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Bypassing Landslides in the Himalayas through Climate Resilient Infrastructures (Tunnels) using the Principles of Norwegian Method of Tunnelling

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ABSTRACT

Tunnels are considered as climate resilient infrastructures which have been used to overcome challenges faced due to landslides in many parts of the world. In the European Alps and in Scandinavia several hundreds of kilometers of tunnels have been constructed to bypass chronic landslide prone areas. The Norwegian Geotechnical Institute (NGI) has been involved in the design and monitoring of several tunnels and caverns over the past two decades in the Himalayan Region of India and in Bhutan. Due to the complex geological and tectonic settings prevalent in the Himalayas, it has been experienced that detailed engineering geological mapping, rock mass characterization, geophysical investigations and numerical modelling for verifying the rock support requirements in tunnels are warranted for the successful completion of these infrastructure projects. This paper describes some case studies of tunnels that have been constructed and planned in the Himalayas for bypassing landslides. The studies performed provide a better insight into the prevailing rock mass conditions along a proposed tunnel alignment. The data gathered has helped to better understand the behavior of the rock mass in underground openings. A key component of the Norwegian Method of Tunnelling (NMT), which includes the application of reinforced ribs of shotcrete (RRS), is described. This technique has been successfully implemented at an ongoing rail tunnel project in the Himalayas by Rail Vikas Nigam Ltd. In Norway RRS has replaced expensive steel sets and cast concrete arches in tunnels. This type of rock support is considered as both cost efficient and more flexible in application because it is not prefabricated.

Keywords: Norwegian Method of Tunnelling; Reinforced Ribs of Shotcrete; Numerical modelling; Rock mass characterization

1. INTRODUCTION

In recent years a large number of tunnels have been constructed throughout the world including in the Himalayas to bypass chronic landslide prone areas. Numerous challenges have been faced during the construction of these tunnels in the Himalayas due to the presence of heavily jointed and weak rock mass conditions. The problems faced during tunnelling in such rocks include loosening of the rock mass and squeezing. Loosening results in the separation of the rock mass from the main body and produces a dead load requiring heavy rock support. Squeezing rock mass results in large deformation in tunnels where the state of stress following excavation exceeds the strength of the rock. If such rock mass conditions are not foreseen, then the cost of construction can escalate exponentially. This has occurred in many of the underground projects in the Himalayas where both time and resources have been underestimated prior to the commencement of a project such as a road, railway, or hydropower tunnel.

In view of the above, detailed feasibility studies are often warranted before the commencement of an important infrastructure project such as a road or a rail tunnel head race tunnel. The purpose of such a study is to gain an insight into the rock mass conditions for stability purposes, rock support requirements, for proper planning of construction and much more. Not conducting these investigations may lead to significant delays and cost over-runs, as experienced by the numerous projects where large and unforeseen problems occurred during construction. Modern tools such as airborne resistivity surveys using AEM (Airborne Electro-Magnetic) technology combined with ground based geophysical investigations and engineering geological mapping can help identify weak zones along the tunnel alignment thereby avoiding problematic areas which can save significant resources to the project. This paper describes how rock engineering challenges can be overcome for construction of climate resilient infrastructures in the Himalayas.

Figure 1 - Jammu-Srinagar road (293km) in the Himalayan region of Northern India

2. CASE STUDIES

Several bypass road tunnels are being made in the Indian Himalayas to shorten the communication routes and to avoid complex landslides, debris flows and snow avalanches. Along the Jammu-Srinagar road in Northern India (Fig.1), eleven tunnels are under construction in the Indian Himalayas (Goel et al., 2015). A 9.4 km long Chenani-Nashri tunnel (Now named as Dr. Shyama Prasad Mukherji tunnel), with a maximum overburden of 1,100 m, has been completed in the year 2017. The tunnel reduces the distance between Jammu and Srinagar by 30 km and cuts the travel time by about two hours. The tunnel, will bypass the snow and landslide prone Kud, Patnitop and Batote on the Jammu-Srinagar national highway. A view of the main tunnel adjoining the escape tunnel is shown in Fig. 2. Work on the other tunnel projects are underway and once constructed, these will reduce the length of 293 km between Jammu and Srinagar by 62 km, and the distance of 231 km in mountainous terrain will be covered in about 4 hours.

