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Seismic Load Consideration in Design of Tunnels and Tunnel Portals in The Himalayan Region

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Abstract

Tunnels on rocks are less susceptible to damage resulting from seismic events than the surface structure (i) due to proportionate reduction in ground motion with depth and subsequent reduction in seismic coefficient, (ii) increased modulus with proportionate depth, and (iii) small excavation dimension with respect to much larger seismic wavelength. The chief parameters which can influence the damage of tunnels owing to seismicity, are earthquake magnitude, distance from epicenter, peak ground acceleration, geology of tunnel media, rock mass quality, tunnel-depth from surface, location and orientation of Faults, magnitude and direction of in-situ stresses, types of support system and character of tunnels.

In Himalayan rocks, many problems experienced during tunneling are due to high level of seismicity, encounter of many geological features such as fault zone, thrust zone, shear zone, high in-situ stresses, low rock cover, high ingress of water, buried channel, geothermal gradient, and ingress of gases etc. Therefore, the impact of earthquake on tunnels is required to be studied in detail, so that adequates support measures are provided for design of the support system and lining of the tunnel. This paper discusses a case study of designs of tunnels and tunnel portals for a seismic condition in the Himalayan region and attempts to cross-check performance and behavior of such tunnels during any seismic event.

Keywords: Tunnel, Seismic load, Rock mass parameters, Seismic Coefficient, Rock support, Himalayan region.

1. Introduction

Tunneling is an integral part of modern infrastructures of Himalayan terrain; and is used for a wide range of applications, including highway, railways and hydro power projects. Any tunneling and underground facility built in an area prone to seismic activity, must withstand both seismic and static loadings.

As per the tectonic model of the Himalayan zone, it is clear that, Himalaya is in a state of persistent compression resulting from continued northward movement of the Indian plate towards the Asian plate. And also, there is temporal crustal adjustment which is evident from the current seismicity. And the rate of convergence between the Indian plate and Asian plate has a direct bearing on the seismicity in the Himalayan Region. The seismically sensitive Himalayan zone has been witnessing earthquakes of different magnitude and intensities. In the tectonically active young mountain, the rocks found during tunneling are relatively incompetent and affected by several folds, faults, thrusts of various magnitudes. It is impossible to prevent seismic events from occurring, but their disastrous effects can be minimized appreciably through understanding of their nature, causes, frequency, magnitude and impact area. Himalaya is the tectonically active region with a history of number of earthquakes, weak and fragile rock with regional and smaller structures features. This makes the tunneling in Himalaya a challenging task.

2. Tectonic Model of Himalaya

Himalayan reason is a tectonically active zone caused by collision of the Indian plate with the Asian plate during Eocene- Oligocene period. Geologically, Himalayan zone is divided into three main subdivisions: Outer Himalaya, Middle or Lesser Himalayas and Great Himalaya. Himalayas have been formed after the collision of the Indian plate with the Asian plate. The front edge of the northward moving Indian plate consists of ocean sediments resting on hard basement rocks. The intense compression on the boundary has resulted in folding and faulting and melting on the deeper parts. The outer Himalayas, in the southern zone have elevations up to 900m; the Middle or lesser Himalayas have elevations up to about 3200m, and the Great Himalayas have elevation ranging from 3000 to 8000m. The regions north of the Great Himalayas is the Tethyan Himalayas with an elevation ranging from 3000 to 4200m. The Northern edge of the Tethyan Himalaya is the collision zone of the Asian and the Indian plates. Parallel Fault system separates these zones: the Indo gangatic plain and the outer Himalayas are separated by the Himalayan Frontal Fault (HFF), the Outer Himalaya and the Lesser Himalayas by the Main Boundary Thrust (MBT), and the Lesser Himalayas and Great Himalayas by Main Central Thrust (MCT). Since the northward shift of the Indian plate is still shifting, the mountain building process is still continuing, and the zone is still seismically active.

