Importance of Seismic Aspects of Underground Structures in Hydro Power Projects in Himalayas

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Abstract

For a long time, it has been generally believed that earthquake effects on underground structures are not very important as they are assumed to move together with the foundation rock during earthquake. Accordingly, earthquake action is often ignored in the design of underground structures. However, some underground structures significantly damaged in recent large earthquakes including the 1995 Kobe, Japan, the 1999 Chi-Chi, Taiwan, the 1999 Turkey, the 2008 China. As the number of case histories of underground structures subject to earthquake action has increased, the engineers have started to recognize that, although underground structures in rock have good resistance against earthquake, it is important to include seismic aspects in the design process to obtain a more reliable design. Hydropower projects contain different types of underground structures namely diversion tunnels, head race tunnel, tail race tunnel, surge shaft, powerhouse cavern and transformer hall cavern etc. Hydro power projects, especially in Himalayan region, fall in very severe earthquake zone. A strong earthquake may cause failure of rock portion of underground structures. Special problems may be encountered such as spalling of concrete, cracks in lining, leakage of tunnels, rock fall/landslides at tunnel portals and hydrodynamic action in pressure tunnels. Therefore, earthquake resistant design of underground structures of hydro power projects is of great importance in geologically difficult zones like Himalaya, where the tectonic influences, the intense jointing and continued deformations, the contrasting rock types and the clay filled fault zones, all make the region most vulnerable to earthquakes. This paper covers the importance of seismic aspects in designing of underground structures of hydro power projects especially in Himalayan region where many new hydropower projects are being planned. As a case study, numerical analysis using RS^2 software has been used for investigating the effects of seismicity on underground caverns of Hydro power project.

1. Introduction:

Underground structures were considered safe to earthquake action for many years, as they did not experience the same high levels of shaking as surface structures. This perception was supported by the relative good historic performance of tunnels and underground structures. However, there are many examples of severe damages during large earthquakes reported in literatures. Some of them are 1995 Kobe, Japan, the 1999 Chi-Chi, Taiwan, the 1999 Turkey, the 2008 China. The study of tunnel behaviours on seismic loads and also the damage of these structures, emphasize the necessity of stability under dynamic loading generated by earthquake. Hydropower plants contain different types of underground structures namely diversion tunnels, head race tunnel, tail race tunnel, surge shaft, powerhouse cavern and transformer hall cavern etc. The behaviour of these underground structures in seismic conditions is significantly different from that of surface structures. While inertia of the structures plays a dominant role for surface structures, the response of the confining rock mass has significant influence on the behaviour of tunnels and caverns. The aim of this paper is to analyse the effect of seismic aspects on stability of the underground structures. As a case study, the stability state of the powerhouse cavern of Naitwar Mori HEP is analysed using *RS*^{2} (*Phase*^{2} 9.0) software which has the facility to model seismic loads through pseudo-static approach. Naitwar Mori HEP is under construction in Himalaya region in Uttrakhand state of India.

2. Case histories of underground structures damaged by earthquakes:

The most important cases of underground structures damaged by earthquakes, which raised the attention to the vulnerability of underground structures to earthquake, are as follow:

Kobe, Japan**:** The Great Hanshin earthquake or Kobe earthquake, occurred on January 17, 1995 Japan. Daikai Station on the underground Kobe Rapid Railway line collapsed, bringing down part of National Route 28 above it. The station is located about 20 km from the epicenter of the earthquake. The moment magnitude scale (Mw) of the earthquake was 6.9 and strong ground motion lasted for 20 seconds.

Chi-Chi, Taiwan: Also known as the 921 earthquake was happened on September 21, 1999 at central Taiwan. It measured 7.3 on the Richter scale. Many maintained tunnels suffered significant damage to various extents. The earthquake magnitude was 7.3 on the Richter scale and it was related to the reaction of the 60 km Chelungpu Fault. It was found that among the 57 investigated tunnels, 49 of them were damaged.

Turkey: The 1999 Düzce earthquake hit Turkey on 12 November with a moment magnitude of 7.2.and caused an extensive damage in the 16-m wide under construction twin Bolu tunnel. The length of the surface fault rupture was estimated to be 40 km.