Figure 2 - A view of Chenani-Nashri main and escape tunnels (Photo: dailyexcelsior.com)

It is estimated that the reduced travel time will result in a saving of fuel worth USD 50,000 per day on traffic projections (NBM & CW, 2017).

Another tunnel in the Himalayas that has been completed is the Rohtang Pass tunnel in Himachal Pradesh in Northern India (Figs. 3a and 3b). The authors of this manuscript visited the portal of this tunnel, which is at 3000 m above sea level, during the design and planning stage of the tunnel and witnessed the complex geological and geotechnical conditions prevailing at the site. The tunnel was built under the Rohtang Pass in the eastern Pir Panjal range of the Himalayas on the Leh-Manali Highway. With 8.8 km (5.5 mi) tunnel length, this has reduced the distance between Manali and Keylong by about 60 km. Rohtang pass receives heavy snowfall and blizzards during winter months and was open for road traffic only four to six months in a year before the completion of the tunnel.

Figure 3a - The southern portal at Rohtang pass

3. MITIGATING LANDSLIDES IN BHUTAN HIMALAYA

Several tunnels are under planning in Bhutan Himalaya, which is located in Eastern Himalayas (Fig.1), to avoid major landslide areas. These include the Jumbja tunnel along the Phuentsholing-Thimpu highway and the Thimpu-Wangdue road tunnel to reduce the distance between the capital Thimpu and the town of Wangdue. Feasibility studies for both the tunnels has been performed (Bhasin et al., 2016). A major landslide called Jumbja landslide is located at about 42 km from Indian-Bhutan border town of Phuentsholing. This slide has a width of about 400 m (Fig. 4).

Figure 3b - The original road above the Rohtang pass (John Hill, 2007)