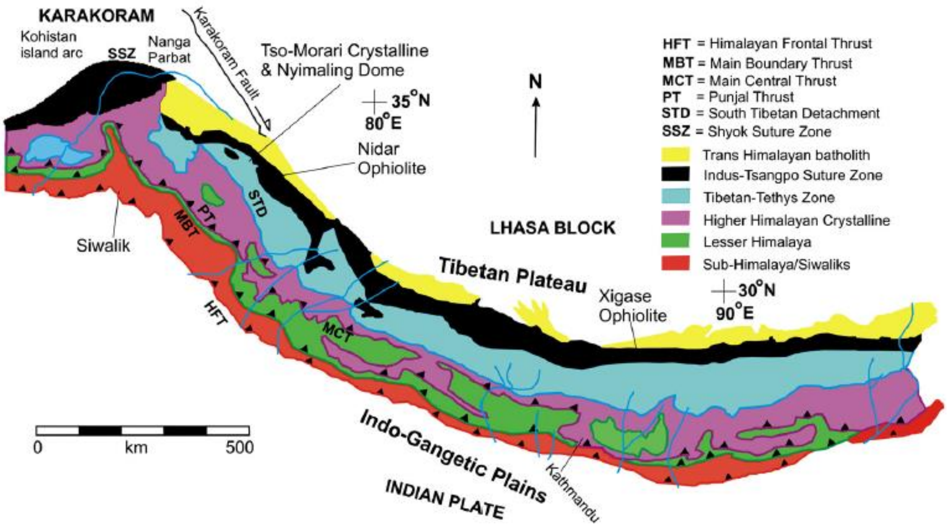


Fig. 1. Geological & Tectonic setup of Himalaya

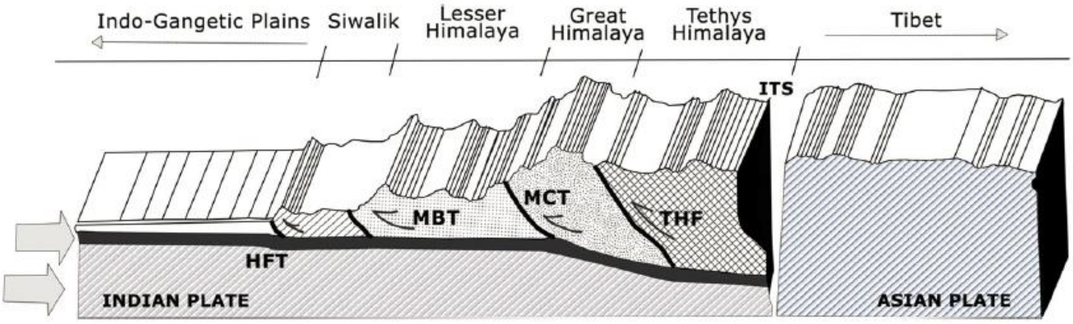


Fig. 2. Geological cross section of Himalaya

3. Major Earthquakes of Himalaya

Many major earthquakes of different, intensity occurring during past centuries, dominate the seismicity of Himalayan zone. The major ones among them are: 1897 earthquake associated with the rupture in the south of Himalaya beneath the Shilling plateau, (M=8.7). The 1905 Kangra Earthquake (M=8.6), the 1934 Bihar-Nepal earthquake (M=8.4), the 1950 Assam Earthquake (M=8.7), and more earthquakes of magnitude >7 have occurred during the year 1916, 1936 and 1947. From 1991 to 2000 three significant and damaging earthquakes with M=>6.5 have occurred in the Himalaya; 1988 (M=6.6), 1991 (M=6.6), 1999 (M=6.3). An earthquake of the magnitude 7.9 has stuck recently in 2015 in the north-west of Kathmandu-Nepal.

