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Seismic Impacts on Tunnels in Different Rock Mass

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Abstract

Several cases of tunnel damage during major earthquakes have challenged the conventional belief that tunnel structures are relatively safe during seismic events. These experiments remind us that the seismic behavior of hydroelectric tunnels needs to be studied in more detail. Therefore, a 2-D plane strain pseudo-static approach is used to determine the seismic impacts on different sized tunnels in different rock mass using finite element modelling software. Different post failure characteristics such as elastic – brittle plastic, strain softening and elastic – perfectly plastic has been used to model the rock mass. In this study, different size of tunnel ranging from 2.00m - 8.00m and rock-mass properties varying from GSI 30 - 75 was used to examine the effect rock mass quality on different sized tunnels. The study showed that for a constant seismic loading, the magnitude of axial force for both the static and seismic cases increase as the tunnel dimension increases and rock mass quality decreases. This increment was seen to be significant in case of poor rock mass and larger tunnel sizes.

Keywords

Seismic axial force, Geological Strength Index (GSI), Tunnel

1. Introduction

Nepal lies in one of the most seismically active regions in the world where earthquakes of high magnitude occur at regular intervals causing significant damages to structures, life-lines, including huge loss of life and properties. Due to the availability of fast-flowing rivers and steep terrain in this region, a large no. of hydropower projects with varying size are being constructed day by day. As per the data presented in Nepal Tunneling Conference 2019, 220.0 km length of tunnel is already constructed, around 195.00km length of tunnel is being constructed for various ongoing hydropower projects and more than 600.0km length of tunnel construction is planned for various infrastructure projects.

Usually, the underground structures are considered less susceptible to damages caused due to seismicity in comparison to surface structures due to various factors such as reduction in amplitude of ground motion with increase in depth and consequent reduction in seismic coefficient, increased modulus of elasticity with depth, small excavation dimension with respect to the much larger seismic wave length, etc. The response of surface structure during earthquake is determined by its inertia, while the behaviour of underground structures is governed by the confining rock mass. The degree and extent of damages to these underground structures are determined by source, depth I& magnitude of earthquake, epicentral distance, Peak Ground Acceleration (PGA), Rock mass properties, height of overburden, depth of the tunnel, location and orientation of any faults, in-situ stress, types of support system and utility of the tunnel. [1].

Significant cases of damages to tunnel during earthquake event are reported like cases of 1995 Kobe, Japan; 1999 Kocaeli, Turkey; 1999 Chi-Chi Taiwan; 2004 Niigata, Japan; 2008 Wenchuan, China earthquakes [2]. Damages in the form of failures of sidewalls, uplift of bottom pavement, cracking of tunnel lining, spalling of concrete and shearing failure of tunnel liner have been majorly observed during the seismic events all around the world [3].

During 2015 Gorkha earthquake, 15 hydropower projects under construction and operation in Nepal were damaged. Out of these, cases of cracking of shotcrete and rock falls were seen in Bhairabkunda (3 MW), Sindhupalchowk and Rasuwagadhi (111 MW), Rasuwa respectively [4].

The body and the surface waves produced by an earthquake when interacting with an underground tunnel, the tunnel can undergo three types of deformations depending on the mode of movement of the particles caused by these seismic waves that pass, namely: Compression and axial extension, Bending longitudinal and oval / shelving (Figure 1). The axial deformation is produced when the seismic waves cause the particle to move in the direction parallel to the axis of the tunnel. Similarly, when the components of seismic waves cause the particle to move perpendicular to the longitudinal axis, longitudinal bending is seen whereas, shear waves which travel perpendicular to the axis of tunnel causes ovaling effect by distorting the tunnel cross-section [5].