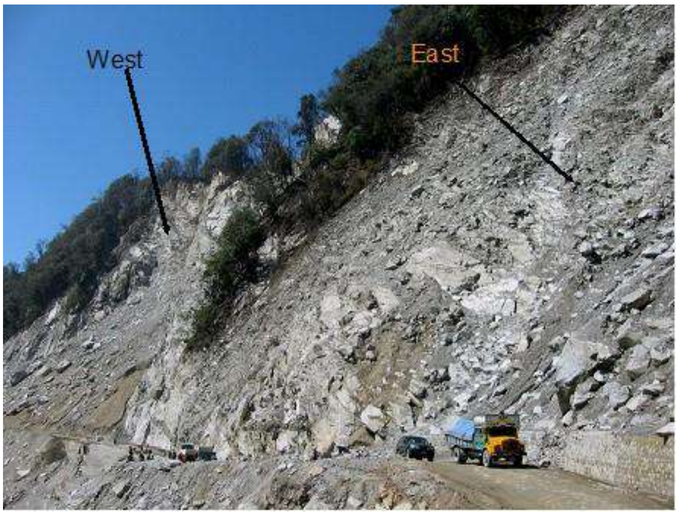

Figure 4 - The 400 m wide Jumbja slide in Bhutan

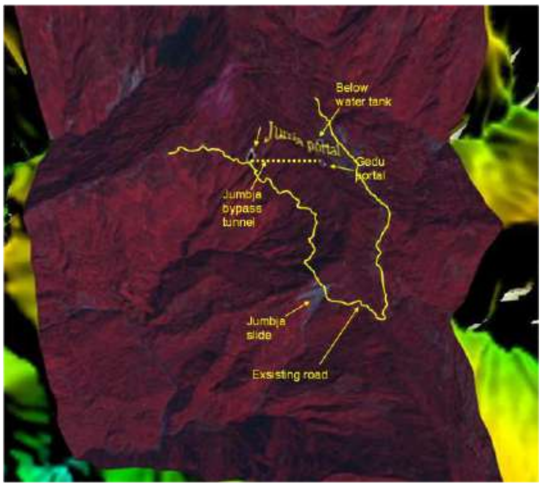

Figure 5a - Satellite image of the area showing the Jumbja slide

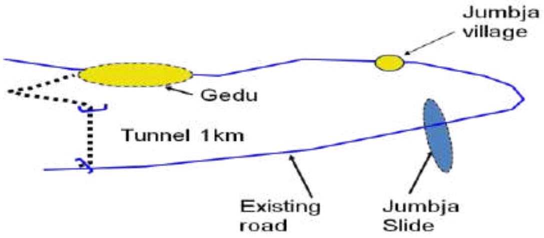

Figure 5b - Sketch of the area around the Jumbja slide

The landslide, which first came in the year 2000, was a rockslide in gneissic rock formation. At present, most of the slide consists of large boulders embedded in soil and the slide can be divided into a western and an eastern part. The short-term mitigation measures for stabilizing the slide included careful scaling of the rock mass, wire mesh on the slope to retain the unstable rock masses from loosening and falling down to the road. However, considering the scale of the landslide and the size of the loose blocks, the measures suggested would only serve for a short period of time. Hence, these were not implemented. The long-term mitigation measure would be to bypass the slide by constructing a tunnel near the affected area. Satellite images were procured and geotechnical investigation were carried out to plan the bypass tunnel as shown in Fig. 5a. A one km tunnel is planned through a ridge to bypass the Jumbja slide (Fig. 5b).

The rock mass conditions around the slide were characterized for tunnelling purposes. The Q-system of rock mass classification (Barton et al., 1974), developed at NGI, was used to derive the geotechnical parameters needed for predicting the performance of the rock mass. The rock quality around the site varies from highly competent to sheared and weathered rock.

The typical rock mass quality obtained from surface exposures in the western part of slide varied between the following Q-values:

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} = \frac{90}{9} \times \frac{1.5}{2} \times \frac{1}{1} = 7.5 \tag{1}$$

Corresponding to fair rock quality as given in Eq. 1, and

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} = \frac{50}{15} \times \frac{1}{6} \times \frac{1}{20} = 0.03 \tag{2}$$

Corresponding to extremely poor rock quality as given in Eq. 2.

With the above rock mass quality, tunnelling is feasible with appropriate tunnel support measures using the Q-system support chart (Fig. 6). It was established that the long-term benefits of constructing a tunnel to bypass the Jumbja landslide outweigh the short-term maintenance costs for the existing road in the landslide area. A simple cost-benefit analysis was conducted as shown underneath.

- The driving cost of a vehicle per km in Bhutan Himalaya is estimated to be slightly less than USD 1/km

- There are about 2000 vehicles that pass each day through the landslide affected area.
- The number of km saved, if one drives through a proposed tunnel (Fig. 5b) is estimated to be 7 km.
- The cost saving per day for all the vehicles ≈ 2000 ×1 × 7 ≈ USD 14,000
- The cost saving/year=14000x365 ≈ 5 million USD

It may be emphasized that the above cost saving is due to driving alone.

The cost for constructing a road tunnel in Norway in similar rock mass quality with ventilation and lighting is estimated to be USD 20,000 per meter i.e. This means that a one km long tunnel would cost approximately USD 20 million.

From the above analysis, it was concluded that in less than 5 years, savings in driving cost alone would repay the construction cost of tunnel. Some additional savings from constructing a tunnel that have not been highlighted above include saving in time and increased safety etc.

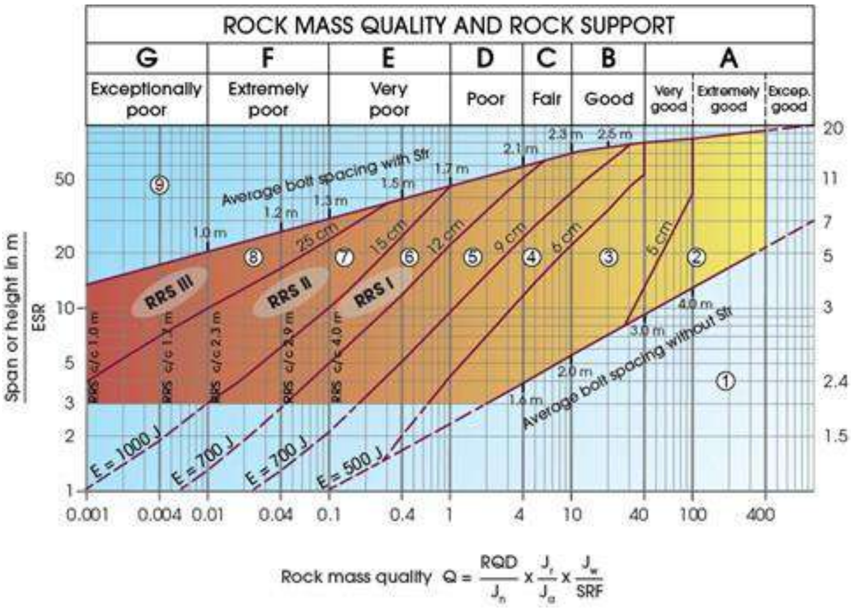

Figure 6 - Rock mass quality Q related to the permanent rock support (NGI, 2017)