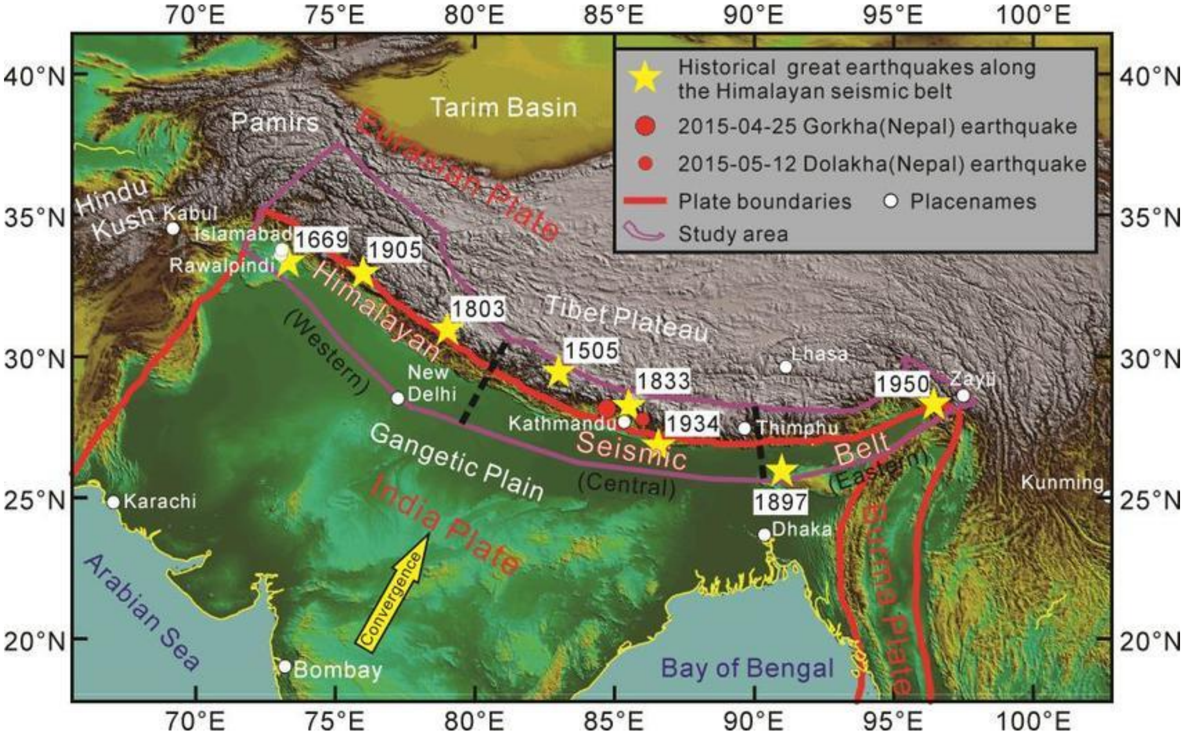


Fig. 3. Major Earthquake along Himalayan zone

4. Performance of underground structure during earthquakes

Underground structures suffer appreciably less damage than surface structures--reported damage decreases with increased overburden depth. A deep tunnel seems to be safer and less vulnerable seismically than a shallow tunnel. Lined and grouted tunnels are safer than unlined tunnels in a rock. Shaking damage can be reduced by stabilizing the ground around the tunnel, and by improving the contact between the lining and the surrounding ground, through grouting. Damage may be related to the peak ground acceleration and velocity based on the magnitude and epicentral distance of the effected earthquake. Duration of strong motion-shaking during earthquake is of utmost importance, because it may cause fatigue failure and the resultant, large deformation. Ground motion may amplify upon incidence with a tunnel, if wavelengths are between one and fourth times the tunnel diameters.

