Numerical Analysis of the Stability of Tunnels in Seismic Regions

R. Bhasin and T. Pabst
Norwegian Geotechnical Institute, Norway.

ABSTRACT: Numerical simulations are performed to assess the stability of underground structures in seismic regions. Different rock mass models have been simulated to represent the rock mass qualities in the NGI Q-system of rock mass classification. In all the rock mass models, the performance of rock support has been analyzed to study the effect of seismicity on rock support interaction. This paper provides some important insights into the behaviour of rock support in tunnels under the effect of seismic loading. Numerical experiments show that for a continuum weak rock mass the maximum axial force on the tunnel lining increases significantly when dynamic loading is applied as compared to static loading. For a competent rock mass the increase in maximum axial force on the lining is insignificant when dynamic loading is applied. A case study on the stability of a large underground cavern with earthquake loading is illustrated.

1 INTRODUCTION

The design of underground facilities to withstand seismic loading has aspects that are very different from the seismic design of surface structures (Hashash et al. 2001). Generally only portal areas of tunnels or fault crossings suffer severe damage. The damage to tunnels greatly reduces with increased overburden due to the reduced intensity of shaking experienced at depth. The predominant surface (Rayleigh) waves decay almost exponentially with depth, and below the surface incident and reflected waves interfere so that the total amplitude is usually reduced.

Recent case studies reveal that some underground structures have undergone severe damages during recent large earthquakes such as 1995 Kobe, Japan, the 1999 Chi-Chi, Taiwan, the 1999 Kocaeli, Turkey and the 2008 Wenchen (Tibet-China) (Bhasin et al, 2006; Aydan et al, 2010). Research studies in this field, which were mainly initiated by such evidences, showed that the impact of earthquakes on tunnel lining can be significant, especially in weaker rocks.

This paper presents numerical studies conducted to investigate the effect of earthquakes on tunnels placed in rock masses with different rock mass quality Q. The variation in maximum axial force on the lining (MAFL) for tunnels placed in different rock mass types, under both seismic and static loading, were studied for their dependence on dimension and depth of the tunnel and the rock mass quality index Q.

For most underground structures, the inertia of the surrounding soil/rock is large relative to the inertia of the structure. Thus the seismic response of a tunnel is dominated by the surrounding ground response and not the inertial properties of the tunnel structure itself (Okamoto et al. 1973). The behaviour of a tunnel is sometimes approximated to that of an elastic beam subject to deformations imposed by the surrounding ground. Three types of deformations express the response of underground structures to seismic conditions (Owen and Scholl, 1981):

1) axial compression and extension
2) longitudinal bending
3) ovaling/racking

Design considerations for axial and bending deformations are generally in the direction along the tunnel axis (Wang, 1993). Ovaling or racking deformations in a tunnel structure develop when shear waves propagate normal or nearly normal to the tunnel axis, resulting in a distortion of the cross-sectional shape of the tunnel lining.

2 Q-SYSTEM AND MODELLING

The NGI Q-system (Barton et al, 1974) is a rock classification method used to determine the support for a tunnel placed in a particular rock mass quality. The Q-value of the rock mass is calculated from the six parameters determined in field using the standard tables. An updated support chart (Grimstad et al, 2003) is available to determine the support type for the calculated Q-value. Five rock mass classes, which can be classified using four different Q-values simulated using different elastic and strength parameters, are adopted for this study. These five rock classes and their corresponding Q values are shown in Table 1 (Tshering et al, 2011).

Table 1. The description and range of Q values for the five rock classes modeled in this study. Adapted from Waltham (2009).

Class	I	II	III	IV	V
Description	Verygood rock	Good rock	Fair rock	Poor rock	Verypoor rock
Q value	> 40	10-40	4-10	1-4	< 1

The finite element modeling (FEM) program Phase^2 from Rocscience Inc. was used to simulate underground excavation support and reinforcement, through modeling rock mass-support interaction. Similarly, the effect of earthquakes on underground structures can be investigated using the pseudo-static seismic analysis procedure incorporated in Phase^2. During pseudo-static seismic analysis, an additional load, equal to a given percentage of the body force, or self-weight, of the finite element, is added to simulate seismic loading (Rocscience, 2011). The ratio between this additional load and the original body force is called the seismic coefficient and may have both horizontal and vertical components.