4. MITIGATING LANDSLIDES IN SIKKIM HIMALAYA

Sikkim is a relatively small state in Eastern Himalaya sandwiched between Nepal and Bhutan. There are frequent disruptions in transport communication routes throughout the state due to landslides. One major landslide, which has been investigated in the area, is the Burdang landslide on national highway 10 (Fig. 7a). The area near the Burdang landslide consists of metamorphic arenaceous and argillaceous rocks intruded by basic sills that have been metamorphosed to epidiorite and talcose phyllites. The landslide occurred in a phyllitic rock formation; the total volume of the released rock mass was between 100,000 and 200,000 m^3. After investigating the landslide and deriving the geotechnical parameters needed for predicting the performance of the rock mass, it was decided that a tunnel could be constructed beneath the landslide (Bhasin et al., 2002). Recently, the first author visited the site and observed that a relatively short tunnel about 50 m in length was constructed along the route whereas the rest of the slope has been stabilized through plantation and by construction of a retaining wall (Fig. 7b).

Figure 7a - The Burdang slide on National Highway 10

Figure 7b - Recent construction of a tunnel and retaining wall for mitigation of the Burdang landslide

5. NORWEGIAN CASES

In areas of difficult topography in Norway, hundreds of kilometers of tunnels have been constructed to help shorten road routes and permit development without disturbing the existing landscape. The great majority of the road tunnels constructed in Norway have been intended to improve transport conditions in rural district.

Before embarking on a tunnel project, there is always a discussion and debate in Norway on various mitigation measures for keeping the road safe and open throughout the year. A simple cost benefit analysis is performed taking into consideration the long-term benefits to the society as a whole. Very often, it is concluded that a tunnel is the best long-term solution that provides a good communication link to overcome the rough Norwegian topography with fjords and mountains where existing slope instability hazards exist (Grimstad, 1986). Some recent examples of tunnels constructed in rugged Norwegian topography are presented below.

5.1 Laerdal Tunnel

The Laerdal tunnel is the World's longest road tunnel with a length of 24.5 km. It was built to have an all-weather connectivity between the two largest cities Oslo and Bergen through the European highway E16. The Laerdal tunnel is a D-shaped road tunnel with an excavation size of 56.5 m^2. The maximum theoretical vertical stress was about 39 MPa and the major stress was sub-horizontal. The tunnel avoids difficult mountain crossings, which are open only about 5 months annually (Fig. 8) and make a ferry free connection between Norway's two largest cities. There was no connection without a long ferry link that took approximately 1 hour. Another improvement is that the inner part of the County Sogn and Fjordane has got a new and safe link to Bergen, the capital of west Norway. The tunnel has a maximum overburden of 1450 m, which corresponds to a vertical stress of approximately 39 MPa. During the excavation, spalling and rock burst were observed in large parts of the tunnel. The tunnel had a maximum overburden of 1450 m and rock burst and spalling were encountered when the overburden was over 1000 m. In areas with intensive spalling and rock burst, cracks were developed in the sprayed concrete during construction, even when proper rock bolting was carried out. The cost of the tunnel, which was completed in the year 2000, was about 1 billion NOK. Figure 9 shows the entrance and one of the safety caverns allowing a U-turn for long vehicles inside the road tunnel. The Q-system was used to classify the rock and the Norwegian Method of Tunnelling (NMT) principles were used for the construction of the tunnel (Grimstad and Kvale, 1999).

Figure 8 - Summer-road above the Laerdal tunnel

Figure 9 - Entrance to Laerdal tunnel (left) and a safety cavern inside World's longest road tunnel (right)

Typical recorded rock mass qualities from the tunnel were:

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} = \frac{90-100}{3} \times \frac{4}{1} \times \frac{1}{200} = 0.6-0.7 \tag{3}$$

In the above case, massive rock is affected by heavy spalling and rock burst immediately after blasting.

