

Tunnels, the Sustainable Means of Transportation Pathways in Natural Disaster Prone Darjeeling-Sikkim Himalaya (DSH)



Pratap Chandra Dhang 

Abstract Sivok-Rangpo Rail Line Project (SRRP) is traversing along the Teesta River Valley through the seismically active Darjeeling and Kalimpong Hills in between MBT and MCT of Darjeeling-Sikkim Himalaya (DSH). Therefore, many environmentalists and geologists claimed that this project dominated by tunnels may invite natural disasters and the tunnels will not be safe under seismic events. From the studies like empirical correlations between measured peak ground accelerations (g) and observed damage in tunnels, the following tendencies have been revealed: (a) up to a peak acceleration of 0.2 g, slight damage, (b) from 0.2 g to 0.6 g, serious damage in unlined tunnels and in tunnels devoid modern lining, (c) from 0.6 g to 0.9 g, serious damage on tunnels having plain concrete lining (unreinforced). Though most severe earthquakes in Sikkim and adjoining areas had peak ground acceleration ranges from 0.15 g to 0.45 g only, which indicate that the modern lined tunnels constructed by NATM are very much safe under massive earthquakes, and NATM designs have all considerable factors for earthquake-induced ground movement in them. The transportation tunnels ensure less damage to the environments and biodiversity and are also used to avoid instable slopes which fail during earthquake-induced ground vibration. Therefore, tunnels are considered as safe and useful in sustainable infrastructural developments in this seismically active Himalayan region.

Keywords Himalaya · NATM · PGA · SRRP · Tunnels · Landslides

1 Introduction

The Himalayan orogenic system of about 2500 km has evolved in response to collision of the Indian and Eurasian plates, which caused sequential thrusting (Main Central Thrust or MCT, Main Boundary Thrust or MBT, Main Frontal Thrust or MFT, etc.), and riding of different thrust blocks on each other [2]. This long and

P. C. Dhang (✉)
9/1 Akshaytara Apartments, Siliguri, W.B 734 001, India
e-mail: pratap09.isi@gmail.com

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wide stretch of Himalayan region is devoid of proper infrastructural developments due to its inaccessibility and prone to natural disasters. However, recently Indian Railways and National Highway Authority of India have taken the initiative to extend the railways and roadways into the mighty Himalayan ranges. Therefore, numerous railway projects like Udhampur-Srinagar-Baramullah Rail Link (USBRL) Project in Jammu & Kashmir Himalaya, Rishikesh-Karnaprayag Railway Project in Uttarakhand, Sivok-Rangpo Rail Line Project (SRRP) in Darjeeling-Sikkim Himalaya, Bhalukpong-Tawang Railway Line Project in Arunachal Himalaya, etc., are under-going. All these projects are characterized by 80–85% tunnels to ensure less harm to the environment and biodiversity and also to avoid unstable hill slopes. Frequent earthquakes and other natural hazards, such as flashfloods and landslides, etc., are inherent to the Himalayan regions (IS 1893 (Part 1); 2002), [5]. Himalaya is under-going rapid uplift at rates of about 0.5 mm/year [44]. Present project is situated in between the Main Boundary Thrust (MBT) and Main Central Thrust (MCT); hence seismo-tectonically the region is very active, where earthquake of magnitude ≥ 6 may occur. Recent seismicity in Himalaya is restricted in two distinct zones, one is between MBT/MFT and MCT and the other is beyond Indus Tsangpo Suture (ITS) [31]. Therefore, the doubt regarding the safety of the tunnels comes into existence. Even local peoples and administrations have questions about the stability of the tunnels under the seismic activities.

Sivok-Rangpo Rail Line Project (SRRP) is traversing along the Teesta R. in Darjeeling Sikkim Himalaya (DSH). This region is considered as one of the most prone to natural disasters in terms of earthquakes and landslides. Therefore, many environmentalists and geologists questioned about the stability of the tunnels and also claimed that this project may invite further natural disasters. The tunnelling works in seismically active Himalayan region are new in India, however, the Alpine regions or the seismically very active Japan has prolific development in tunnelling. Recently the studies have been conducted in developed countries of Europe, America and Asia to analyze the effect of earthquakes on the tunnels [8, 13, 35, 38, 45, 47]. These researches show that underground structures are seismic resistant, however, there are geological conditions which may induce indirect earthquake damage to tunnels like fault zone activated by earthquake, sudden changes in condition due to contrasts in geomechanical properties of rocks, potentially liquefiable soils, pore fluids and marked anisotropy in local stress field [27]. These damages are often characterized by irreversible displacements, heavy water inflow, mechanical instability at tunnel portals, soil settlement and rupture due to liquefaction, etc.