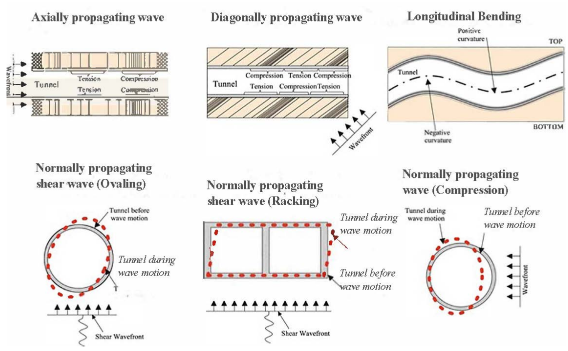

Figure 1: Different modes of deformation of tunnel causes by propagation of seismic waves

2. Objectives

The general objective of this research is to analyze the impact of earthquake on different sized tunnels excavated in various quality of rock mass by conducting the numerical parametric analysis of various parameters using pseudo – static analysis. Specific objectives are:

1. To determine the effect of earthquake on tunnels excavated in different quality of rock mass.
2. 2. To determine the seismic impacts on tunnels of different dimensions.

3. Methodology

To carry out the design and numerical analysis of tunnels, two-dimensional (2D) finite element modelling (FEM) software *Phase*$^{2.0}$ by Rocscience Inc. is used. As the tunnel considered is infinitely long and ovaling effect being the most critical deformation during earthquake, 2D plane strain approach is used for the analysis of seismic effects.

3.1 Static Design of Tunnel

3.1.1 Stress Failure Criteria

General stress failure criteria given by Hoek – Brown is used for modelling and analysis which is defined as:

$$\sigma_1' = \sigma_3' + \sigma_{ci}(m_b \frac{\sigma_3'}{\sigma_{ci}} + s)^{\alpha}$$

Where σ_1' being major effective principal stress, σ_3'' being minor effective principal stress, and σ_{ci} being UCS of the intact rock. Other parameters are:

$$m_b = m_i e^{(\frac{GSI-100}{28-14D})}$$

$$s = e^{(\frac{GSI-100}{9-3D})}$$

$$\alpha = \frac{1}{2} + \frac{1}{6}(e^{-\frac{GSI}{15}} - e^{-\frac{20}{3}})$$

where m_b being reduction of m_i ; m_i is the Hoek-Brown constant for intact rock and calculated as curve fitting parameter for Tri-axial test result, GSI represents Geological Strength Index for the surrounding rock mass, and s and α are constants that depend upon the rock mass characteristics. s=1 and α=0.5 are constants which characterize the surrounding rock mass. D is the disturbance factor representing the extent of disturbance in the surrounding rock mass which are caused by a large no. of factors.

3.1.2 Post Failure Characteristics

Elastic-brittle plastic, strain softening and elastic-perfectly plastic criteria are selected for very good, average and very poor rock-masses respectively.

3.2 Seismic Design of Tunnel

In order to simulate the interaction between seismic waves and tunnel, Inertia based pseudo-static method where calculation and vectorial addition of additional force is done to the body force acting in downward direction has been adopted. This additional inertial force is calculated by multiplying the selected seismic coefficient and weight of the element in the model.

3.2.1 Seismic Coefficient

Seismic Coefficients are defined as the dimensionless coefficients used to represent the peak value of earthquake acceleration in terms of accn due to gravity.

Horizontal seismic coefficient (K_h)

$$= \frac{maximum\ PGA\ value\ (PGA)\ max}{acceleration\ due\ to\ gravity\ (g)}$$

Vertical seismic coefficient (K_v)

$$= 0.5\ X\ horizontal\ seismic\ coefficient\ (K_h)$$

3.3 Numerical Modelling in Phase 2.0

A plane strain 2 dimensional model is chosen as the tunnel considered is infinitely long and the deformation of tunnel is restricted to two-dimensional plane. The primary aim of this research is to analyze the influence of tunnel size, quality of rock-mass and PGA on the seismic impacts so, a simple geometrical size, i.e. a circular tunnel is considered (Figure 2).