Assuming that the rock mass behaves as a Coulomb material, the shear strength parameters for the various rock classes were estimated as follows (Table 2)

Table 2. Q-values for five rock classes and their corresponding static deformation modulus $E_{mass,}$ and both peak and residual Mohr-Coulomb parameters (Tshering et al, 2011)

Q-value	E_{mass}	Peak friction angle	Peak cohesion
	GPa	Degree	MPa
1	10.00	15	1
4	15.87	25	2
10	21.54	35	3
40	35.20	45	4

Both elastic and elastic-perfectly-plastic models were analyzed for both static and seismic loadings. In order to investigate the rock mass-support interaction, a 10-cm thick standard beam liner is placed along the tunnel periphery; this beam liner simulates a 10-cm thick shotcrete that is applied to support the excavated tunnel.The variation in maximum axial force on the lining (MAFL) for tunnels placed in different rock mass types, under both seismic and static loading, were studied for their dependence on dimension and depth of the tunnel and the rock mass quality index Q (Tshering et al, 2011).

Both elastic and elastic-perfectly-plastic models were analyzed for both static and seismic loading. For this study, a fixed pseudo-static seismic loading with horizontal coefficient = 0.5 and vertical coefficient v=0 is used for all the experiments.

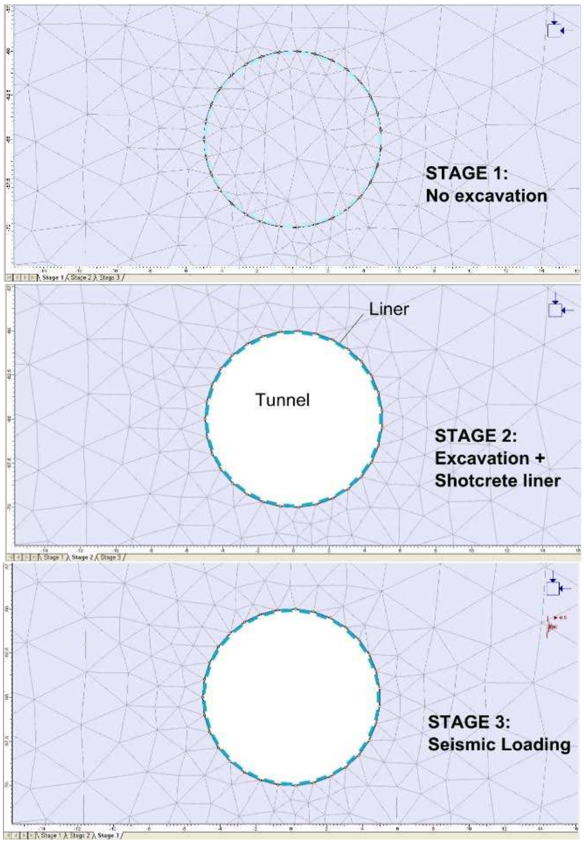

Fig. 1 Three-stage model of a 10-m diameter tunnel.