The present work is based mostly on qualitative approach and on available literatures and case studies. Detailed analysis on seismic design for tunnels is beyond the scope of the present work. And in present study, Peak Ground Acceleration (PGA), the most important earthquake parameter has been used to depict the performance of tunnels in seismically active areas. The objectives of the present work are: (i) to get an overview of the seismo-tectonic set-up of the Sikkim-Darjeeling Himalaya (DSH) with respect to the Sivok-Rangpo Rail Line Project area, and (ii) to assess the probable impacts of seismic events or other natural disasters on the tunnels in the project area.

2 Seismotectonic Set-Up

Sivok-Rangpo Rail Line Project is traversing along the Teesta River through the Darjeeling and Kalimpong Hills of DSH. Several perennial and seasonal streams pass across the alignment of the project. The area is densely vegetated having high relative relief and high stream density. During monsoon (from May to October) these streams are used to be very active and debouches water directly or indirectly into the Teesta River. The area receives heavy to very heavy rainfall, i.e., more than 2600 mm per year. The slope of the hill is probably covered up by slope wash materials, colluvials and soil, which have thickness of about 0–30 m. The overburden material is featured by block in soil matrix. Block size ranges from 10 to 120 cm and are haphazardly embedded within the soil. Soil consists of variable grain size ranging from clay/silt, sand to gravel. Therefore, there are abundant voids and are moderately permeable with cohesion (c) and angle of internal friction (φ) are 0–10 kPa and 25–30° respectively. Thus, the hillslopes are fragile and prone to erosion and landslide (cf. [36]).

The region is tectono-stratigraphically sub-divided into four domains with characteristic stratigraphic and structural attributes, namely, (i) Foothill Belt, (ii) Inner Belt, (iii) Axial Belt, and (iv) Trans-axial Belt. The collision event is associated with multiple deformation phases and it is a part of an active fold-thrust belt. The major tectonic features are Main Frontal Thrust (MFT), Main Boundary Thrust (MBT), Main Central Thrust (MCT) NNW-SSE trending Tista and Gangtok lineaments, WNW-ESE trending Goalpara lineament and SW-NE trending Kanchanjangha Fault, Gish Transverse Fault and major structural feature, known as Rangit Window (Fig. 1) [10, 18, 26, 33]. The MBT and MCT are the main structural elements, along which the Proterozoic Daling rocks override the Gondwana rocks and the Lower Proterozoic high-grade metamorphic rocks of Darjeeling Gneiss override the Middle Proterozoic low-grade metamorphic rocks (schist and phyllite) of Daling Group (Table 1). Different lithological units are disposed in an arcuate regional fold pattern. The core is occupied by the Lesser Himalayan Belt of the Daling Group including the Lingtse-granitoid gneiss. The region also comprises medium- to high-grade crystalline rocks of the Higher Himalayan Belt. The MCT, a prominent ductile shear zone separates the two belts. Gondwana and molasse-type Siwalik sedimentary rocks of the Sub-Himalayan Zone occur in the southern part of the region. Several subsidiary thrusts are also present between MCT and MBT. Neotectonic evidences in frontal Darjeeling-Sikkim Himalaya are well exposed along Teesta R. (near Kalijhora village on NH 31) in the form of out-of-sequence thrusts and displacement of ~150 m eastward by the river while incising ~48 m vertically, giving rise to impaired disjointed strath terraces [32].