The previous studies has shown that the effect of earthquake are usually more at lower depth (usually below 100m). Also, with high over-burden depth, complex phenomenon like rock squeezing and rock-brusts are seen which may interfere with the analysis of seismic effects. So, a fixed depth of 50 metre is selected for the study. For this study, we have modelled the ground as free surface with no stresses and free to move along both the horizontal and vertical directions. Bottom boundary is considered fixed i.e., restrained in both directions. Similarly, the vertical side boundaries are horizontally restrained and allowed to move in only Y direction. The extension of the external boundary varies between 3D to 5D, where D is the diameter of model. A six-node modified triangular element which calculates the stress and strains at the vertices and mid-point of triangle is selected because it variation of stresses and strains can be captured easily. Similarly, the Gradation Factor which determines the discretization of all the boundaries is chosen as 0.1

3.3.1 Rock mass properties

For this study, three qualities of rock masses as: Very good, Average and Very poor are selected. The different values of parameters selected are from the ongoing Maya Khola Hydropower Project (14.9 MW) being constructed at Sankhuwasabha district, Nepal. The different values of rock-mass properties taken for this study are given in table 1:

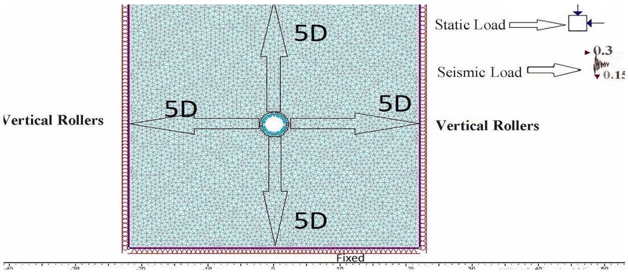

Figure 2: A representative model for circular tunnel with extent of boundary condition, static and seismic load

Table 1: Table showing different values of rock-mass properties taken for representative rock masses.

Description	Very good quality	Average quality	Very Poor quality
Intact-rock-strength (σ_{ci})	135 MPa	65 MPa	30 MPa
Hoek-Brown constant (m_i)	25	12	8
Geological Strength Index (GSI)	75	50	30
Deformation Modulus (E_m)	19500 MPa	2500 MPa	550 MPa
Poisson's Ratio (ν)	0.2	0.25	0.3
Disturbance Factor (D)	0.5	0.5	0.5
Post - Peak characteristics			
Deformation Modulus (E_m)	11700 MPa	1000 MPa	550 MPa
Geological Strength Index (GSI)	45	20	30

3.3.2 Staging

The effect of earthquake has been investigated by modelling in three stages which are as follows:

Stage 1 (No Excavation): In this stage, the model is subjected to a hydrostatic stress condition where the over-burden stress increases linearly as a function of over-burden depth z and unit weight of rock-mass (γ). The relationship is given by: $\sigma_1 = \gamma$ x z where σ_1 being major principal stress in the 2D plane No excavation is done in this stage.

Stage 2 (Excavation and support liner): In this stage, the tunnel is excavated and support liner of 100 mm thick plane cement shotcrete is provided For simplicity, immediate application of support liner after excavation is assumed. The values of different parameters of shotcrete lining are shown in table 2:

Table 2: Values of different parameters of shotcrete

Thickness (m)	0.1
Poisson's Ratio	0.2
Modulus of Elasticity (MPa)	25000
Material Type	Elastic

Stage 3 (Excavation, support liner and earthquake loading): In this stage, earthquake load is applied in addition to stage 2. In this stage, earthquake load is applied in addition to stage 2. In this study, we have adopted horizontal and vertical seismic coefficient as 0.3 and -0.15 respectively.

3.3.3 Seismic Axial Force on the lining

In-order to determine the seismic effects on the tunnels, at first, axial force generated on each and every element of the support liner in both the stages (2 and 3) is measured. Then, the difference in axial force generated during seismic loading and static loading at the same location is calculated for all the elements of the liner. The differences in the values of axial force generated at the lining is called the Seismic Axial Force, which is the main parameter to study the earthquake effect on tunnels.

