnel depth (m)	Ratio of ground motion at tunnel depth to ratio of surface ground motion
≤6	1.0
6-15	0.9
15-30	0.8
>30	0.7

Figs. 7 to 10 show the results of horizontal and vertical seismic coefficients applying modes and the values of rock bolts' axial forces for a tunnel with a diameter of 8 meters and in depth of 35 meters. The earthquakes magnitude is 7 on the Richter scale.

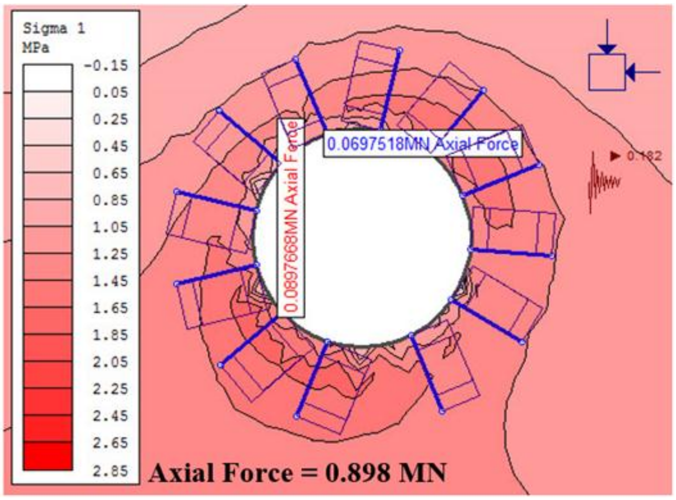

Figure 7. Contour plot of major principal stress (σ_1) and axial force of rock bolts for case 1: $K_h = 0.182$ and $K_v = 0$.

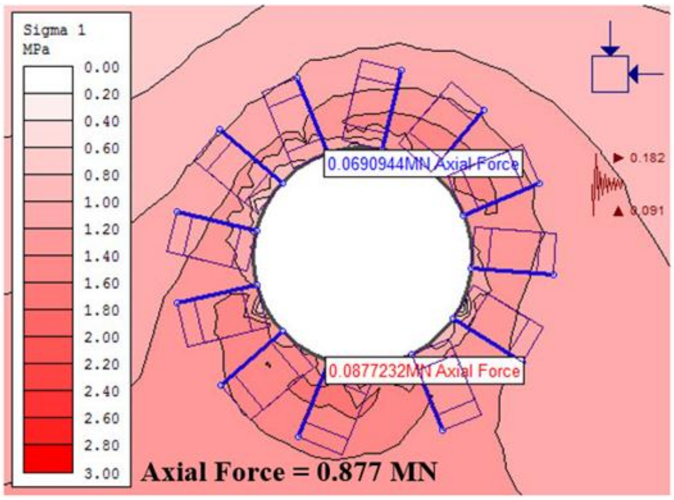

Figure 8. Contour plot of major principal stress (σ_1) and axial force of rock bolts for case 2: $K_h = 0.182$ and $K_v = 0.091$.

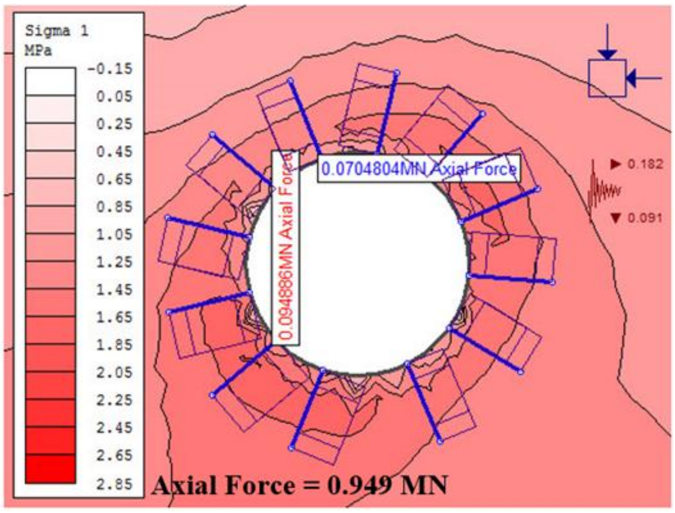

Figure 9. Contour plot of major principal stress (σ_1) and axial force of rock bolts for case 3: $K_h = 0.182$ and $K_v = -0.091$.