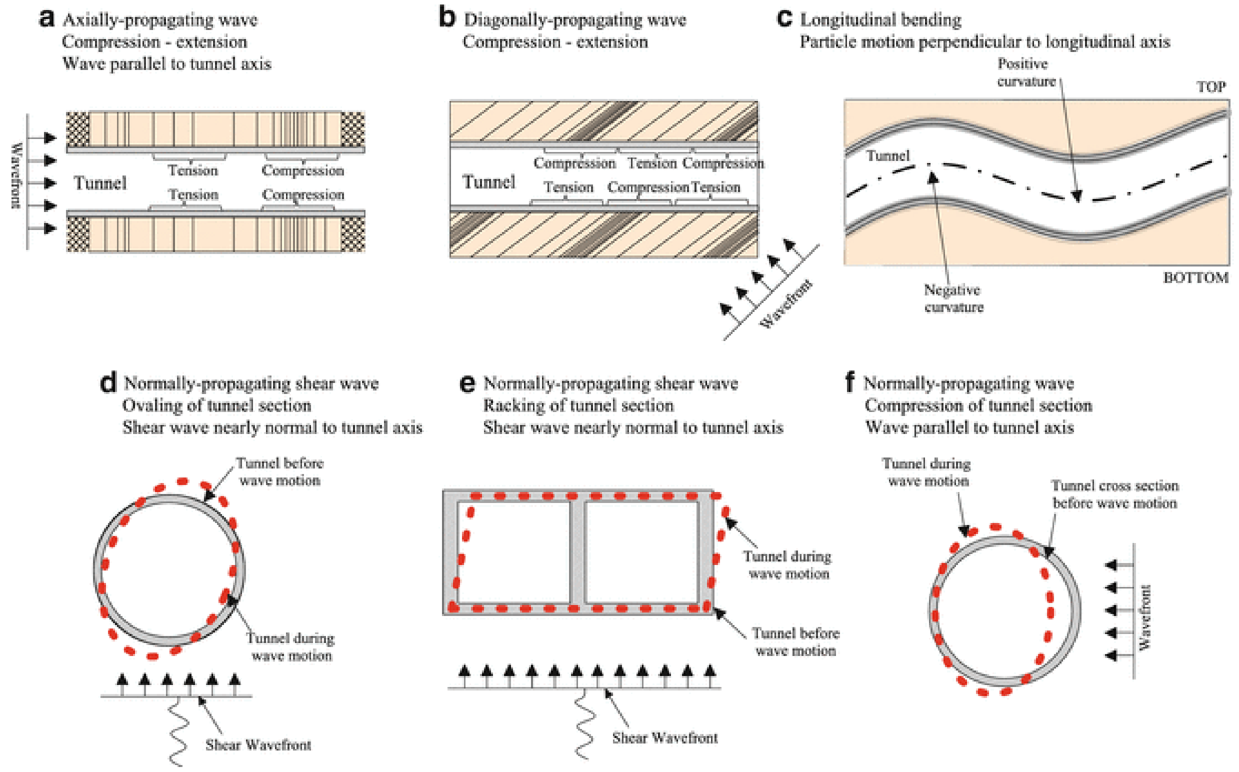


Fig. 4. Deformation modes of tunnels due to Seismic waves (After Owen & Scholl 1981)

5. Failure mechanism of tunnels during earthquakes

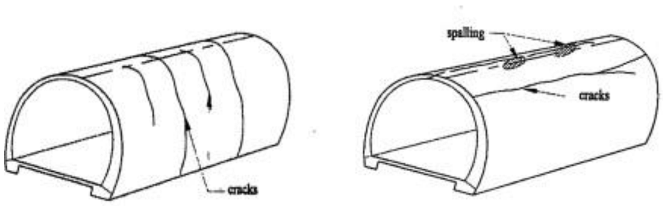
Failure of tunnels resulting from earthquake is generally manifested in one or a combination of following forms: i. earthquake induced surrounding rock failures, such as liquefaction or landslide/ rockslide at tunnel portals. ii. failures from fault displacement, iii. failures from ground shaking or ground vibration. Tunnel displacement by fault movement usually results in serious damages. It was found that most of the tunnel damages from fault movement were caused by unavoidable alignment of tunnel across the fault.

The tunnel can present three kinds of deformation under the seismic events; compression and tension deformation, longitudinal deformation, and shear deformation. Tunnels undergo different earthquake loads for its different positions which are related to fault displacement, source of epicenter. Earthquake waves weaken gradually as they disseminate for wave diffusion and the earth damping.

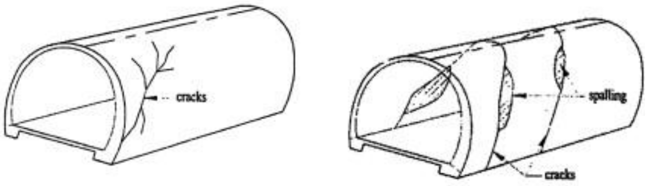
There are many factors influencing the tunnel failure during earthquakes; the first factor is earthquake motion, such as earthquake intensity. The second factor is structural condition of tunnels, such as the lined one, its interaction with the surrounding rocks, and construction quality. The third factor is, tunneling media; like rock condition, rock cover, any fault zone crossing the tunnel. Underground structure failures during earthquake increase with the increase of the seismic motion acceleration and the decrease of the overburdened rock cover depth.

