SEISMIC ANALYSIS OF HORSESHOE TUNNELS UNDER DYNAMIC LOADS DUE TO EARTHQUAKES

Navid Hosseini[1], Kazem Oraee[2], and Mehran Gholinejad[3]

ABSTRACT: Due to seismic events, such as earthquakes, the elastic waves propagate through a medium. The impact of these waves on underground structures is to provide dynamic forces and moments that may affect the stability of underground structures. The aim of this paper is to analyse the effects of seismic loads on the stability of horseshoe tunnels. As a case study, the stability state of the main access entry to C1 coal seam of Tabas collieries in Iran are analyzed using Phase2 software in static and dynamic states. It is often assumed that the effect of earthquakes on underground structures such as tunnels is negligible but the results of this study show that the stress caused by seismic loads can be harmful to the tunnel stability. It is concluded that the stress and displacement balance of forces around the tunnel are adversely affected and due to redistribution of these forces that create undue concentration in some areas, instability occurs in the tunnel. The paper also concludes that increasing the stiffness of the support system can increase the effect of the seismic loads. The analysis provided in this paper together with the conclusions obtained can serve as useful tools for the tunnel design engineers, especially in areas susceptible to seismic phenomena.

INTRODUCTION

In the past it has always been assumed that earthquakes have no major effect on tunnels, however the study of tunnel behaviours on seismic loads and also the damage of these structures, emphasize the necessity of the stability study under dynamic loading generated by earthquake (Williams, 1997).

Tabas coalfield is a main coal reserve that is located in the central part of Iran. The coal is mined by mechanized longwall mining method based on physical properties and geometry of coal seam (Hosseini, 2008). Several excavation tunnels are needed when using the longwall method (Oraee, 2001). However, due to several faults in Tabas collieries\\ the stability study of these tunnels under dynamic and seismic loading is needful. Therefore in this paper as a typical case the stability of the main access tunnel in C1 coal seam is studied.

THE EFFECT OF SEISMIC WAVES ON UNDERGROUND STRUCTURE STABILITY

Each earthquake wave has a different effect on tunnel stability; these are described as follow:

P-waves

P-waves are usually concomitant with horizontal S-waves. P-waves create the axial compressive and tension on underground structure, while the horizontal S-waves only create a horizontal vibration (Wang, 1993). Therefore the horizontal S-waves have the major effect on high structure while their effect on underground structure is poor. Tunnels and other flexible linear underground structures based on a flexible ring, such as the support system can tolerate the effect of horizontal S-waves. P-waves rapidly propagate in the ground, and are thus the first waves affecting the structure.

Vertical S-waves

Vertical S-waves are a principal kind of elastic waves and carry about 65 percentage of the released seismic energy. These waves cause vertical displacement of the structure system and seriously damage the major structure, but for tunnels and other underground structures the effects are negligible, since using the flexible support system will neutralize the effect of these waves (Ebrahimi, *et al*, 2006). The velocity of vertical S-waves is less than that of the horizontal waves. Therefore the periodical

[1]. *Mining Department, Islamic Azad University, South Tehran Branch, Iran*
[2]. *Professor, University of Stirling, UK*
[3]. *Mining Department, Islamic Azad University, South Tehran Branch, Iran*

interval between vertical and horizontal S-waves relates to the distance between the structure and earthquake hypocenter.

Rayleigh waves

In Rayleigh waves, the direction of the spinning motion in the highest zone and direction of waves are opposite; the path of particle motion is elliptical and the large diameter is perpendicular to the direction of wave propagation. Rayleigh waves like the vertical S-waves are critical for high structure damages (Wang, 1993). The underground structures are vertically displaced based on height as a consequence of these waves.

Love waves

Love waves are a special type of horizontal S-waves which result in horizontal displacement. This displacement decreases by increasing the depth of the structure. Generally, a love wave is an important factor in threatening the underground structure. Tunnels experience the lateral dynamic displacement due to impact by love waves; the effect of the impact is different on different parts of the structure (Ebrahimi, *et al*, 2006). If the stress added is more than that of the structure safety limit, the lateral stiffness of underground structure must be increased for coordinating with a new loading state.