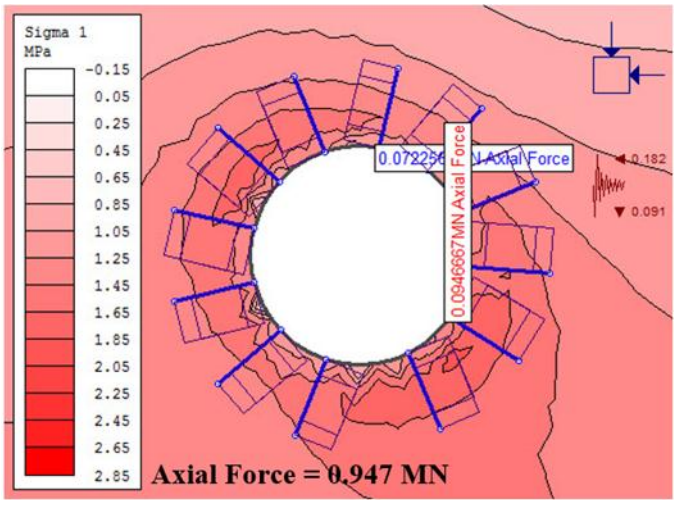

Figure 10. Contour plot of major principal stress (σ_1) and axial force of rock bolts for case 4: $K_h = -0.182$ and $K_v = -0.091$.

Run the models in pseudo-static mode, clarify the axial force of rock bolts and state of major principal stress (σ_1) contours around the tunnel. As the results show, when the direction of the vertical seismic coefficient in the same direction with the gravitational force, the magnitude of the stresses around the tunnel is greater and in fact the alignment of vertical seismic coefficient with gravitational force resulted in the highest axial force of rock bolts that shown in Figs. 9. and 10. But the direction of horizontal seismic coefficient does not make any drastic change in value of rock bolts' axial force. Also, when the vertical seismic coefficient is in opposite direction of gravitational force (Fig. 8.), the lowest axial force of rock bolts has been obtained because it reduces the displacement of tunnel. In this condition, the rock bolts are under lower tensile stresses which are presented as the axial force for them.

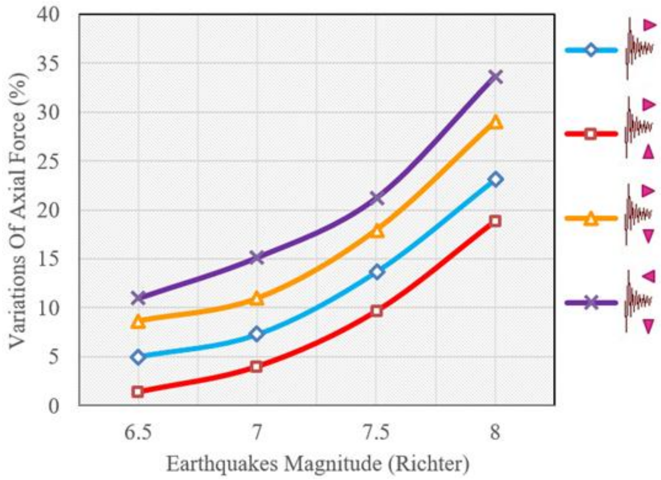

Figure 11. Variations of axial force in terms of earthquake magnitudes for a circular tunnel with diameter of 8 meters, in depth of 10 meters.