6. Stability of tunnel portal during earthquakes

The most vulnerable part of the tunnel during earthquakes is the tunnel portal. Due to the low overburden and low rock cover, tunnel portals are prone to failures during earthquakes. A tunnel portal is weak part of a tunnel for earthquake and the damage is more if the overburden depth is shallow. Under big earthquake motion, the chance of portal sliding is usual. Therefore, it is easier to predict the effect of seismicity on rock support in tunnel portals.



(a) Transverse Cracks (b) Longitudinal Cracks



(c) Inclined Cracks (d) Extended Cross Cracks

Fig. 5. Tunnel Failures from Ground shaking & ground vibration

7. Tunnel support-design in seismic zone

The principal step in the design of earthquake resistant underground structures is obtaining the level of the ground motion of an anticipated earthquake, so that the underground structures withstand without exceeding a predefined acceptable level. Seismic hazard analysis is undertaken to know an expected level of ground motion at the tunneling zone. There are two methods of analysis; i). Deterministic Seismic Hazard Analysis (DSHA) and ii). Probabilistic Seismic Hazard Analysis (PSHA).

The Deterministic Seismic Hazard Analysis (DSHA) identifies one or more earthquake motions for a site. And a design of underground structures considers that the structure will be able to withstand this or that level of earthquake. The Probabilistic Seismic Hazard Analysis (PSHA) incorporates the uncertainties associated with size, location and reoccurrence rate of earthquakes. Based on the purpose of a structure, the level of a designed earthquake is defined. In a standard practice, dual-level design criteria is followed, whereas in a higher level, commonly known Maximum Design Earthquake (MDE), earthquake is aimed at life-safety at lower level, known as Operating Design Earthquake (ODE). It is for economic risk exposure. In DSHA, the maximum design earthquake is defined by the maximum level of shaking that is expected at site. And in PSHA, MDE is defined as an event that has a small likelihood of occurrence. The ODE is an earthquake that can reasonably be expected to occur at least once during the designed life of the underground structure.

A series of numerical simulations using 2D Finite Element Program are performed to assess the effects of seismicity on tunnel lining. Both linear elastic and elastic-plastic analysis is performed with the rock support interaction. Rock joints also function as models in an analysis applied to study the effect of seismicity on the tunnels in a jointed rock mass.

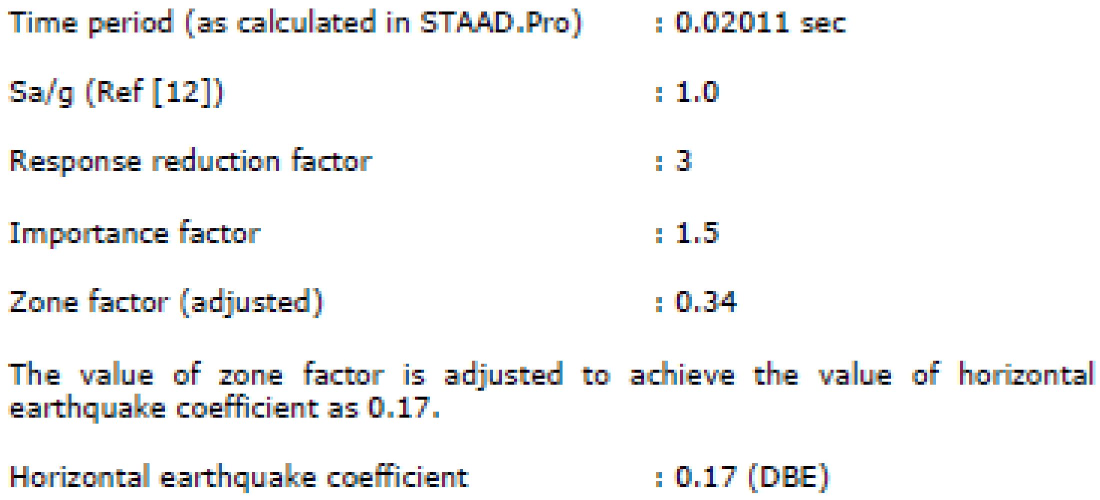
8. Design of a tunnel crossing the fault zone