THE MAIN ACCESS TUNNEL OF C1 COAL SEAM AND SURROUNDING ROCK MASS

One of the main coal seams of Tabas coalfield in Iran is named C1, having 2 meters thickness and is associated with sandstone, siltstone and mudstone layers. Based on studies (Hosseini, 2008, Oraee, 2009), the geo-mechanical properties of coal seam and surrounding rock mass are given in Table 1.

Table 1 - Geo-mechanical properties of coal seam and surrounding rock mass

Rock type	$\sigma_{ci}\ (MPa)$	m_i	GSI	$D\ (kg/m^3)$	$E_i\ (GPa)$	v
Sandstone	16.1	17	29	2700	5.281	0.32
Siltstone	25.6	12	21	2730	2.838	0.31
Siltstone & Sandstone	57.8	15	24	2715	4.885	0.31
Mudstone	10.1	9	19	2650	0.343	0.30
Coal	7.0	12	19	1350	0.260	0.29

In this table, σ_{ci} is a uni-axial compressive strength of intact rock, m_i is a constant of intact rock, GSI is a geological strength index, D is a density, E_i is a young's modulus and v is Poisson's ratio. In tunnel stability analysis also the estimation of further mechanical properties of surrounding rock mass are required. For this purpose, Rocdata software provided by Rocscience Inc. (2009) is used to estimate the full geo-mechanical parameters of rock mass by comparison to the main rock failure criteria such as Hoek-Brown, Mohr-Coulomb, Braton-Bandis and Power Curve. Based on the data in Table 1, and by using the RocData software, the estimation of other rock mass parameters is presented in Table 2. Based on tunnel excavation method and engineering judgment (Hosseini, 2008), the selected disturbance factor (Oraee, *et al,* 2009) is 0.3.

In this table, C and $\emptyset$ are the cohesion and friction angles based on the Mohr-Coulomb criterion, σ_t is the rock mass tensile strength, σ_C is the uniaxial rock mass compressive strength, σ_{Cm} is the global rock mass compressive strength and E_m is the rock mass modulus of deformation. Due to large deposit and using of mechanized longwall mining, the main access tunnel in C1 coal seam must be stable for a long time and even during the entire life of the mine. This tunnel is excavated into a horseshoe section shape, with width and height of 5 m and 3.5 m, respectively. The average of overburden density is calculated at 2.7 t / m^2 per cubic meter, and the tunnel depth of ground surface is 40.8 m (Oraee, *et al,* 2009). The in-situ stress state is calculated by equations (Sheoru, 1994) as follows:

$$\sigma_v = \gamma . h \tag{1}$$

$$k = 0.25 + 7E_h(0.001 + \frac{1}{h}) \quad (2)$$

$$\sigma_h = k.\sigma_v \quad (3)$$

Table 2 - The estimated rock mass geo-mechanical parameters by RocData software

Rock type	Mohr-Coulomb		Rock mass parameters			
	$C\ (MPa)$	$\emptyset\ (Deg.)$	$\sigma_t\ (MPa)$	$\sigma_C\ (MPa)$	$\sigma_{Cm}\ (MPa)$	$E_m\ (MPa)$
Sandstone	0.144	41.01	-0.0029	0.163	1.787	651.37
Siltstone	0.120	37.42	-0.0034	0.131	1.810	316.01
Siltstone & Sandstone	0.189	47.01	-0.0079	0.387	5.127	414.61
Mudstone	0.071	27.32	-0.0015	0.043	0.565	263.64
Coal	0.045	32.00	-0.0008	0.030	0.458	263.64

Where, σ_v is the vertical in-situ stress, γ is the average density of overburden, h is the depth below ground surface, k is the ratio of horizontal to vertical in-situ stress, E_h is the average of horizontal deformability modulus and σ_h is the horizontal in-situ stress. Based on Equation (1), σ_v is calculated 1.081 MPa. It is safe to assert that E_h is underestimated and therefore k is less than the stated value, i.e. considered to be the worst possible scenario. Therefore, E_h is selected as 0.25 GPa and k is calculated as 0.3 using Equation (2). Therefore based on equation (3), σ_h is 0.32 MPa.