Figure 1 Collapse of the Daikai Station during Kobe earthquake & Tunnel collapse during Wenchuan earthquake

China: Great Wenchuan earthquake also known as the First Great Sichuan earthquake or Wenchuan earthquake, occurred at May 12, 2008.Measuring at 8.0 M Wenchuan earthquake caused different degrees of damage to the 11 tunnels of the

Volume XLII, Nos. 1 & 2
June-December 2017

Dujiangyan to Wenchuan highway near the epicentre; 4 were seriously damaged, 3 moderately damaged and 4 slightly damaged.

3. Seismic Effect on Underground Structures:

Earthquake is the vibration of earth's surface caused by waves coming from a source of disturbance inside the earth. Earthquake vibrations originate from the point of initiation of rupture and propagates in all directions. These vibrations travel through the rocks in the form of elastic waves. Mainly there are three types of waves associated with propagation of an elastic stress wave generated by an earthquake. These are primary (P) waves, secondary (S) waves and surface waves (Rayleigh & Love waves). These waves have a different effect on

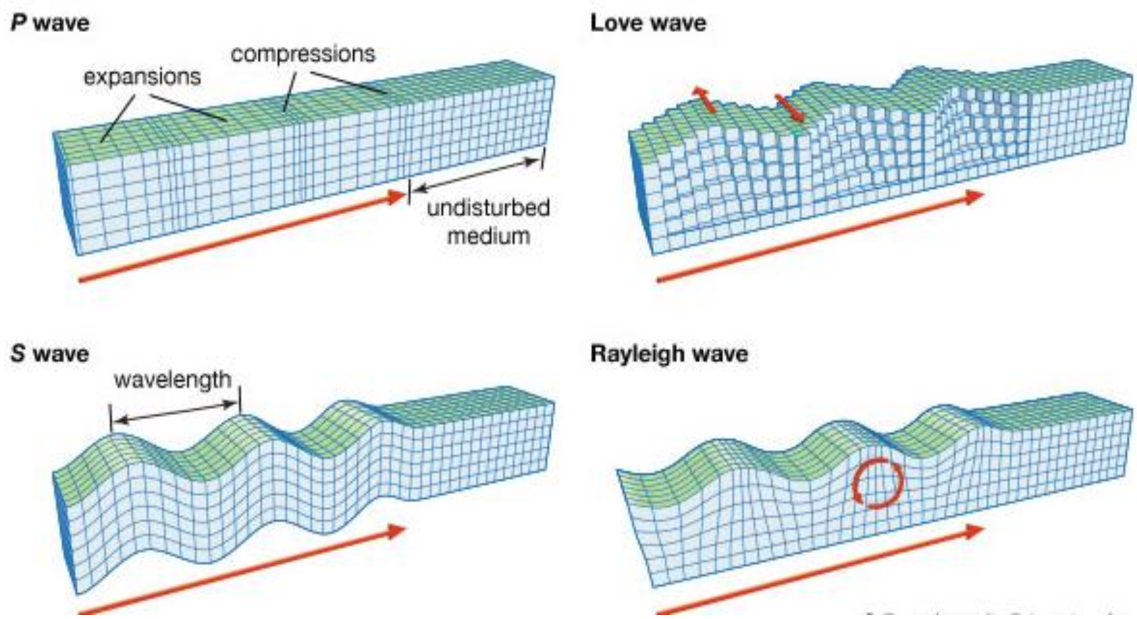

Figure 2 Seismic waves

stability of underground structures. P-waves create the axial compressive and tension on underground structures, while horizontal and vertical S-waves have negligible effects on underground structure, since using flexible support system will neutralize the effect of these waves. Due to Rayleigh waves underground structures are vertically displaced based on height as a consequence of these waves. Underground structures experience the lateral dynamic displacement due to impact by love waves, these waves are dangerous to the underground structures. Generally, three types of deformation deformations are possible in underground structures due to seismic loading: axial, longitudinal curvature and ovaling or racking, (Owen and Scholl (1981),) (Figure 3). Axial deformations in tunnels are generated by the components of seismic waves that produce motions parallel to the axis of the tunnel and cause alternating compression and tension. Bending deformations are caused by the components of seismic waves producing particle motions perpendicular to the longitudinal axis. 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.