Frequent earthquakes and other natural hazards, such as flashfloods and landslides, etc., are inherent to the Himalayan regions [5, 9, 15, 28, 42]. The clustering of epicentres of earthquakes is recognised to occur between MCT and MBT [37] (Fig. 2). The stress continuously builds up along the major thrusts and sudden release of the stress causes frequent tremors. And strongest concentration of epicentres between 27

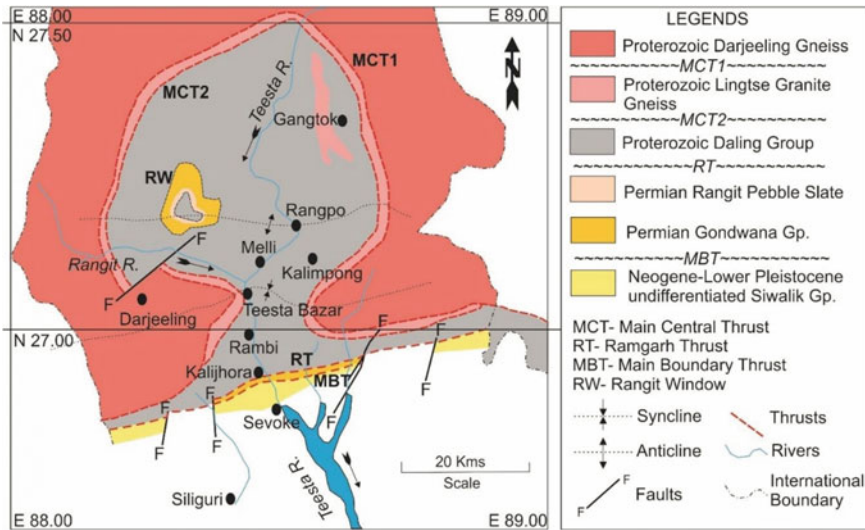


Fig. 1 Geological map of the Sikkim-Darjeeling Himalaya (modified and simplified after [18]). SRRP alignment traverses along the Teesta R. from Sevoke to Rangpo

and 27.5° N indicates that the Tista half-window recorded majority of seismic events [30]. It has been revealed from focal mechanism that the region experiences both thrust and strike-slip earthquakes occur in this area [20, 34]. The present project area lies in this active seismic zone, which is classified under Zone IV (IS 1893 (Part I) 2002). The seismic intensity in the region is VIII on Modified Mercalli intensity scale (MM scale) [43]. Most of the earthquakes occur at shallow depth. Seismic events here are associated with strain accumulation associated with the northward tectonic movement of Indian Plate [43]. The region is under compressive stress regime and σ_1 lies horizontally in N-S direction (cf. [21]). Recent studies revealed that northward motion of the Indian Plate exceeds 14 mm/year. GPS data indicate in the western most Himalaya near Kashmir, the convergence rate is ~ 12 mm/a, similarly, at the Central Himalaya, the rate attained 17 mm/a, whereas, around Assam and Sikkim area the rate is about 15 mm/a [5]. The seismic activity in this part is not uniform and Darjeeling-Sikkim Himalaya has not experienced major earthquakes, except a few. Nath et al. [33] presented a seismic hazard map of the Sikkim Himalaya, lying between Nepal and Bhutan Himalaya, in terms of horizontal peak ground accelerations with 10% exceedance probability over the next 50 years. They also showed that from the composite fault plane solution from the strong motion events about thrust faulting with strike slip component along MBT. Global Seismic Hazard Assessment Program (GSHAP) also characterized Sikkim region as surrounded by 8 seismic source zones. The impacts of the earthquakes and of consequent landslides in DSH can be seen through huge loss of life and properties.

Table 1 Tectonostratigraphy of Darjeeling-Sikkim Himalaya (DSH)

| Group | Subgroup/Formation | Lithology | Age |
|--------------------------------|--|--|---------------------------|
| Darjeeling Gneiss | | Migmatitic gneiss | Proterozoic |
| <i>MCT 1</i> | | | |
| Lingste Granite-Gneiss | | Granite-gneiss (Mylonite) | Proterozoic |
| <i>MCT 2</i> | | | |
| Daling Group | Buxa Fm | Massive thick dolomites, cherts and bands of phyllite | Proterozoic |
| | Reyang Fm | Slate, phyllite, quartzite | |
| | Gorubathan Fm | Phyllite, schist | |
| <i>Ramgarh Thrust (RT)</i> | | | |
| Rangit Pebble Slate (Talchir?) | | Diamictite, rhythmite, quartzite, marl | Permian |
| Gondwana Group | Damuda Subgroup | Sandstone, carbo. shale and coal | |
| <i>MBT</i> | | | |
| Siwalik Group | Upper | Murti Boulder Bed | Neogene to L. Pleistocene |
| | | Parbu Grit (pebbly-coarse-medium sandstone) | |
| | Middle | Geabdat Sandstone (medium to coarse sandstone, shale, pebble beds) | |
| Lower | Chunabati (fine to medium sandstone, siltstone, mudstone, marl and conglomerate) | | |