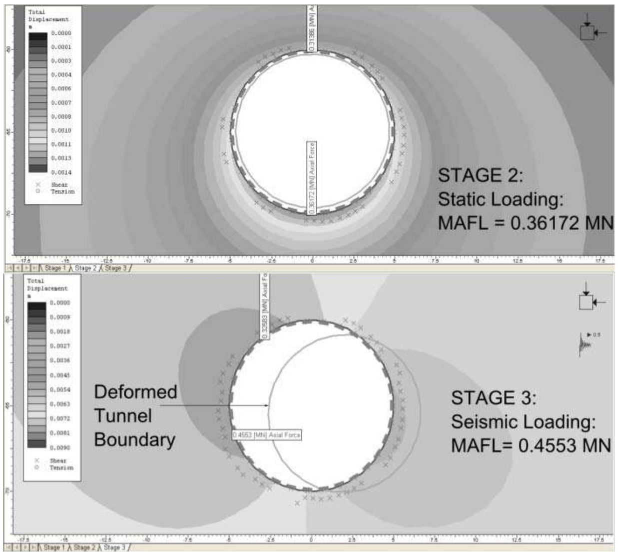

Fig. 2 Displacement contour plots for stage 2 and stage 3 shown in Fig. 3. The MAFL and the boundary of the deformed tunnel for the two stages is shown here

Three stages of numerical modelling was performed. The first stage gets the model to equilibrium before excavating the tunnel; physically this represents consolidation due to its own weight. The second stage is to get the model to attain static equilibrium after excavation of the tunnel and installation of the shotcrete liner and then seismic loading is added to the second stage in stage 3 (see Fig. 1)

The result, showing total displacement contours, after application seismic loading is shown in Fig. 2. The elements shown by 'x'-marks in the final result plot are yielded elements.

3 NUMERICAL RESULTS

As observed in previous studies (Bhasin et al., 2006a; Abokhalil, 2007), the increase in MAFL due to seismic loading, which is the difference between MAFL for static and seismic loading (referred to as seismic force on the lining in this paper), for elastic materials is lower than the increase in MAFL for elastic-plastic materials; the increase in MAFL for elastic model for Q=1 is half of the increase MAFL for elastic-perfectly-plastic model for the same rock mass quality. For the four rock classes (Fig. 3), there is an about 12% increase in MAFL due to seismic loading for elastic models, and the % increase due to seismic loading for elastic perfectly plastic materials is about 20-26%.

The variation of MAFL as function of tunnel diameter for the four rock classes at a depth of 60 m is shown in Fig. 4. The MAFL, which is a representative of the support pressure, increases with increasing tunnel dimension for the rock mass with Q=1. The rock mass with Q=1 behaves as elastic-perfectly-plastic material at this depth and has developed a plastic zone around the tunnel periphery. For rock mass with Q=1, there is an increase in absolute MAFL as tunnel diameter increases from 5 to 20 m, but the increase in MAFL for elastic model is lower than for elastic-perfectly-plastic models.

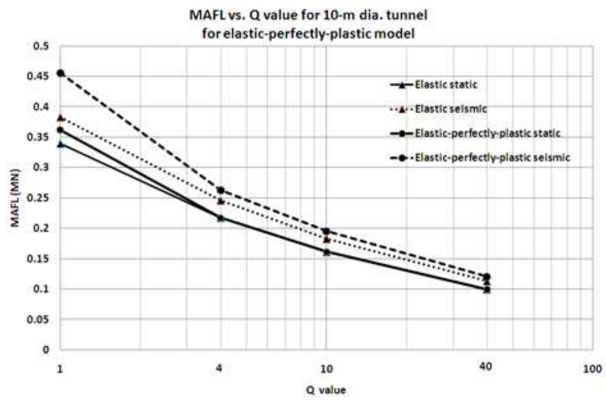

Fig. 3 MAFL for both static and seismic loading (h=0.5) for the four rock classes used for this study. The MAFL for elastic and EPP models overlap for good quality rocks with higher Q.

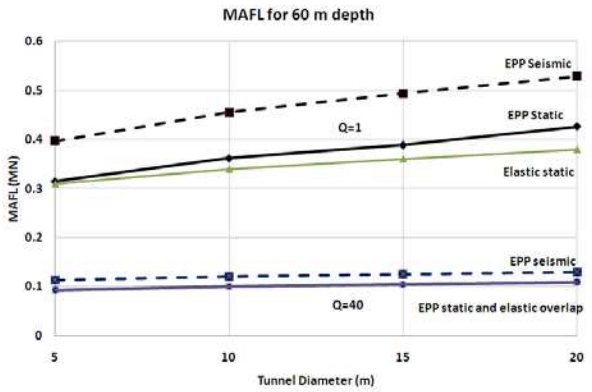

Fig. 4 MAFL for tunnels with diameter from 5 -20 m in rock masses with Q ranging from 1-40 at 60 m. The MAFL for elastic and elastic-perfectly-plastic models overlap for Q=40.