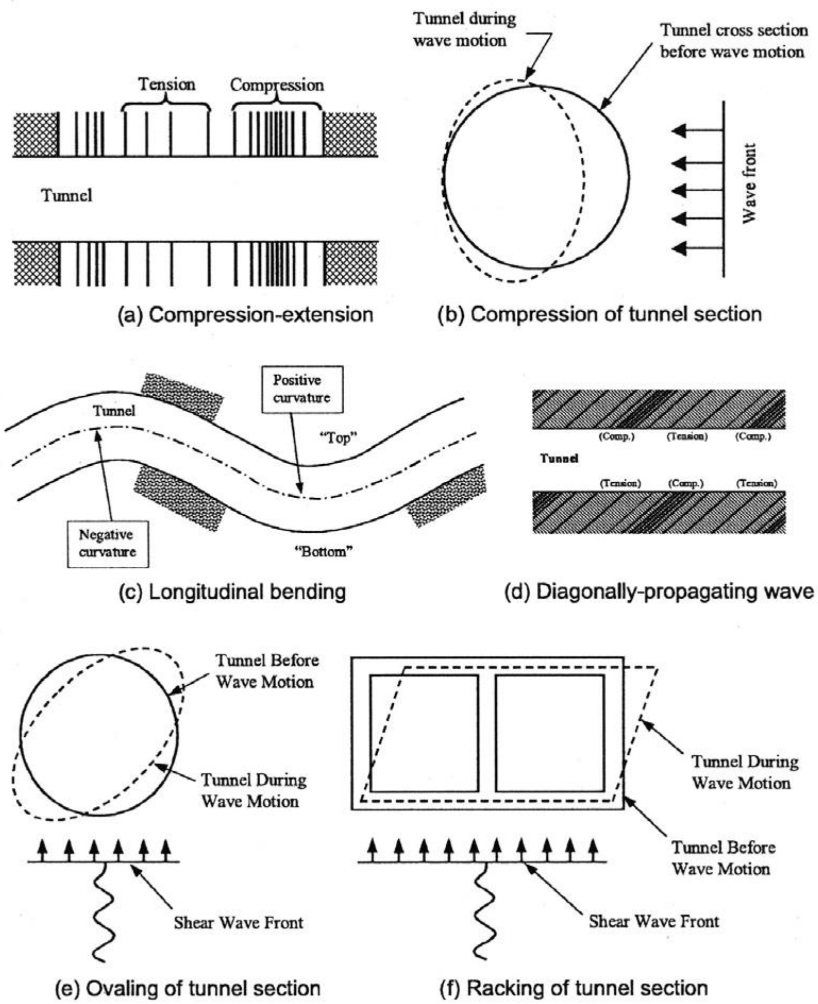

Figure 3 Types of deformations possible in underground structures due to seismic loading (Owen and Scholl)

4. Hydropower Projects in the Himalayas:

Himalayan region has immense amount of hydro-electric potential. The Indian Himalayan region covers the 18% of India's total geographical area and have 78% (1,16,652 MW) of total exploitable potential of India due to the presence of perennial river systems in 2400 km Long Himalaya. Several hydro electrical projects are constructed and are being constructed to tap this hydro power potential available in the Himalayas especially in the north and northeastern regions of India. Himalayas are geologically young active and have complex geological formations. The mountains are full of regional faults and major thrust zones. The tectonic influences, the intense jointing and continued deformation, the contrasting rock types, the clay-filled fault zones, all combine to test the ingenuity of the designer. It is quite a challenge to plan, design and execute underground structures in the Himalayas, as they are the youngest mountain ranges and tectonically very active. The region has been rocked by several damaging earthquakes, the 1905 Kangra Earthquake (Magnitude 7.8), the 1934 Bihar-Nepal Earthquake (Magnitude of 8.0), the 1950 Assam Earthquake (Magnitude of 8.7), The 1991 Uttarkashi Earthquake (Magnitude of 6.6), the Chamoli Earthquake of 1999(Magnitude of 6.8), the Great Kashmir Earthquake of 2005 (Magnitude of 7.6) and Nepal Earthquake (2015-Magnitude of 7.8) etc.