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} = \frac{80-100}{6} \times \frac{1.5}{1-2} \times \frac{1}{1-5} = 2.0-25 \tag{4}$$

In this case, no sign of stress could be observed at the face but deformations may occur and therefore the SRF value is up to five.

The tunnel, which is one of many that lies along the European Route E16, allows uninhibited flow of traffic while preserving the alpine environment of the region.

As mentioned earlier, many places in Norway, where natural hazards such as landslides and rock fall exist, have been linked by tunnels. Some other examples are given underneath.

The Bjørkås tunnel was completed in 2016 to avoid rock fall hazards on an existing road in the south-west of Norway. The Norwegian construction company Risa built the tunnel that is about 1.4 km long. Figure 10 clearly shows the advantages of constructing such a tunnel for the safety of people by avoiding slope instabilities. The Bjørkås tunnel was constructed to avoid frequent rock falls on the existing road. Since the tunnel is located in the North of Norway where the temperatures remain below zero for many months of the year, freezing and thawing of the jointed rock led to opening of the cracks resulting in frequent rock falls. The span of the tunnel is 9.5 meter and is D shaped.

Figure 10 - Bjørkås tunnel bypassing hazardous rock fall areas along the coast

In the Himalayas, there exists many roads where half tunnels have been constructed (Fig.11). These roads can be moved inside the mountain valley side by constructing tunnels similar to the Bjørkås tunnel.

Another example in Norway is the European highway number 6 (E6) Nordnes-Skardal tunnel to avoid rock fall along the coastal road. This tunnel is close to the city of Tromsø, which is beyond the Arctic Circle. Figure 12 shows a map of the area and the frequent rock falls, which occurs on the road. The constructed tunnel is 5.8 km long and has reduced the distance in E6 by 8 km. The theoretical profile of the tunnel is 9,5m where the speed of vehicles can be up to 90 km/hour. Figure 13 shows the constructed portal of the tunnel to bypass rock fall areas.

Figure 11 - Half tunnels in Himachal Pradesh, India

Figure 12 - Rock fall on the road in Nordnesfjellet (North Norway near Tromsø)

Figure 13 - The entrance to Nordnes tunnel from the Mandalen side

6. SPECIAL FEATURES OF THE NORWEGIAN TUNNELLING TECHNOLOGY

One of the key features of Norwegian Tunnelling Technology is that tunnel and cavern support selection is based on the rock mass classification with the Q-system. The Q-system is designed to assist in feasibility studies, site characterization when mapping rock exposures, and is used systematically once tunnelling begins (Barton and Grimstad, 2014). The Q-system, needs to be used by engineering geologists with some reliable training and experience. Based on the Q-system and on the principles of Norwegian Tunnelling, a single-shell support method is advocated in contrast to the expensive double-shell NATM-style (New Austrian Tunnelling Method) tunnelling. There are no contribution or consideration of any temporary supports in Norwegian Tunnelling as in NATM. The temporary support in Norwegian Tunnelling is a part of the permanent support. In Norwegian Tunnelling care is taken in the choice and quality of rock support and reinforcement components which include bolting, fibre reinforced shotcrete and if needed reinforced ribs of shotcrete (RRS). The use of steel sets is avoided in Norwegian Tunnelling and has been replaced by RRS, which requires experienced workmanship (Fig. 14).

The execution of RRS is described by Grimstad et al. (2003) and in NPRA Technology Report No. 2538 (2010). NGI has instrumented several sections of RRS in tunnels and has numerically modelled RRS to verify and calibrate the load and rock support requirements in tunnels (Bhasin et al., 1999). Arches can be built with curved pre-deformed 20 mm diameter rebars with the arch foot founded and anchored to the rock by long anchors or casting of the invert. The above technology report also describes the execution of spiling bolts and forepoling in combination with reinforced ribs of shotcrete (Fig. 15). The combined method ensures that spiling bolts will have anchoring both inside the rock mass ahead of the blast round and in the shotcrete arch at the face (Berggren et al., 2014). Cast-in-place invert slabs are described for Rock Mass Classes with extremely adverse rock mass quality.