NUMERICAL MODELING

The Phase2 software produced by Rocscience Inc. (2009), is used for modelling of the main access tunnel of C1 coal seam. This software is a numerical code, based on the two-dimension finite element method. For studying the tunnel stability the Mohr-Coulomb criterion is selected due to geo-mechanical properties of rock mass (Brady and Brown, 2004). The affected zone is considered to be three times the dimension of the tunnel as in a *Box Shape*. The meshing is triangular but with getting nearer to the tunnel for increasing the analysis accuracy, the node density increases and therefore the mesh fines. The tunnel modelled by Phase2 is depicted in Figure 1. As seen in this figure, in Phase2 modelling the geometry and state of associated layers and the coal seam are defined relative to the tunnel.

Static and dynamic analysis

After tunnel modelling in the Phase2 code, the model is run to analyse the tunnel stability in static and dynamic conditions. The Phase2 software calculated the value of each mesh node based on two dimension finite element method, having the ability of pseudo dynamic analysis and hence can simulate the effect of earthquake on tunnel stability.

Using statistical methods and probability analysis based on studies in Tabas coalfield (Hosseini, 2008), the peak seismic acceleration due to earthquake by using field data and results of faulty studies in region, is calculated 0.29g for return period of 500 years. To study the tunnel stability state under such an earthquake act, in next stage after the static analysis, the horizontal seismic acceleration 0.29 is applied on the model. Therefore, the tunnel stability in static and dynamic conditions for horseshoe tunnels is analyzed. The maximum principal stress (σ_1) and the minimum principal stress (σ_3) in static and dynamic analysis is shown in Figure 2.

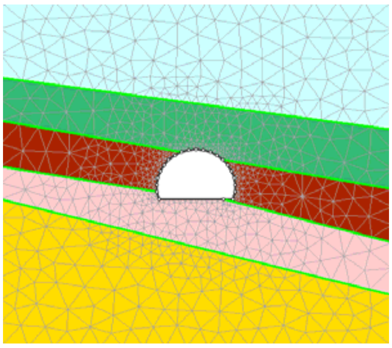

Figure 1 - The tunnel modelled by Phase2 software

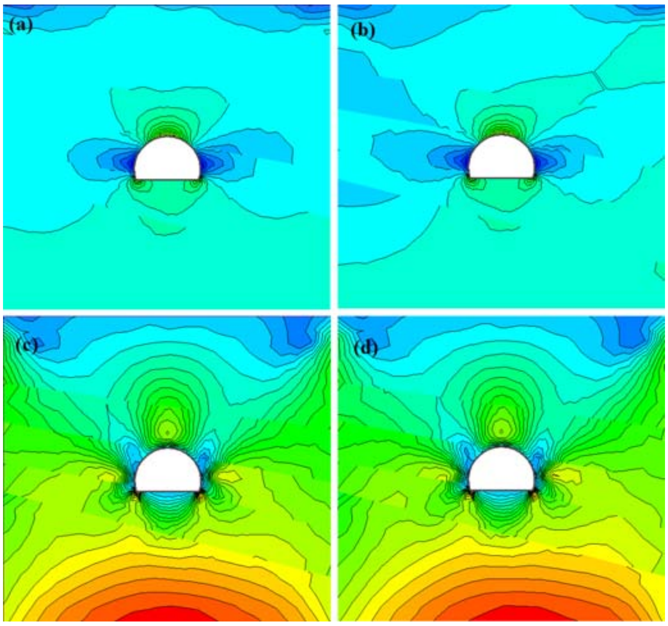

Figure 2 - The stress state of tunnel periphery, a) σ_1 in static analysis, b) σ_1 in dynamic analysis, c) σ_3 in static analysis and d) σ_3 in dynamic analysis

As seen in Figure 2, both the maximum and minimum principal stresses are increased after applying the dynamic loads. However the increase in σ_1 is more than that inσ_3.

In Figure 3, the displacement in static and dynamic conditions is shown. Due to the application of the dynamic stress the displacement state of tunnel periphery is changed, and the displacement in tunnel to the left side is more than to the right side. Also the strength factor is one of stability analysis criterion. The strength factor of tunnel periphery in static and dynamic analysis is shown in Figure 4. Although the strength factor by applying the dynamic stress of earthquake is changed, this variation is not significant.