In Fault zones, tunnels should be designed to accommodate an expected fault displacement and allow repairs of damaged lining afterward. Design strategies for tunnels crossing active fault-zone, depends upon the magnitude of displacement and width of the zone over which that displacement is distributed. If large displacements are concentrated in a narrow zone. A retrofit design will most likely consist of enlarging the tunnel across and beyond the displacement zone. The development of cracks in lining, due to both elongation and compression, may result in an unacceptable water inflow. In case of water conveying tunnel, flexible coupling may be an adequate solution. Tunnels may be backfilled with frangible backpacking such as cellular concrete. Cellular concrete has relatively low yield strength to minimize the lateral loads in tunnel lining. But it has adequate strength to resist normal rock pressure and other seismic loads such as minor ground shock and rock loosening or other vertical load above excavation, only if fault movement is small or distributed. It is possible that the tunnel may be designed to accommodate fault displacement by providing articulation of tunnel liner with ductile joints. This allows the tunnel to distort into an S- shape through the fault zone without rupture. The closer the joint spacing, the better the performance of the tunnel liner.

9. Case study of Vishnugad Pipalkoti Hydro Project (India)

The 444MW Vishnugad-Pipalkoti Hydro power project, under construction, is part of seismic zone -V of the Indian Himalaya, which corresponds to a zone factor of 0.36 (Effective Peak Ground Acceleration in terms of ‘g’ as per IS 1893: Part 2002). The north dipping Main Central Thrust (MCT) lies about 02 km northeast of the project site. All the project components of this project are located far away from the Main Central Thrust.

In the poor and very poor rock zones of tunnels, seismic loading due to inertia is considered in the self weight of lining. The seismic effect in the structure is directly considered as per the pseudo-static method. The following seismic parameters have been considered for designing as per site specific seismic study report of the project.



Time period (as calculated in STAAD.Pro) : 0.02011 sec

Sa/g (Ref [12]) : 1.0

Response reduction factor : 3

Importance factor : 1.5

Zone factor (adjusted) : 0.34

The value of zone factor is adjusted to achieve the value of horizontal earthquake coefficient as 0.17.

Horizontal earthquake coefficient : 0.17 (DBE)