Rail Vikas Nigam Limited (RVNL) is the first organization in the country that has successfully implemented RRS in their ongoing rail tunnel project in Rishikesh. The second author has been instrumental in the successful implementation of RRS in various pilot tunnels. The costs of rock support using RRS in poor to extremely rock masses i.e., Q values ranging from less than 4 to 0.001, have ranged from 5 to 11 lakh Indian rupees per metre in the tunnel depending upon the rock mass quality in the year 2021. These costs are more or less in the same range as those experienced in Norway under similar rock conditions. It is estimated that using traditional steel ribs or cast concrete arches in such rock mass conditions would have more than doubled the cost of rock support. The third author has experience from a head race tunnel in Tala Hydroelectric project where extremely poor rock mass conditions were encountered and traditional steel sets and cast concrete arches were used in addition to umbrella arch. The per meter cost of tunnel in that zone was estimated to be more than Rs. 20 lakh when constructed in year 2003.

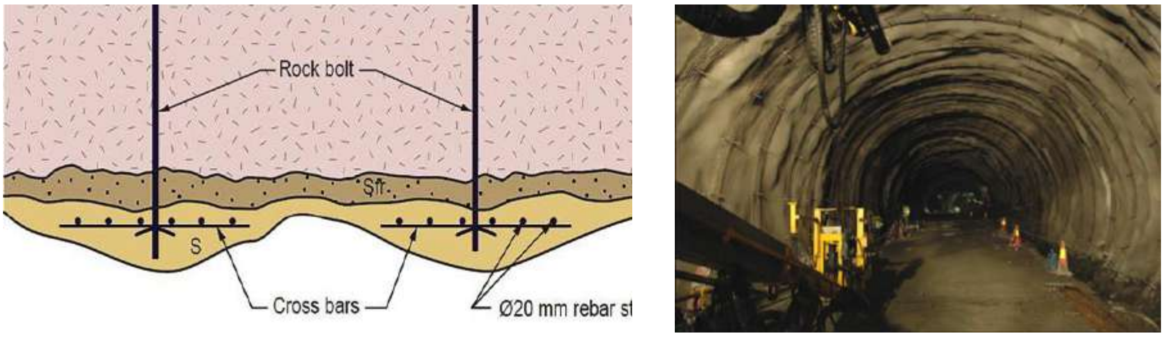

Figure 14 - RRS and its execution in a tunnel in Oslo (Grimstad et al., 2003; NPRA, 2010)

7. TUNNEL SUPPORT STRATEGY IN SEISMIC REGIONS

In the Himalayas any tunnel support strategy should take into consideration the effect of seismicity in tunnels. Barton (1984) advocated the use of simple rule of thumb to select appropriate rock reinforcement for underground structures in seismic regions. Based on the Q-system of rock mass classification (Barton et al., 1974), it was suggested that the rock mass quality number ‘Q’ in seismic regions may be assumed as half compared to Q-static (Eq. 5).

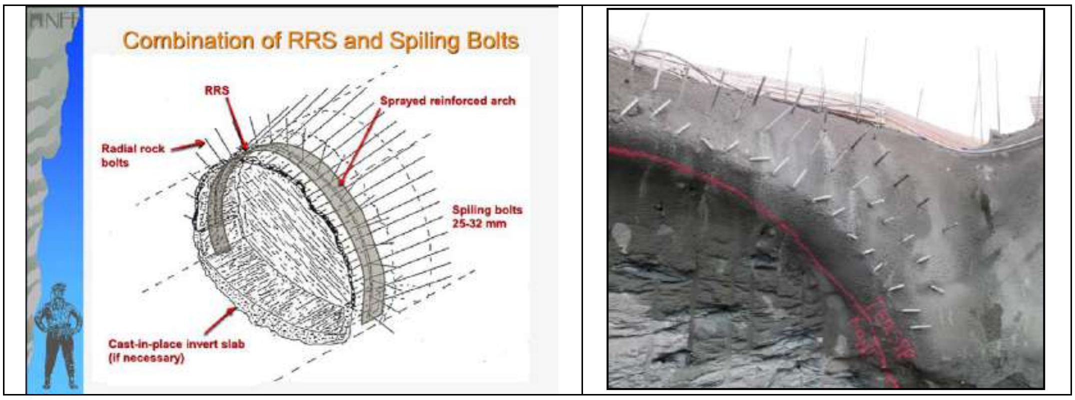

Figure 15 - Principle of combined RRS and spiling bolts (NPRA, 2010) (left), spiling bolts and sprayed concrete in a tunnel in Norway