4. Analysis and Results

4.1 Effect of Tunnel Dimension

In order to study the effect of tunnel dimension, nos. of models were prepared by varying the tunnel size.

For the variation of tunnel dimensions, sizes were selected for the on-going headrace tunnel in different parts of the country. Out of 35 ongoing headrace tunnel construction (2019), the tunnel dimension (diameter) was found to be varying between minimum of 2.2 m to maximum of 9.00m.

So, for this study following dimension of headrace tunnels were taken as shown in table 3:

Table 3: Table showing different size of ongoing headrace tunnel excavation in Nepal

Name of Project	Actual Size	Adopted Size for Study
Maya Khola Hydropower Project (14.9 MW)	2.50m	2.00m
Mristi Khola Hydroelectric Project (42 MW)	4.00m	4.00m
Kabeli A Hydroelectric Project (30 MW)	6.00m	6.00m
Arun III (900 MW)	9.00m	8.00m

Seismic axial force generated along the periphery of tunnel liner for different diameter and Geological Strength Index (GSI) values are shown in the figures below. Figure 3 shows the plot of seismic axial force in tunnel of size 2.0m. Figures 4, 5 and 6 shows the same for tunnel of size 4.0m, 6.0m and 8.0m respectively. It is seen that the values of axial force for both static and seismic loading condition increases with the increase in tunnel dimension.

The value of maximum seismic axial force was calculated for each and every element of the support liner for all tunnel sizes and tabulated below:

Table 4: Values of maximum seismic axial force for different sized tunnel

For GSI 75	D=2.0m	D=4.0m	D=6.0m	D=8.0m
Max. Seismic Axial Force	6.59	14.08	21.63	29.21
Distance Along Liner	0.078	0.157	0.235	0.314
For GSI 50	D=2.0m	D=4.0m	D=6.0m	D=8.0m
Max. Seismic Axial Force	21.54	51.51	84.00	118.2
Distance Along Liner	0.078	0.157	0.235	0.314
For GSI 30	D=2.0m	D=4.0m	D=6.0m	D=8.0m
Max. Seismic Axial Force	46.11	147.27	278.72	424.9
Distance Along Liner	0.078	0.157	0.235	0.314

For very good quality rock mass (GSI 75), it is seen that the maximum seismic axial force has increased by only 7-8 kN. Whereas for average and poor quality rock mass, the increment is around 30-35 kN and 100-160 kN respectively.

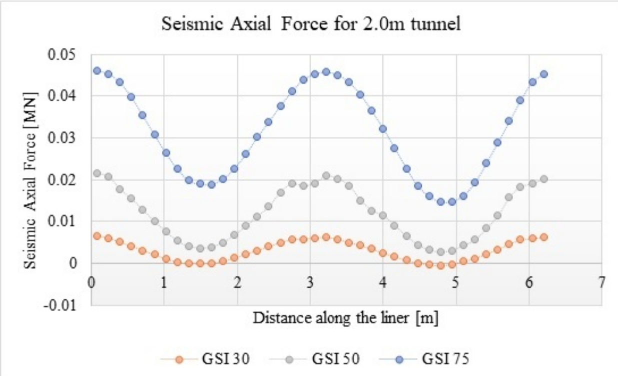

Figure 3: Plot of seismic axial force calculated along the periphery of support liner for 2.0 m tunnel for different GSI values

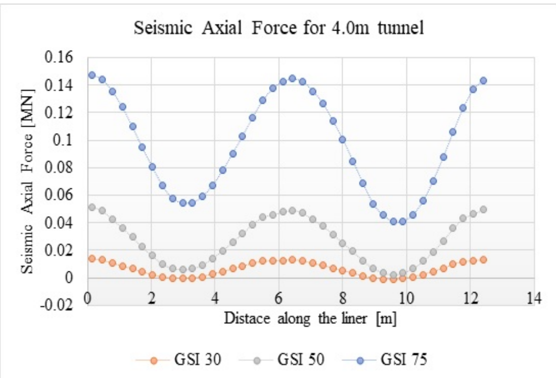

Figure 4: Plot of seismic axial force calculated along the periphery of support liner for 4.0 m tunnel for different GSI values