3 Peak Ground Acceleration (PGA)

The Peak Ground Acceleration (PGA) is an important parameter for earthquake engineering. As per USGS Earthquake Glossary ‘When the ground is shaking during an earthquake, it also experiences acceleration. The peak acceleration is the largest increase in velocity recorded by a particular station during an earthquake’. PGA is expressed as a fraction of gravitational acceleration. According to USGS, ‘g’ is the acceleration of gravity, i.e., $9.8 \text{ (m/s}^2\text{)}$, when there is an earthquake, the forces caused by the shaking are measured as a percentage of gravity. On the other hand, seismic intensity scale is being used for measuring the intensity of shaking produced by earthquake, which is also known as Modified Mercalli Intensity Scale (MM scale). The correlation between PGA and MM scale has been provided in Table 2. The

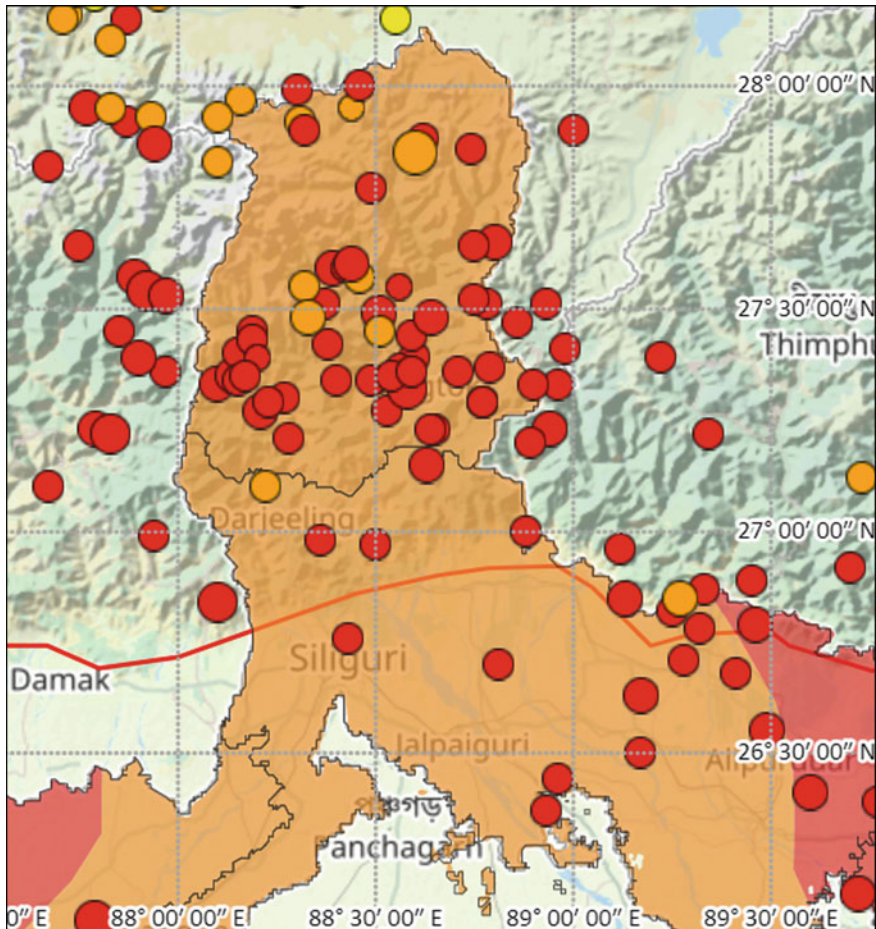


Fig. 2 Epicentres of earthquakes around Darjeeling-Sikkim Himalaya (DSH) and surrounding regions in last 70 years. *Source* National Centre for Seismology

seismic zones in India have been made on the basis of intensity of shaking [16, 23]. Raisinghani and Purohit [40] presented a correlation between the magnitude, PGA and intensity of some of the major earthquakes occurred in India between 1934 and 2015 (Table 3).