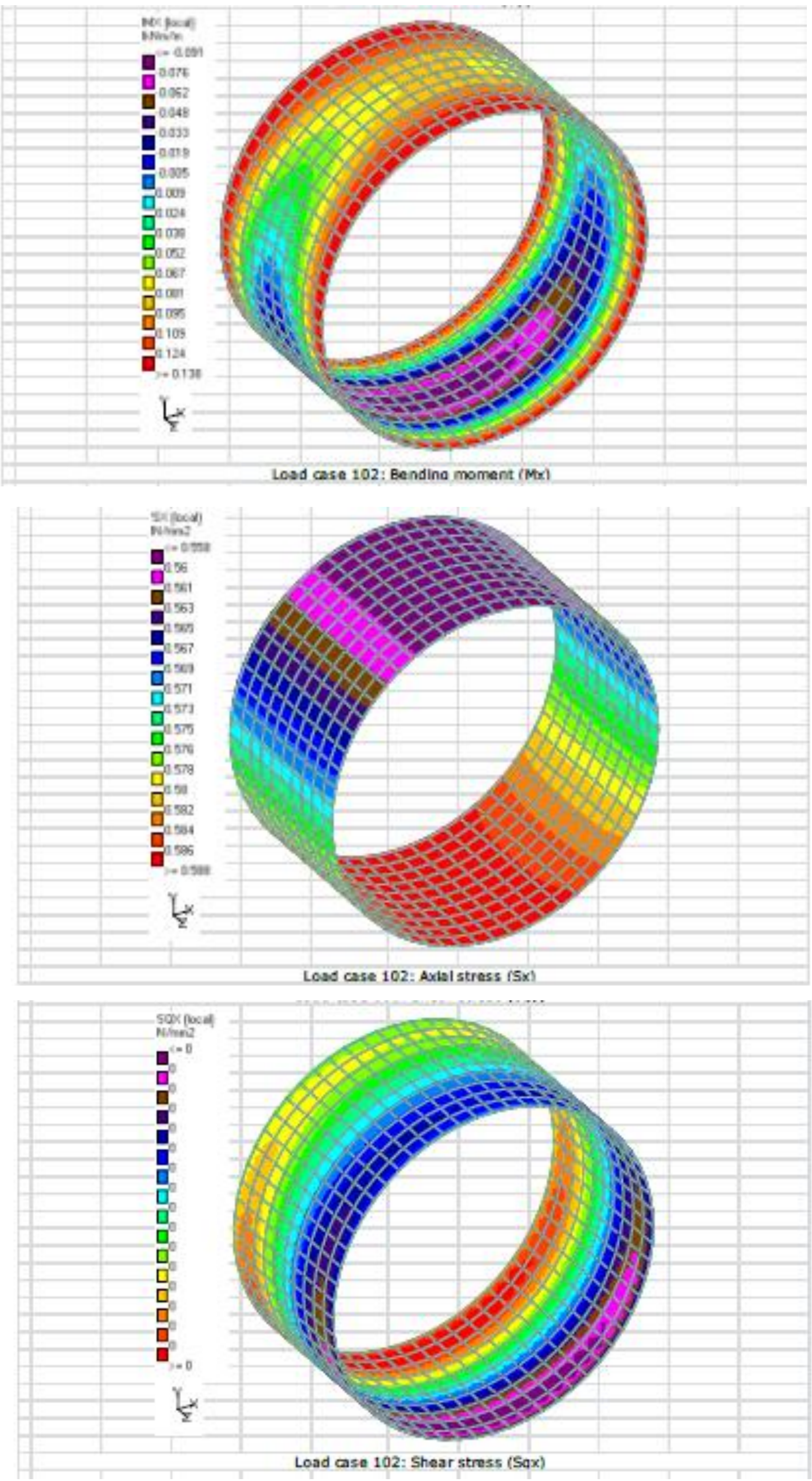
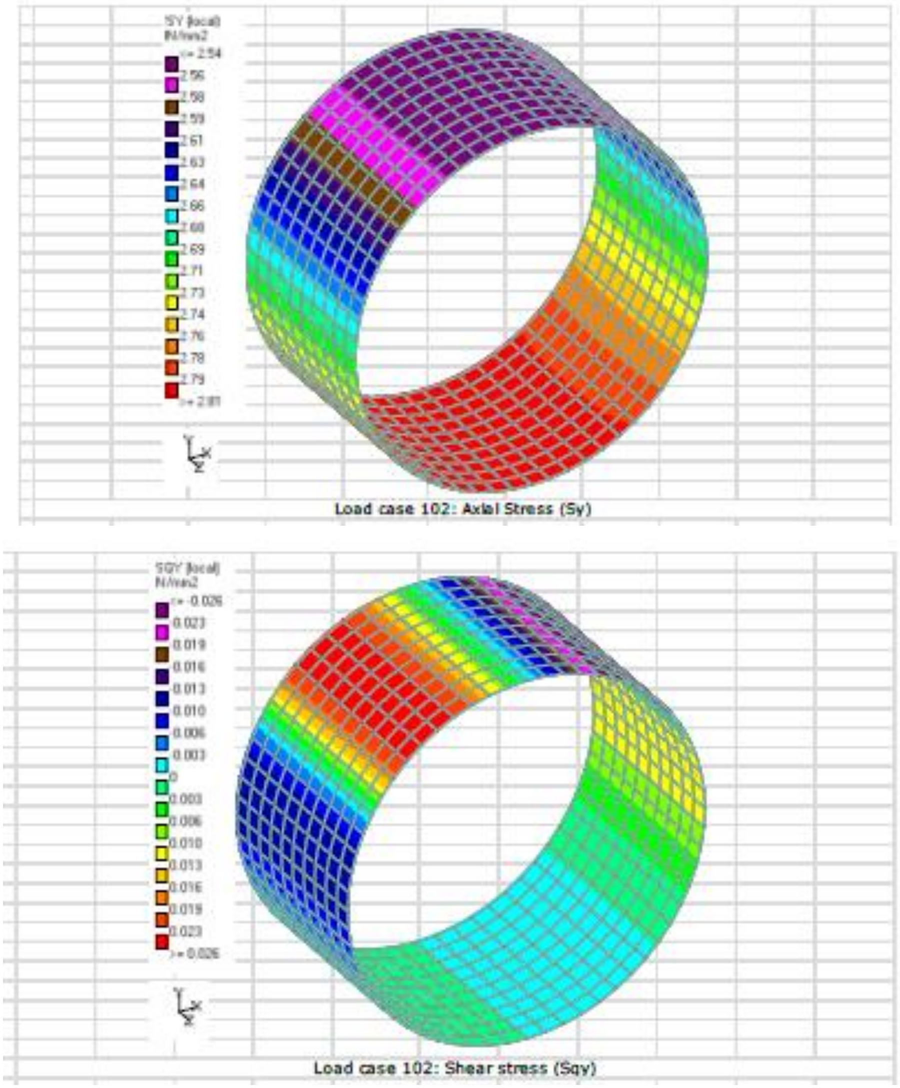