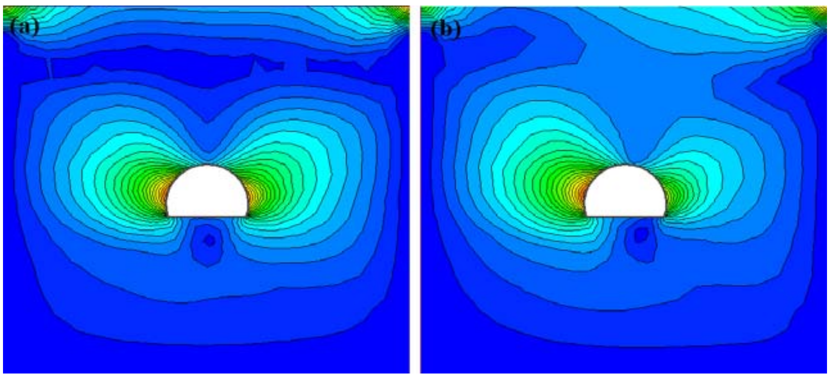

Figure 3 - The displacement of tunnel periphery, a) in static analysis, b) in dynamic analysis

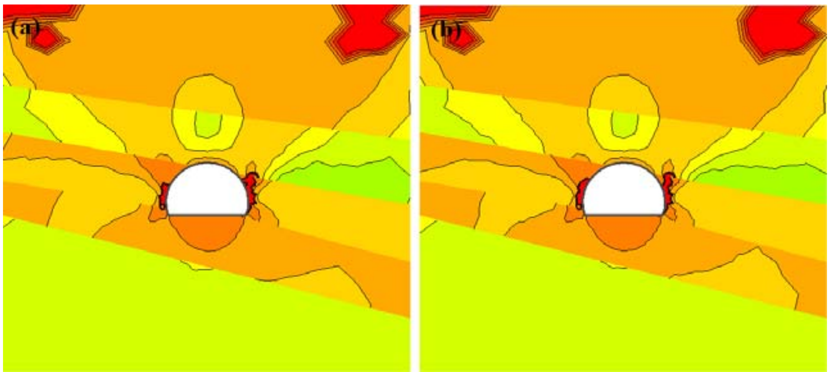

Figure 4 - The strength factor of tunnel periphery, a) in static analysis, b) in dynamic analysis

Based on the initial stress analysis and considering the displacement, the design of a support system is required for tunnel stability. Therefore the shotcrete with the young modulus of 30 GPa, and the Poisson ratio of 0.2 is used as the support system. First, one shotcrete layer with 50 mm thickness is applied in the model, and the displacement in static and dynamic analysis is determined. Then the shotcrete thickness increases to 150 mm while the other conditions remain same. The displacement with 50 mm and 150 mm shotcrete in static and dynamic analysis is shown in Figure 5.