Extensive data regarding PGA in DSH is not available, however, recently some works have been undertaken. A study has been conducted by [33] at nine stations in Sikkim by installing strong motion accelerographs for continuous monitoring of the earthquake signals. They have collected data from 80 earthquakes ($M = 3\text{--}5.6$) recorded during 1998–2003 and analyzed the data to present a hazard scenario in the Sikkim Himalaya. The PGA has been estimated for the scenario earthquake of magnitude 8.3 at a depth of 26.25, and it has been found that there is spatial

Table 2 Correlation between MM scale, PGA and PGV (after USGS)

| Mod. Mercalli intensity scale (MM) | Acceleration (g) | Velocity (cm/s) | Perceived shaking | Potential damage |
|------------------------------------|------------------|-----------------|-------------------|------------------|
| I | <0.000464 | <0.0215 | Not felt | None |
| II–III | 0.00297 | 0.135–1.41 | Weak | None |
| IV | 0.0276 | 1.41–4.65 | Light | None |
| V | 0.115 | 4.65–9.64 | Moderate | Very light |
| VI | 0.215 | 9.64–20 | Strong | Light |
| VII | 0.401 | 20–41.4 | Very strong | Moderate |
| VIII | 0.747 | 41.4–85.8 | Severe | Mod. to heavy |
| IX | 1.39 | 85.8–178 | Violent | Heavy |
| X+ | >1.39 | >178 | Extreme | Very heavy |

Table 3 Details of major earthquakes occurred in India and seismic zones of India (modified after Raisinghani and Purohit 2016)

| Sl. No | Event location | Year | Magnitude | PGA | MM scale |
|--------|------------------|------|-----------|--------|----------|
| 1 | Bihar-Nepal | 1934 | 8.2 | 0.3 g | IX |
| 2 | Assam | 1950 | 8.7 | – | X |
| 3 | India-Burma | 1988 | 7.2 | 0.34 g | VIII |
| 4 | India-Bangladesh | 1988 | 5.8 | 0.1 g | VI–VII |
| 5 | Garhwal | 1991 | 7.1 | 0.3 g | VIII |
| 6 | Uttarkashi | 1967 | 7.0 | 0.29 g | IX |
| 7 | Koyna | 1967 | 6.5 | 0.4 g | VIII |
| 8 | Chamoli | 1999 | 6.6 | 0.34 g | VIII |
| 9 | Bhuj | 2001 | 7.7 | 0.38 g | VIII |
| 10 | Kashmir | 2005 | 7.6 | 0.23 g | VIII |
| 11 | Sikkim | 2011 | 6.9 | 0.35 g | VI |
| 12 | Nepal | 2015 | 7.9 | 0.25 g | IX |

variation with high at Singtam and adjoining areas and low at Lachen (Table 4). Research on recent high-intensity earthquakes in DSH and surrounding areas have been conducted, among them two major earthquakes are 18 September 2011 NW Sikkim Earthquake ($M = 6.9$) and 25 April 2015 Kathmandu Valley, Nepal Earthquake ($M = 7.8$) [15, 28]. In both the cases reported max. intensity was VII in MM scale and caused huge damages with economic losses and numerous casualties. But most of the damages were considered to be due to poor construction of houses and hilly landslide-prone terrain. Macro seismic field observation of Sikkim Earthquake was made by Mahajan et al. [29] and they found that there was an asymmetrical distribution and heterogeneous damage pattern in the region. The intensity distribution