On the other hand, rock masses with Q≥ 4 are still below the elastic limit and behave as elastic material. The variation in absolute MAFL as function of tunnel diameter for rock mass with Q=40 is shown in Fig. 4 for comparison. This corroborates the previous findings by Goel et al. (1996) and Bhasin et al. (2006b) that the support pressure is affected by tunnel dimension for weak rocks with plastic behavior and effect of tunnel dimension on support pressure for good rocks, with elastic behavior, is insignificant.

4 CASE STUDY ON THE STABILITY OF A LARGE UNDERGROUND CAVERN IN THE HIMALAYAS

The effect of earthquake on the stability of a large underground powerhouse in Bhutan Himalaya has recently been studied. The powerhouse is located close to a major thrust zone called MCT (Main Central Thrust) which is marking the boundary between the lesser and higher Himalayas. The underground powerhouse, which constitutes a major component of Hydro Power Project, is experiencing a certain number of instabilities. Approximately 5 percent of the bolts in the powerhouse are reported to have failed and the walls of the cavern are continuing to converge, albeit at a slow rate since its completion (3-6 mm per year). Plans are underway to stabilize this important underground structure. The cavern is about 200m long, 45 m high and 20 m wide (see Fig. 5). The rock support system consists of 26.5 mm diameter and 12 m long fully grouted tensioned Dywidag bolts, plus 150 mm thick shotcrete. Static and dynamic modelling using the distinct element programme UDEC was performed to compare the results with earthquake loading (Fig. 6). Preliminary results from the study showed that if the movement was limited to less than 20 cm under static conditions, it could largely exceed one meter in case of an earthquake. The peak ground accelerations were assumed to be 1 m/s^2 for this study. This case showed that the cavern stability is highly vulnerable to earthquake. Based on this study, recommendations have been proposed to stabilize the walls of the cavern.

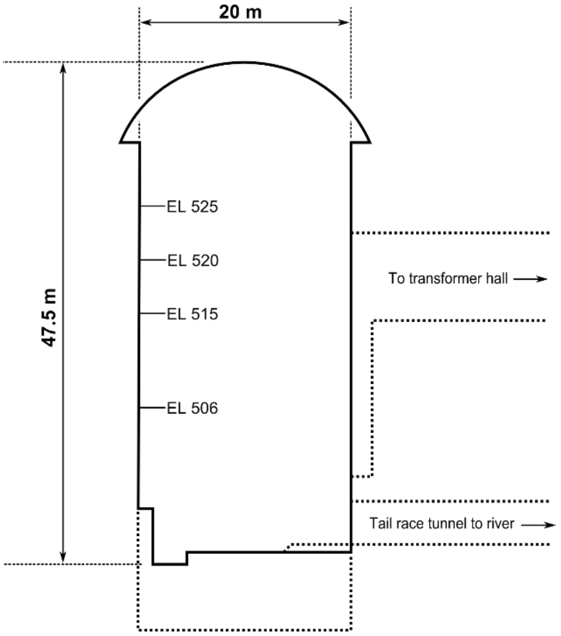

Fig. 5 Cross section of the machine hall cavern. Elevations are given in meters

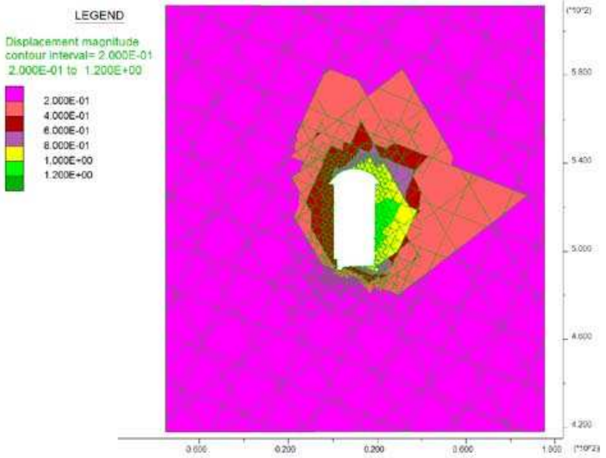

Fig. 6 Displacement contours around the cavern.