5. Underground Caverns of Power house and Transformer Hall of Naitwar Mori H.E. Project:

Underground Powerhouse cavern and transformer hall cavern of Naitwar Mori H. E. Project are located on the right bank of Tons river in the Purola crystalline group which consist of mainly gneisses, dark grey pebbly, conglomeratic gneisses, biotite gneisses, quartz mica schist, chlorite mica schist with porphyroblastic gneisses and basic intrusive. Powerhouse cavern have overall size of 18.6 m (Width) and 57.70m (Length) and 33 m (Height). The Transformer cavern have overall size of 11.90 m (Width) and 73.11m (Length) and 13.6 m (Height) has been placed parallel to and at the downstream side of the Powerhouse cavern. A rock pillar of 35 m thickness remains between both caverns, in order not to overstress the rock mass and in turn to reduce rock support requirements. As per geological investigations, the rock encountered at power house site is poor to fair category of porphyritic gneiss having the properties as shown in Table 1.

Table 1
Rock Mass Properties

Sr. No	Rock Mass properties	Value
1.	Deformation Modulus, E(Gpa)	27.5
2.	Poisson's ratio, υ	0.24
3.	Friction Angle, ϕ	39
4.	Tensile Strength,(Mpa)	6.12
5.	Unit Weight (kN/m^3)	27
6.	Uniaxial rock mass strength (MPa)	49.92

The in-situ stress measurement was conducted at the drift of powerhouse cavern by hydraulic fracture method and the average value of stresses are found to be as σ_v(Vertical in-situ stress)=4.35 Mpa, σ_1(Maximum principal stresss)=5.386 Mpa and σ_3 (Maximum principal stresss)=2.693 Mpa. The ratio (k) of horizontal to vertical in-situ stress is 1.236. The seismic history of the area shows that in the last 150 years about 36 earthquakes of damaging effects (Magnitude >5, Richter) have been experienced in region and most of these occur in the 50 km wide belt following the trace of Main Central Thrust (MCT). The site specific values of MCE level peak ground acceleration(PGA) for horizontal and vertical components are found to be 0.49g and 0.33g respectively. The values of the DBE level PGA for horizontal and vertical components are found to be 0.32g and 0.21g respectively. The site falls in seismic zone IV of Indian standard. In present study a horizontal seismic coefficient of 0.3 and a downward vertical seismic coefficient of 0.2 (negative for downward direction) have been adopted.

6. Numerical analysis of caverns under seismic loads:

The RS^2 (*Phase*^{2} 9.0) software by Rocscience has been used for modelling and analysis of underground caverns of powerhouse and transformer hall of Naitwar Mori H.E. This software is a numerical code based upon two-dimension finite element method and commonly used for analysis and design of underground excavation including rock support. The software has the facility to carryout dynamic analysis of underground structures due to earthquake loading using the pseudo-static seismic analysis procedure. The analysis presented here has been done in two part. In first part independent cavern of powerhouse is analysed and in second part both caverns are analysed. In both the models the horizontal and vertical lateral boundaries has been considered three times the dimension of excavation as in a box. Mohr-Columb Criterion have been selected. The meshing is triangular and is fine near the caverns boundary for increasing the analysis accuracy. Caverns modelled in both cases are depicted in Figure 4. The rock mass properties as shown in Table 1 have been used for the numerical simulations. After caverns modelling, the models are run to analyse in static and dynamic conditions. In RS^2