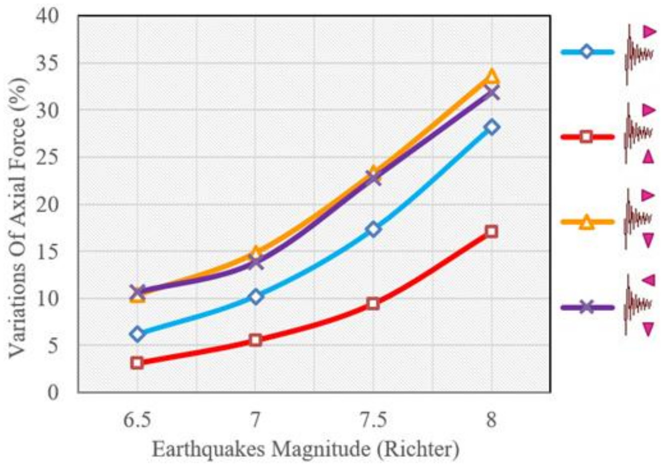

Figure 12. Variations of axial force in terms of earthquake magnitudes for a circular tunnel with diameter of 8 meters, in depth of 25 meters.

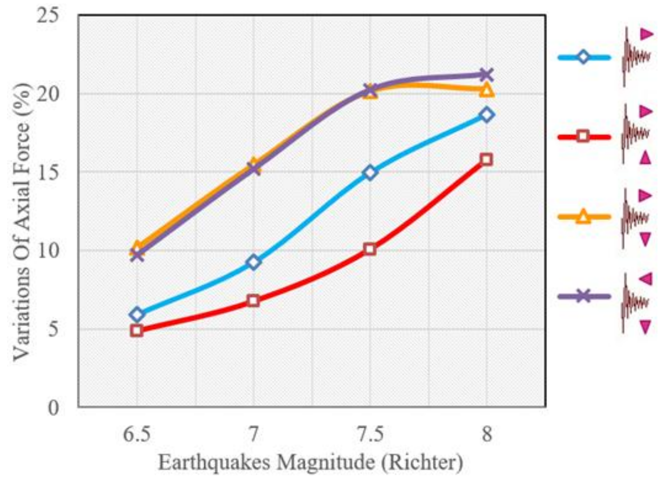

Figure 13. Variations of axial force in terms of earthquake magnitudes for a circular tunnel with diameter of 6 meters, in depth of 35 meters.

Figs. 11 to 13 represent axial force of rock bolts variations in different earthquake magnitudes. The variations of axial force are difference between static and pseudo-static axial force values. As the results show, with increasing the earthquake magnitude, the variations of axial force has increased for all seismic loading scenarios because, the total displacements around tunnels have been increased. But, we see lowest variations for red curves that vertical seismic coefficient applied in opposite direction of gravitational force and the highest variations observed in purple and yellow curves which are very close to together and coincident in large areas. So it can be concluded that the vertical seismic coefficient can influence the axial force of rock bolts mounted in tunnels and it variations which is very important and can influence the stability of tunnel with destruction of the rock bolts in excessive tensions.

Furthermore, with increasing the tunnel depth, the growth rate of axial force variations has decreased. Because the effect of earthquake acceleration on the tunnel gradually reduces with depth increasing and in this condition, stresses applied to the tunnel reduces too which observed with displacements reduction in tunnel.

IV. CONCLUSIONS

The results of the evaluations show that when the direction of the vertical seismic coefficient (K_v) in the same direction as the gravitational force, the magnitude of the stresses around the tunnel is greater which resulted in the highest axial force of rock bolts in flat grounds. Also, with increasing the earthquake magnitude, the variations of axial force have increased for all of seismic loading scenarios. But the opposite direction of vertical seismic coefficient (K_v) with gravitational force leads to obtaining the lowest axial force of rock bolts and it variations because of the tunnel displacement reduction and lower tensile stresses that affects to the tunnel. Moreover, with increasing the tunnel depth, the growth rate of axial force variations has decreased, because of the over burden increasing that reduces the displacements of tunnel and the impact of earthquake acceleration on the tunnel which is gradually reduced with depth factor.

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