Fig.6, Rock class-IV (Load case- Earthquake + tunnel filled condition)



Load case 102: Axial Stress (Sy)

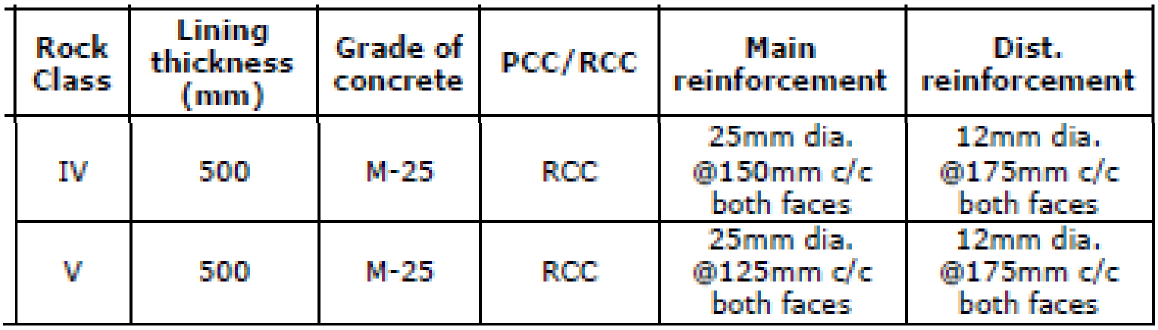
Load case 102: Shear stress (Sqy)

Fig.7, Rock class-V (Load case- Earthquake + tunnel filled condition)

Table.1. Maximum Reactions & Deflection

Rock Class	**Loading conditions**	**Max. My**	**Max. Mx**	**Max. Sy**	**Max. Sqy**	**Max. deflection**
		(kN-m)	**(kN-m)**	**(N/mm^2)**	**(N/mm^2)**	**(mm)**
IV	loads	145.03	73.294	-3.369	0.314	2.553
	Internal loads	0.188	0.138	2.938	0	0.8
V	External loads	193.79	84.629	-3.366	-0.359	4.473
	Internal loads	18.541	3.802	3.44	0.022	1.633

Table-2 Lining Thickness and grade of concrete & reinforcement for tunnel



Rock Class	Lining thickness (mm)	Grade of concrete	PCC/RCC	Main reinforcement	Dist. reinforcement
IV	500	M-25	RCC	25mm dia. @150mm c/c both faces	12mm dia. @175mm c/c both faces
V	500	M-25	RCC	25mm dia. @125mm c/c both faces	12mm dia. @175mm c/c both faces

Lining thickness of 500mm (M-25) with 25mm dia. reinforcement 150mm c/c on both faces found suitable to withstand the earthquake loading condition of Head Race Tunnel at Rock class –IV & V zone.

10. Conclusion

It is often assumed that the underground structures are safe against the earthquake and deep structures are safer than surface structures. Tunnels and underground structures can be damaged during strong earthquakes. Impact of earthquakes on tunnels and underground structures is required to be studied in details, so that adequate safety margin is provided for in the design of the support system and lining. Factors including size and depth of excavation, rock mass parameters, and suitable seismic coefficient in horizontal and vertical direction influenced the computation of force generated due to seismic load. Numerical modeling with different combinations of parameters can be adopted. Tunnels crossing Fault Zone or Thrust Zone should be designed to accommodate an expected Fault displacement and allow repairs of damaged lining afterward.

In particular tunnels portals are vulnerable to the mass movement. Therefore, all underground structures of Himalayan region should be checked and designed against earthquake. Tunnels crossing an active fault zone need special attention while finalizing the design.

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