Table 4 Spatial distribution of measured PGA values at nine strong motion stations in Sikkim by [33]

| Sl. No | Stations | Lat/Long | PGA values | Remarks |
|--------|-----------|---------------|------------|---------|
| 1 | Aritar | 27.18N/88.67E | 0.31 | |
| 2 | Chunthang | 27.60N/88.64E | 0.22 | |
| 3 | Gangtok | 27.33N/88.62E | 0.33 | |
| 4 | Jorethang | 27.13N/88.28E | 0.31 | |
| 5 | Lachen | 27.71N/88.55E | 0.20 | Lowest |
| 6 | Mangan | 27.52N/88.53E | 0.28 | |
| 7 | Melli | 27.09N/88.45E | 0.33 | |
| 8 | Geyzing | 27.28N/88.27E | 0.30 | |
| 9 | Singtam | 27.23N/88.49E | 0.38 | Highest |

map indicates max. PGA of 0.45 g at Chunthang, and it reduced toward north, 0.25 g at Theng, Bichhu and 0.15 g at Gangtok. Whereas, the max. PGA was 0.25 g (ranges 0.16–0.25 g) reported during Nepal Earthquake having shallow depth of 10–15 km [46].

4 Earthquakes and Tunnels

The general observations regarding seismic performance of underground structures [19] are:

- (i) Underground structures suffer less damage than surface structures
- (ii) Reported damage decreases with increasing overburden depth
- (iii) Lined and grouted tunnels are safer than unlined tunnels
- (iv) Tunnels are more stable under a symmetric load, which improves ground-lining interaction
- (v) Damage may be related to PGA and velocity based on the magnitude and epicentral distance of the affected earthquake.

Further from the earlier studies like empirical correlations between measured peak ground accelerations or PGA (g) and observed damage in tunnels, the following tendencies have been revealed: (a) up to a peak acceleration of 0.2 g, slight damage, (b) from 0.2 g to 0.6 g, serious damage in unlined tunnels and in tunnels devoid modern lining, (c) from 0.6 g to 0.9 g, serious damage on tunnels having plain concrete lining (unreinforced). The underground structures are assumed to be seismic resistant since they are buried deeply in rock/soil layers, however, in case the tunnel experiences strong shaking and if it is traversing across faults or other adverse geological conditions, there will probability of damage. Zhang et al. [48] classified seismic damages in tunnels into five following patterns: (1) Cracks of tunnel lining, (2) Damage of construction joints, (3) Groundwater leakage, (4) Spalling and

collapse of concrete lining, and (5) Damage of pavement. It has been observed that during earthquake, mostly the local cracks are developed on lining, in case there is any damage. The famous Bolu Tunnel, Turkey has been studied regarding seismic performance of tunnel [19]. The twin tunnels were constructed using NATM, where continuous monitoring of primary liner convergence was performed and modifications in support elements done accordingly. August 17, 1999 Kocaeli Earthquake had minimal impact, whereas, November 12, 1999 Duzce Earthquake caused a collapse of 300 m from the eastern portal. However, the collapse took place in clay gauge material in unfinished section and no tectonic displacement observed [27].

Recently the most severe earthquakes occurred at Kashmir (in 2005 with max. intensity of 7.6) and Sikkim Himalayas (in 2011 with max. intensity of 6.9). The peak ground acceleration of these earthquakes ranges from 0.15 g to 0.45 g only [4, 6, 41, 46]. Raisinighani and Purohit [40] presented a list of severe earthquakes in India with their magnitude, PGA and intensity (Table 3). From the list it has been clear that the most important parameter taken into consideration for the performance of structures in earthquake, i.e., PGA ranges from 0.1 g to 0.38 g, thus indicating that the tunnels may be affected by slight damage or serious damage, in case, the tunnels are devoid of lining. Therefore, the tunnels are very much safe under such massive earthquakes.

There are geological conditions which may induce earthquake damage to tunnels like fault zone activated by earthquake (fault displacement), sudden changes in condition due to contrasts in geomechanical properties of rocks, potentially liquefiable soils, pore fluids and marked anisotropy in local stress field [19]. These damages are often characterized by irreversible displacements, heavy water inflow, mechanical instability at tunnel portals, soil settlement and rupture due to liquefaction, etc. For these, modern geophysical and geotechnical investigation methods are being applied during the pre-design and design phase of these Himalayan tunnels as per guidelines of AFPS/AFTES. Multidisciplinary approach and incorporation of several factors (both static and dynamic conditions) into the designs of the underground structures to sustain the vibratory motion of the earthquakes have also been taken into consideration (cf. [1]).