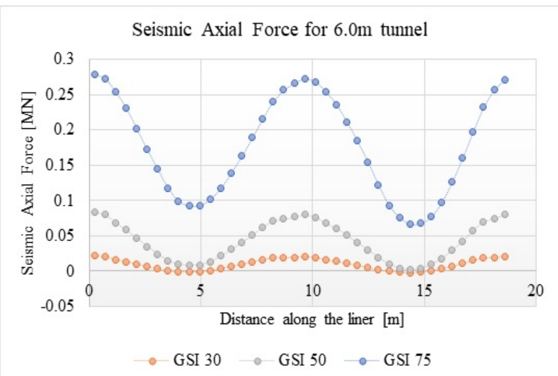

Figure 5: Plot of seismic axial force calculated along the periphery of support liner for 6.0 m tunnel for different GSI values

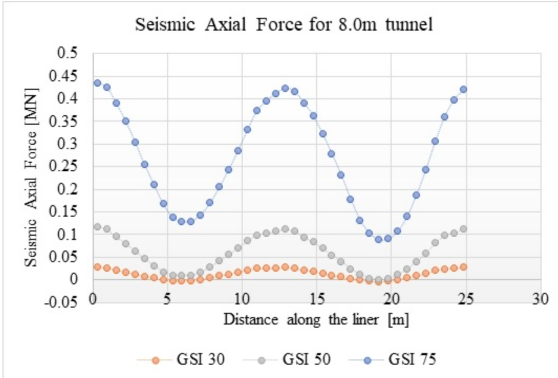

Figure 6: Plot of seismic axial force calculated along the periphery of support liner for 8.0 m tunnel for different GSI values

This pattern of increase in maximum seismic axial force is also shown with help of graph in figure no 7.

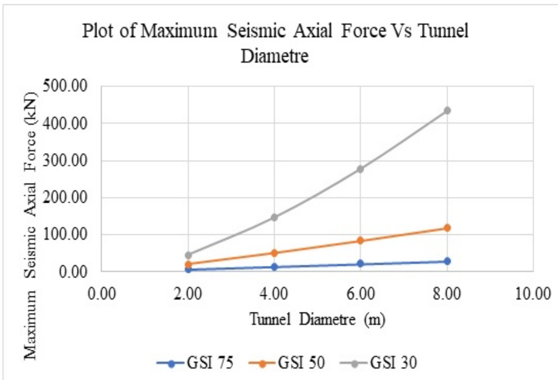

Figure 7: Plot of variation of maximum seismic axial force for different sized tunnel

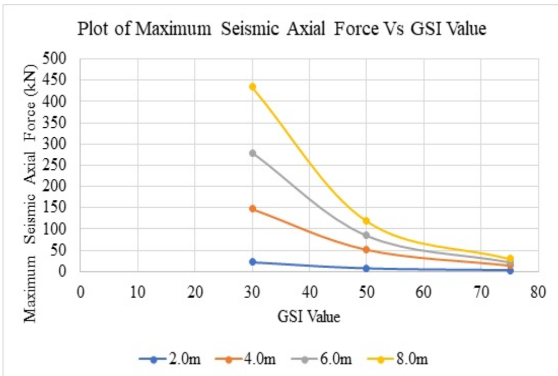

Figure 8: Plot of variation of maximum seismic axial force for rock mass of different quality

From the graph, it is obvious that the trend in increment of maximum seismic axial force for high quality rock mass is insignificant which is shown by the "flat" line. However, for the poor rocks, the increase is quite significant as clearly shown by the high slope line. The plot of maximum seismic axial force vs. tunnel diameter also shows that there is linear increase in maximum force irrespective of tunnel diameter.