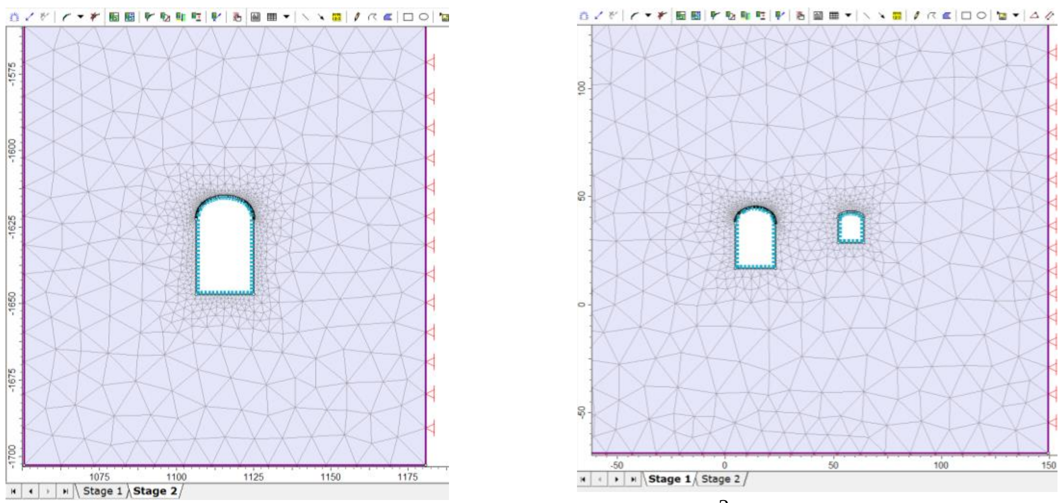

Figure 4 Caverns modelled by The RS^2 software

software the seismic loading is quasi-static and allows the user to define seismic coefficients for the horizontal and/or vertical directions. Here horizontal seismic coefficient of 0.3 and a downward vertical seismic coefficient of 0.2 (negative for downward direction) are adopted. On application of seismic co-efficient, an additional body force has been applied to each finite element in the mesh. Seismic analysis on tunnels with different combinations of horizontal and vertical seismic co-efficient shows that maximum stresses are produced on tunnel periphery when vertical seismic co efficient is acting downwards, in the same direction as that of gravitational force (Rajinder Bhasin, et al, 2008). Therefore, in present study, a combinations of horizontal and vertical downward seismic coefficients were applied in order to study the effect of seismic force. The in-situ stress (static) adopted is stress field due to gravity. The results of analysis are depicted in the Figure 5 to Figure10. Figure 5 to Figure 7 shows the