Distortion of the cross section and increase in stress may occur due to compressive-tensile loads during earthquake-induced ground movement and stiffness of the lining, therefore, addition of earthquake joints design of flexible support systems is inherent here. The design of the tunnels in these regions is based on New Austrian Tunnelling Method (NATM), which put emphasis on ground behaviour reactions on creation of underground opening and to mobilize self-supporting capability of the ground by dual flexible lining without continuous deformation monitoring [25]. Structural verifications of the lining are used to be performed according to EN 1992 (Eurocode 2) for Ultimate Limit State (ULS) and Serviceability Limit State (SLS). Further to mention that tunnels can be subdivided into two parts, viz. tunnel portal areas (vertical cover up to 20 m) and deep structures (vertical cover beyond 20 m). Tunnel portal areas are considered as surface structures and heavy reinforced lining is used to done here. Whereas, the deep lying part of the tunnels is not significantly affected by earthquake

damage because loads are attenuated at depth. However, special arrangements for active fault crossings zones, like enlargement of excavation section, stress controller, etc., are also supposed to be used.

5 New Austrian Tunnelling Method (NATM)

New Austrian Tunnelling Method (NATM) is an observational method, which is based on a concept whereby the ground surrounding an underground opening becomes a load bearing structural component through activation of a ring-like body of supporting ground [25, 39]. NATM is tunnelling concept starting from the initial design stages of an underground structure until the execution and construction. At present the designs of tunnels in Himalayan regions are mostly based on NATM, which is based on a concept whereby the ground surrounding an underground opening becomes a load bearing structural component through activation of a ring-like body of supporting ground. NATM also known as Sequential Excavation Method (SEM) works on understanding of the behavior of the ground as it reacts to the creation of an underground opening. The cross-section of the tunnels is a modified horse-shoe shape to promote smooth stress redistribution around newly created opening. Primary support (shotcrete, lattice girder and rockbolts) allowed a controlled ground deflection to mobilize inherent shear strength in the ground and to initiate load distribution. It also avoided development of wedge failure and generated a rock mass ring with significantly improved ground strength. Concavely rounded excavation surfaces initiate confinement forces and limit bending and tension forces (Fig. 3).

The primary stress in the surrounding ground before excavation depends upon the overburden pressure and the tectonic stresses. In case of the tunnels in SRRP, the overburden pressure is not very high but the tectonic stresses are high due to its nearness to the thrusts (MBT, MCT, etc.). After the excavation of tunnel, the tangential stresses increased. The induced tangential and radial stresses exceed strength of the surrounding ground, which yielded a plastic zone around the tunnel, which significantly controlled the tunnel behaviour (Fig. 3). Depending on the geological and geotechnical conditions, different failure modes are used to be defined, and depending on the potential failure modes, project specific requirements, boundary conditions and specific construction measures to ensure stability have been chosen. Considering the behavioural categories and in-situ stress depending on overburden, appropriate support measures have been used, which is made possible by considering precedent experiences in other similar tunnels. Supports were further verified by Confinement-Convergence Method (CCM) and numerical models. Based on the ground characteristics and the determined ground behaviour a feasible construction concept is chosen, consisting of excavation method, excavation sequence, support measures and auxiliary methods [7, 17, 22]. To evaluate the deformation, 3D monitoring and tunnel instrumentation are used to be done, for which bireflex targets as Deformation Monitoring Points (DMP) were installed in the tunnel roof and at