5 CONCLUSIONS

The results from the preceding numerical experiments have shown that the maximum axial force on the lining of a tunnel is dependent on the tunnel size. In elastic medium (e.g. competent rock masses with high Q-values) the increase in the maximum axial force on the lining when either the tunnel dimension increases or when dynamic loading is applied is not so significant. However, for an elastic-perfectly plastic medium (e.g. weak rock mass with Q-values < 4) there is a significant increase in the force on the lining when either the tunnel dimension is increased or when dynamic loading is applied.

REFERENCES

Abokhalil, M. 2007. Insights into the response of rock tunnels to seismicity. Master thesis in Geosciences, University of Oslo, December 2007

Aydan, O., Ohta, Y., Genis, M., Tokashiki, N., and Ohkubo, K. 2010. Response and Stability of Underground Structures in Rock Mass during Earthquakes. Rock Mechanics and Rock Engineering. Vol. 43: 857-875

Barton, N., R. Lien and J. Lunde. 1974. Engineering classification of rockmasses for the design of tunnel support, Rock Mechanics, Vol. 6, No. 4, pp. 189 236

Bhasin, R., Kaynia, A.M., Paul, D.K., Singh, Y. and Pal, Shilpa., 2006. Seismic behaviour of rock support in tunnels. Proceedings 13th Symposium on Earthquake Engineering, Indian Institute of Technology, Roorkee, December 18-20 2006

Bhasin, R., Magnussen, A. and Grimstand, E. 2006. Effect of Tunnel Size on Stability Problems in Rock Masses, Tunnelling and Underground Space Technology, Vol. 21 (3-4), 405, July 2006

Goel, R.K., Jethwa, J.L. and Dhar, B.B. 1996. Effect of Tunnel Size on Support Pressure. Int. J. Rock Mech., Min. Sci. &GeomechanicsAbstr.Vol. 33(7): 749-755

Grimstad, E., Bhasin, R., Hagen, A.W., Kaynia, A. and Kankes, K. (2003) Q-system advance for sprayed lining, Part 1 Tunnels and Tunneling International (T&T) January 2003 and Part II (T&T) March 2003

Hashash, Y.M.A., Hook, J.J. and Scmidt, B., 2001. Seismic design and analysis of underground structures. Tunnelling and Underground Space Technology 16 (2201) 247-293

Okamoto, S., Tamura, C., Kato, K., Hamada, M., 1973. Behaviors of submerged tunnels during earthquakes. Proceedings of the Fifth Worl Conference on Earthquake Engineering, vol. 1. Rome, Italy, pp.544-553

Owen, G.N., Scholl, R.E., 1981. Earthquake engineering of large underground structures. Repot no. FHWA/RD-80/195. Federal Highway Administration and National Science Foundation.

Rocscience Inc. 2011. Developer's tip: Pseudo-static loading www.rocscience.com

Tshering, T, Bhasin, R., Olsson, R ,& Maupin, V.2011 Numerical analysis of rock support interaction in tunnels in seismic regions. Proceedings 12th International Congress for Rock Mechanics, Beijing, China, October 18-21 2011

Wang, J,-N., 1993. Sesimic design of tunnels: A state-of-the-art approach, monograph 7. Parsons, Brinckerhoff, Quade and Douglas Inc, New York.

Waltham, T. 2009. (Third Edition). Foundations of Engineering Geology. Taylor & Francis.