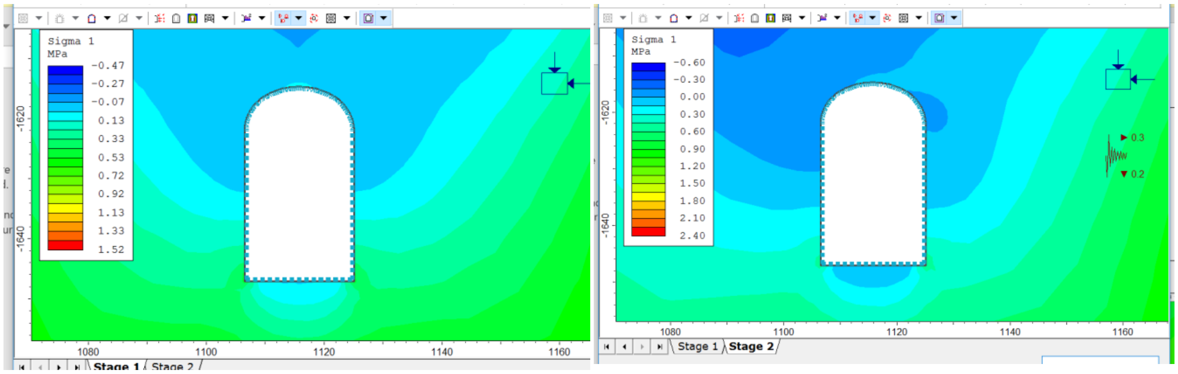

Figure 5 σ_1 in static and seismic analysis

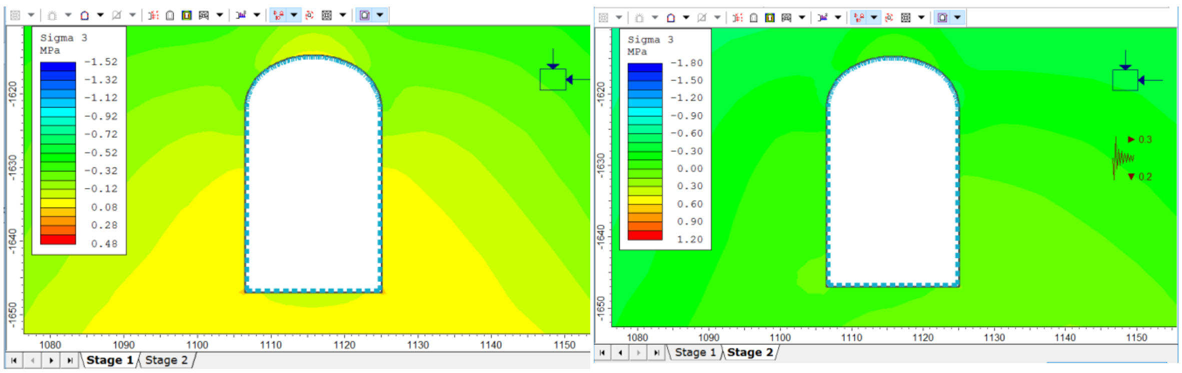

Figure 6 σ_3 in static and seismic analysis

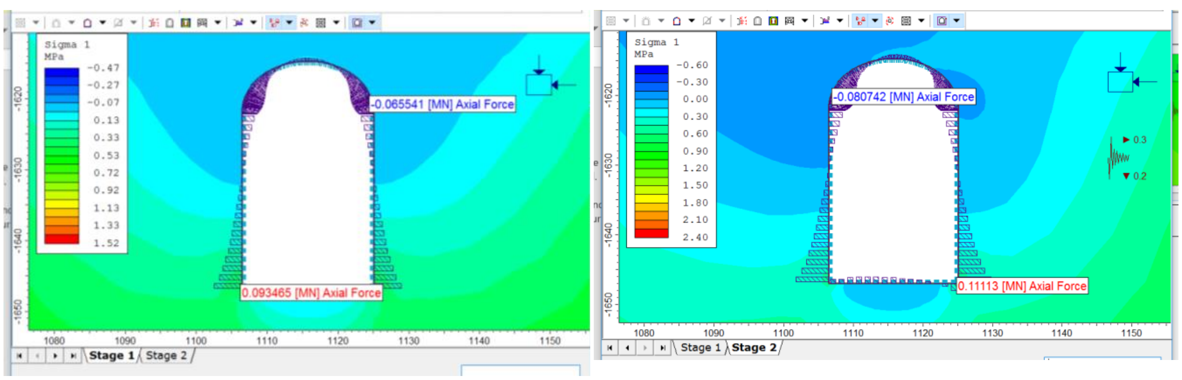

Figure 7 Axial force in support liner (shotcrete) in static and seismic analysis

results for independent powerhouse cavern and the Figure 8. Figure 7 shows the analysis results for independent powerhouse cavern and the Figure 8 to Figure 10 show the analysis results for combined analysis of powerhouse cavern and transformer hall cavern.