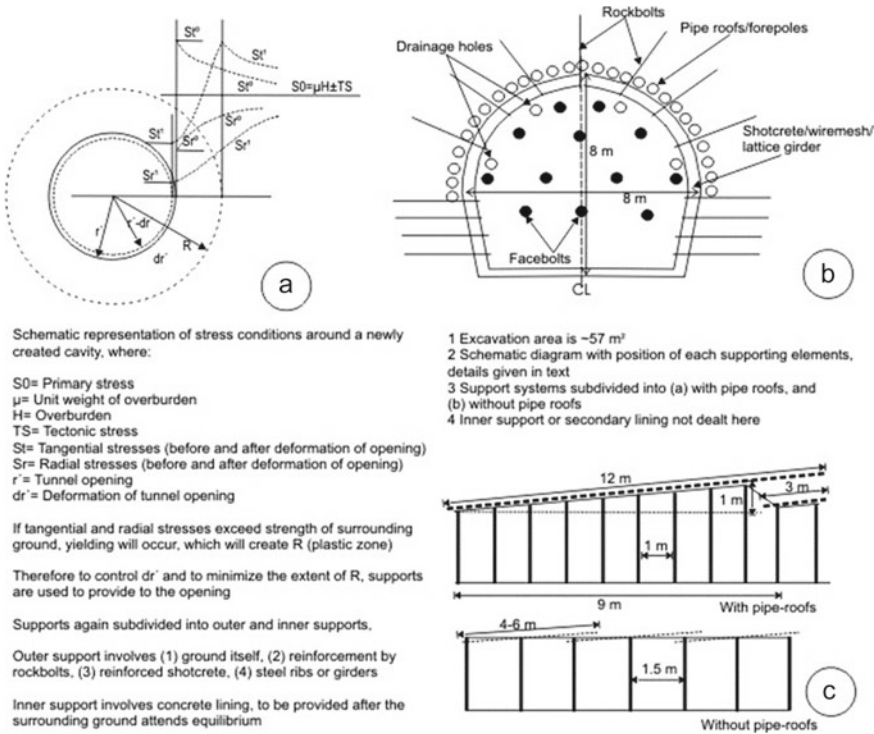


Fig. 3 Concept of NATM and general support systems in NATM

selected points along the tunnel walls (5 in a section). Vertical, horizontal and longitudinal (in tunnel direction) movements were measured from the targets (cf. [3, 27]). Other instruments like extensometer, strain gage, etc., were also used. When the surrounding ground of the tunnel attains its equilibrium state, after confirmation from deformation monitoring, final or secondary or permanent lining, that too, reinforced will be done.

In SEM-NATM, dynamic forces of earthquake have also been considered to design the permanent lining in the tunnels (cf. [24]). Similarly, the designs of the tunnels in DSH have also been done accordingly by following the relevant standards like [23] and guideline ‘Seismic Design for Underground Structures’ of ITA. Structural verifications of the lining are used to be performed according to EN 1992 (Eurocode 2) for Ultimate Limit State (ULS) and Serviceability Limit State (SLS). As the overall ground condition in this DSH is poor to very poor, the reinforced permanent lining has to be used. Tunnel portal areas have been considered as surface structures and heavy reinforced permanent lining has been designed. Whereas, the deep lying part of the tunnels is not significantly affected by earthquake damage because loads are attenuated at depth, the reinforced permanent lining has been designed as per the encountered groundmass condition, as numerous shear zones, local faults, etc., are

encountered throughout. Special arrangements for active fault crossing zones, like enlargement of excavation section, stress controller, etc., can also be considered, if required. Even now-a-days advanced methods, like Tunnel Seismic Prediction (TSP) for predicting such zones in advance are also available, which will allow the tunnelling team to plan properly for these critical zones [11, 12].

6 Conclusion

Recent studies revealed that PGA in DSH is less than 0.4 g and also the estimated PGA for earthquake of magnitude 8.3 is also not high. It is to conclude here that the tunnels in seismically active areas are quite safe as peak ground acceleration during earthquakes never reaches 0.6 g to cause immense damage to the tunnel lining in Himalayan regions and the modern designing aspects of the tunnels have all considerable factors for earthquake induced ground movement in them. However, to increase the reliability of the underground structures and to accommodate larger events at closer distances, it is becoming necessary to consider the effect of dynamic loads generated by earthquake. Some geological features like faults and shear zones, etc., cross the tunnel alignment, therefore, reinforced permanent lining in NATM, use of stress controller, excavation of enlarged section, etc., have also been kept under consideration. Even modern technologies are available for the prediction of any critical zone (including behaviour of the zone), like faults, water bearing zones, etc., which may cause damage to underground structures during earthquakes. Most importantly, the tunnels ensure less damage to the environments and biodiversity and are also used to avoid instable slopes which fail during earthquake induced ground vibration. Tunnels are useful in sustainable infrastructural developments in the seismically active Himalayan regions. There are ample scopes for further study on this topic, as future researches on impact of earthquakes on tunnels quantitatively and estimation of site-specific PGA by instrumentation for considering that in seismic design are required.

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