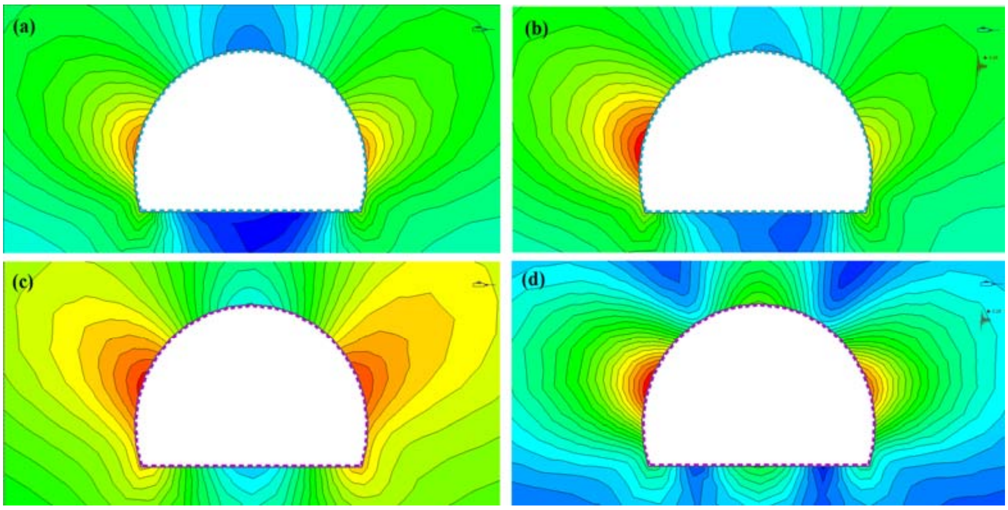

Figure 5 - The displacement with support system, a) shotcrete with 5 cm thickness, static, b) shotcrete 5 cm with thickness, dynamic c) shotcrete with 15 cm thickness, static, d) shotcrete 15 cm with thickness, dynamic

The stress and displacement of tunnel periphery shows that the increasing thickness of the shotcrete layer increases the effect of dynamic stress. The acquired result is verified based on study developments and several similar modelling. Moreover it is also approved that the effect of dynamic loads on tunnel stability increases with the increasing stiffness of the support system.

The results of numerical modelling of Phase2 software shows that after seismic loading the maximum axial force is 0.812 MN, the maximum bending moment is 0.016 MN per meter, and the maximum shear force is 0.11 MN - applied on tunnels that must add to static loads, before the tunnel stability analysis.

CONCLUSIONS

Although the damage of earthquake in an underground structure is less than that on the surface structure, the applied dynamic stress is not negligible. Among elastic waves of an earthquake the love wave is particularly dangerous to the underground structure. The result of the study shows that with applying the dynamic stress by earthquakes, the stress and displacement in tunnel periphery is increased. Therefore, for tunnel stability the support system must be reinforced. However with the increasing thickness or stiffness of the support system, the inertia is increased and thus the tunnel flexibility is reduced. Consequently the effect of the dynamic stress on the tunnel increases. The symmetry of stress and displacement distribution of tunnel periphery is adversely affected due to dynamic loading. Based on the direction of the motion of the seismic wave, displacement on one side of the tunnel is more than that on the other side; therefore the balance is disrupted and the potential of instability increases. Due to increases of the axial force the bending moment and the shear-force applied on tunnel by seismic loading, the dynamic analysis and also static analysis for tunnel stability is required.

REFERENCES

Brady B H G, and Brown E T, 2004. Rock Mechanics for Underground Mining, London, UK: George Allen & Unwin., p. 628

Ebrahimi, Shahriar, K, Rahmannejhad, 2006. Seismic analysis of circle tunnels by Semi-static approach, seventh International Civil Conference, 11-13 May., 2006, University of Science and Technology, Iran.

Hoek E, Carranza-Torres C, and Corkum B, 2002. Hoek-Brown Failure Criterion – 2002 Edition, Available (06/20/09): http://www.rocscience.com/hoek/references/H2002.pdf

Hosseini N, 2008. The geomechanical study of C1 main tunnel – Tabas collieries, Technical Report, Maadankavan Bisotun Co., Tehran, Iran, p. 218

Oraee Kazem, 2001. Underground coal mining, Polytechnic University Press, Tehran, Iran, p. 251

Oraee K, Hosseini N and Qolinejad M, 2009. Estimation of coal pillar strength by finite difference model, in: *proceedings of 2009 Coal Operators' Conference*, Wollongong, Australia, pp. 54-61

Oraee K, Hosseini N, and Qolinejad M, 2009. A new approach for determination of tunnel supporting system using analytical hierarchy process (AHP), in: proceedings of 2009 Coal Operators' Conference, Wollongong, Australia, pp. 78-89

ROCSCIENCE Inc., RocData Software, and Phase2 Software (2009), Available (06/20/09): http://www.rocscience.com

Sheory P R, 1994. A theory for in situ stresses in isotropic and transversely isotropic rock, *Int. J. Rock Mech. Min. Sci. & Geomech.* Abstr. 31(1), pp. 23-34

Wang J, 1993. Seismic Design of Tunnels: A Simple State-of-the-art Design Approach, Monograph 7, Parsons, Brinckerhoff, Quade and Douglas Inc, New York, p. 147

Williams, O, 1997. Engineering and design -tunnels and shafts in rock, U.S. Army Corps of Engineers, Washington, DC 20314-1000, p. 236