4.2 Effect of Rock Mass Quality

In order to determine the seismic effect of rock mass quality on the axial force developed along the shotcrete liner, different sized circular tunnels were modelled and analyzed. Values of Geological Strength Index (GSI) values adopted are 75, 50 and 30. To determine the effect, the maximum seismic axial force was calculated for each and every element of support liner for different sized tunnels and tabulated below.

Table 5: Variation of maximum seismic axial force in different rock mass

For Diameter 2.0m	**GSI 75**	**GSI 50**	**GSI 30**
Max. Seismic Axial Force	6.59	21.54	46.11
Distance Along Liner	0.078	0.078	0.078
For Diameter 4.0m	**GSI 75**	**GSI 50**	**GSI 30**
Max. Seismic Axial Force	14.08	51.51	147.27
Distance Along Liner	0.157	0.157	0.157
For Diameter 6.0m	**GSI 75**	**GSI 50**	**GSI 30**
Max. Seismic Axial Force	21.63	84.00	278.72
Distance Along Liner	0.235	0.235	0.235
For Diameter 8.0m	**GSI 75**	**GSI 50**	**GSI 30**
Max. Seismic Axial Force	29.21	118.22	434.90
Distance Along Liner	0.314	0.314	0.314

For tunnel of size 2.0m, it is seen that the increment of maximum seismic axial force is between 15-25 kN. Whereas for tunnels of size 4.0m, 6.0m and 8.0m, the increment is around 35 – 100kN, 60 - 200 kN and 90 – 320 kN respectively. This trend of increment in maximum seismic axial force generated is also shown with help of graph in figure 8.

From the graph, it is clear that the increment in maximum seismic axial force is insignificant for small size tunnel which is shown but the “flat” line. However, for tunnels of larger size, the increase is quite significant as clearly shown by the high slope line.

5. Discussion and Conclusion

In this study, numerical analysis using finite element modelling software was carried out in rocks modelled as elastic-plastic material for circular tunnels with sizes varying from 2.0m to 8.0m and rock-mass quality in terms of Geological Strength Index (GSI) varying from 30 to 75 for poor to very good quality rocks.

At first, the effect of tunnel dimension on the axial force generated along the tunnel liner was determined for both static and seismic conditions. The results showed that the increase in seismic axial force is quite significant for large sized tunnels in poor rock mass. Whereas for tunnels of small size, the increase in seismic axial force is quite insignificant for very good quality rocks.

For rock mass of better quality, the stresses developed are of lower values and below the elastic limit despite being modelled as elastic-brittle plastic. But, for rock mass of poor quality, the stresses increase and formation of plastic zone surrounding the periphery of tunnel takes place showing elastic-perfectly plastic behaviour. This zone of plastic yielding where accumulation of high stress takes place, increases as the increase in tunnel diametre for rock mass of poor quality which explains the increment of axial force along support liner with the increase in tunnel diameter for both static and seismic condition.

For high quality rock mass GSI 75, the seismic axial forces were seen to increase by 7kN, 15kN and 23kN respectively for 4.0m, 6.0m and 8.0m tunnels. Similarly, for GSI 50 and 30, increments of 30kN; 62kN,97kN and 101kN and 233kN, 389kN were seen respectively. Similar results were obtained in study of effect of rock-mass quality. For poor quality rocks, significant increment of seismic axial force was seen for larger sized tunnels. In case of high-quality rocks, the increment of seismic axial force is independent of tunnel diameter as shown by the flat lines in graph plots.

As a function of GSI value, the magnitude of seismic axial force is seen to decrease with the increase in rock mass quality as rocks of better quality tend to exert lesser load on the tunnel support liner as compared to poor rock mass.