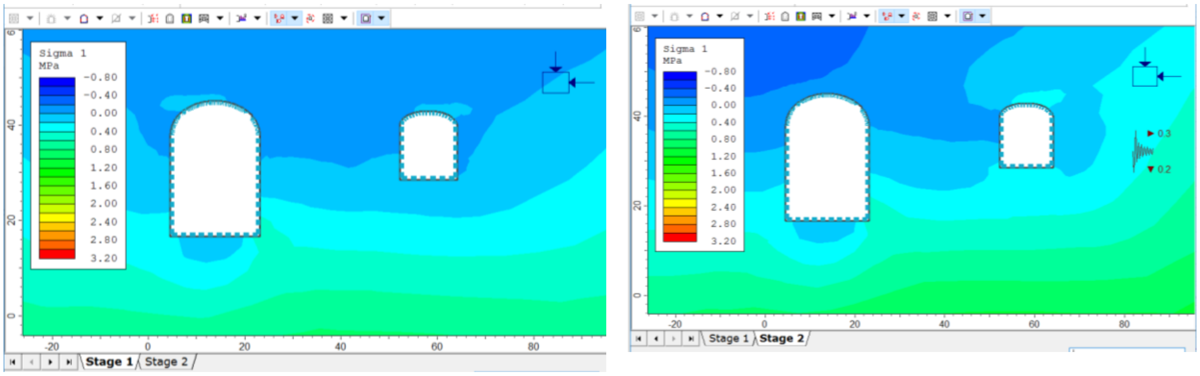

Figure 8: σ_1 in static and seismic analysis

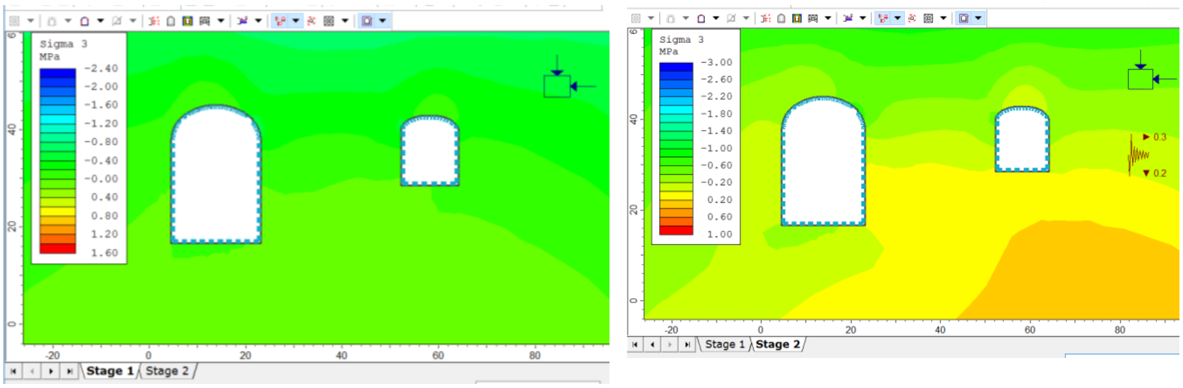

Figure 9: σ_3 in static and seismic analysis

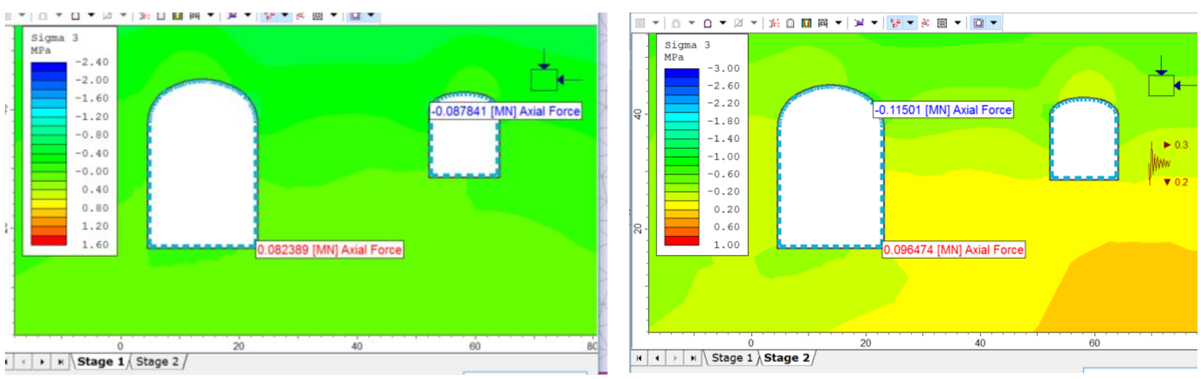

Figure 10: Axial force in support liner(shotcrete) in static and seismic analysis

From the analysis, it is concluded that:

- There is significant increase in both principal stresses and axial forces in support liner (shotcrete) after applying the seismic loading in individual cavern model and in combined caverns model.
- In case of individual cavern model there is increase of 14.70% in major principal stress and 23.26% increase in axial force in support (Shotcrete) after applying the seismic loading.

- In case of combined analysis of powerhouse cavern and transformer hall cavern, there is 33% increase in major stresses and 40.42% increase in axial force of support liner (shotcrete) in powerhouse cavern while there is marginal increase in these values in transformer hall cavern after applying seismic loading from left side.
- When the seismic force is applied from right side, there is 35% increase in major principal stresses and 45.54% increase in axial force in support (Shotcrete) of transformer hall cavern and increase of 14.28% in major principal stresses and 15% in axial force in support (Shotcrete) of powerhouse cavern.
- Result of analysis shows that based upon the direction of motion of seismic wave, the effect of seismic forces is different in each cavern in combined analysis. Also, the effect of seismic forces is more in two caverns as compared to single cavern.

7. Conclusions:

It is generally assumed that underground structures in rock are safe against earthquakes and earthquake action need not be considered in the design, and that deep structures are safer than surface structures. From case histories, it is clear that tunnels and underground structures can be damaged during strong earthquakes. From numerical study of caverns presented here, it has been found that under the seismic loading, there is significant increase in the maximum axial force developed in the shotcrete lining by about 35% in single cavern and about 45% when two caverns are provided parallel to each other. As in most of hydroelectric projects the powerhouse cavern and transformer hall caverns are provided parallel to each other, they should be checked and designed against earthquakes. The maximum axial force in the lining and the percentage increases are only indicative based upon the parameter used. These may vary depending on the changed parameters for other locations. Future research on the impact of earthquakes on the underground structures specially in hydropower is necessary to obtain more reliable designs by evaluating behaviour of these structures using full dynamic ground structure interaction.

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