The 50 % reduction of Q (static) obtained by assuming 2. Stress reduction factor (SRF) in Eq.1 actually gives a 25% increase in support pressure, due to the gradient of the slope in Figure 16. This 25 % increase was surprisingly in the range of 15-44% increase in maximum axial force that was observed for seismic conditions through numerical modelling studies (Bhasin et al., 2008). The above tunnel support strategy agreed well with the numerical studies carried out. It is however, important to add that the use of rock mass reinforcement and tunnel support method such as the Q-system will not be appropriate in cases where adverse geological features such as wedges or faults exists. Such cases warrant special design of reinforcement based on the orientation and strength-deformation properties of the geological features (Mitra and Singh, 1995).

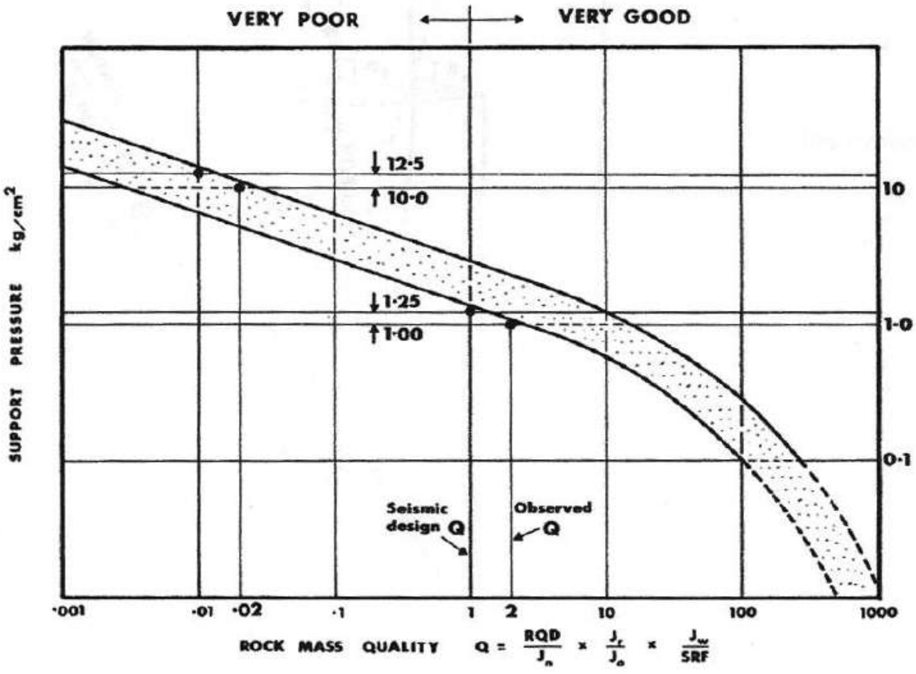

Figure 16 - Seismic reduction of Q-value to obtain 25% increase in support pressure (Barton, 1984)

8. CONCLUSIONS

This paper has provided some examples of tunnelling to bypass major landslide areas in the Himalayas and in Norway. It is experienced that tunnelling is a long-term environment-friendly solution to combat major landslides in mountainous areas with rugged terrain. Several hundreds of kilometers of road and rail tunnels have been built in Norway to combat major landslide and rock fall areas. Cost benefit analysis indicate that in some cases the cost of building a tunnel can be repaid by savings in driving costs in about 5 years due to the reduced driving distances. The other benefits of constructing tunnels in landslide areas include savings in time and increased safety. More than 5000 km of tunnels have been constructed in Norway over the past few decades using Norwegian tunnelling techniques. The application of updated rock support techniques including reinforced ribs of shotcrete (RRS) has replaced the use of passive steel sets in underground support in Norway and the same methodology is being applied in India very effectively. The use of single shell rock support technique in Norwegian tunnelling is considered fast, safe and cost effective. This technology has a good potential to be used for underground excavations in the Himalayas.

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