For small sized tunnel 2.0m, the seismic axial forces were seen to increase by 15kN and 40kN respectively for GSI 50 and GSI 30. Similarly, for 4.0m, 6.0m and 8.0m size tunnels, increments of 37kN, 133kN; 62kN, 257kN and 89kN, 406kN were seen respectively.

References

[1] Sivarajan T. K. Seismic load considerations in the design of underground structures for hydropower projects in the himalayan region. *Recent Advances in Rock Engineering*, 2016.

[2] Roy N. and Sarkar R. A review of seismic damage of mountain tunnels and probable failure mechanisms. *Geotech Geol Eng.*, 2016.

[3] Bhasin R. Abokhalil M. Kaynia A. Høeg K. Paul D. and Pal S. Numerical simulations of earthquake effect in underground structure. *14th Symposium on Earthquake Engineering, Indian Institute of Technology, Roorkee*, page 1384–1394, 2010.

[4] Sunuwar C. S. Nepal earthquake 25 april 2015: Hydro projects damaged, risks and lessons learned for design considerations. *Journal of Nepal Geological Society*, pages 141–149, 2018.

[5] Hashash Y. M. A. Hook J. J. Schmidt B. and Yao J. I.-C. Seismic design and analysis of underground structures. *Tunnelling and Underground Space Technology*, page 247 –293, 2001.

[6] Barton N. Effect of rock mass deformation on tunnel performance in seismic regions. *Advances in Tunnelling Technology and Subsurface Use*, pages 89–99, 1984.

[7] Dowding C. and Rozen A. Damage to rock tunnel from earthquake shaking. *Journal of Geotechnial Engineering ASCE*, page 175–191, 1978.

[8] Dowding C. Estimating earthquake damage from explosion testing of full-scale tunnels. *Advanced Tunnel Technology and Subsurface Use*, pages 113–117, 1984.

[9] Hoek E. C. Carranza-Torres and B. Corkum. Hoek-brown failure criterion-2002 edition. *Proceedings of NARMS-Tac*, pages 267–273, 2002.

[10] Jaramillo A. C. Impact of seismic design on tunnels in rock – case histories. *Underground Space 2*, page 106–114, 2017.

[11] Khakda S. Tunnel closure anlaysis of hydropower tunnels in lesser himalayan region of nepal through case studies. *Doctoral Thesis, Kathmandu University Retrieved from Rock Mechanics and Underground Structure*, 2019.

[12] Potts D. M. Kontoe S., Zdravkovic L. and Menkiti C. O. Case study on seismic tunnel response. *Canadian Geotechnical Journal*, page 1743–1764, 2008.

[13] Lee Y.-K. and Pietruszczak S. A new numerical procedure for elasto-plastic analysis of a circular opening excavated in a strain-softening rock mass. *Tunnelling and Underground Space Technology*, pages 588–599, 2008.

[14] Moldovan R. A. and Popa A. Finite element modelling for tunneling excavation. *Acta Technica Napocensis: Civil Engineering and Architecture.*, 2012.

[15] Penzien J. Seismically induced racking of tunnel linings. *Earthquake Engng Struct. Dyn.*, pages 683–691, 2000.

[16] Rocscience Inc. Phase2 program reference manual. 2001.

[17] Rocscience Inc. Developer's tip: Pseudo-static loading. 2002.

[18] Rocscience Inc. Phase2 - finite element analysis for excavations and slopes. 2011.

[19] Sharma S. and Judd W. R. Underground opening damage from earthquakes. *Engineering Geology*, pages 263–276, 1991.

[20] Singh B. and Goel R. Tunnelling in weak rocks. *Elsevier geo-engineering book series. Elsevier Ltd*, 2006.

[21] Wang W. L. Wang T. T. Su J. J. Lin C. H. Seng C. R. and Huang T. H. Assessment of damage in mountain tunnels due to the taiwan chi-chi earthquake. *Earthquake. Tunnelling and Underground Space Technology*, pages 133–150, 2001.