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# *Case Studies of Tunnels to Bypass Major Landslides in the Himalaya*

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## ABSTRACT

Tunnelling is considered as a long-term environmentally friendly solution to combat major landslides in hilly areas, especially in the complex and rugged terrain of the Himalaya. Recently several new road tunnels have been constructed in the Himalaya to bypass major landslide prone-areas for keeping the communication routes open throughout the year. Simple cost benefit analysis indicate that bypassing chronic landslides through tunnels are much more advantageous in the long-term than maintaining and repairing major landslide prone areas. In several European countries including Norway, several thousand kilometers of tunnels have been constructed to avoid unstable sloping areas and for keeping the communication routes open throughout the year. In this paper, some examples are presented which show how tunnelling solutions can outweigh the costs of maintaining landslide prone area in the Himalaya. Some aspects of Norwegian Tunnelling Technology, which is considered safe and cost efficient, are presented. The application of updated rock support techniques, including reinforced ribs of shotcrete (RRS), which is a key component of the Norwegian Method of Tunnelling (NMT), is highlighted.

***Keywords:*** Tunnel; Landslide; Q value; NMT; Cost benefit analysis

## 1. INTRODUCTION

Tunnelling to bypass major landslide areas is considered as a good and long-term solution to reduce an existing hazard. Many governments throughout the world are considering tunnelling technology to overcome the country's hilly terrain, especially in landslide-prone areas. In Norway, hundreds of kilometers of tunnels have been constructed in areas prone to landslides and snow avalanches. The Norwegian Tunnelling Technology is considered safe, efficient and cost effective compared to other tunnelling techniques such the New Austrian Tunnelling Method (Barton et al., 1992, Grimstad and Barton, 1993). This paper presents some case studies where tunnels have been constructed to bypass landslide prone areas. A simple cost-benefit analysis is presented for a tunnel to bypass a major landslide area in the Himalaya. This case shows that the advantages of constructing a tunnel outweigh the maintenance costs for keeping the road open to vehicular traffic.

## 2. HIMALAYAN CASE STUDIES

Several bypass road tunnels are being made in the Indian Himalaya to avoid complex landslides, debris flows and snow avalanches. Along the Jammu-Srinagar road, 11 tunnels are under construction in the Indian Himalaya (Goel et al., 2012). A 9.4 km long Chenani-Nashri tunnel, with a maximum overburden of 1,100 m, has recently been completed. The tunnel reduces the distance between Jammu and Srinagar by 30 km and cut travel time by 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 Figure 1. Work on the other 12 tunnel projects (also part of Jammu-Srinagar Highway's four-lane highway project) is in full swing. Once constructed, these will reduce the length of the 293 km between Jammu and Srinagar by 62 km, and the distance of 231 km will be covered in 4-4.5 hours. It is estimated that the reduced travel time will result in a saving of fuel worth Rs 27 lakh per day on traffic projections (www.nbmcw.com/metro-tunneling/36371-chenani-nashri-tunnel-an-engineering-marvel.html).

The National Highways and Infrastructure Development Corporation Ltd (NHIDCL) has decided to apply the same technology for the upcoming 14 km Zoji la tunnel between Leh and Srinagar.

Fig. 1 - A view of Chenani-Nashri main tunnel and adjoining escape tunnel (photo: dailyexcelsior.com)

Another tunnel that is currently under construction is the Rohtang Pass tunnel (Fig. 2). The authors of this manuscript visited the portal of this tunnel during the design and planning stage with personnel from CSMRS. The tunnel is being built under the Rohtang Pass in the eastern Pir Panjal range of the Himalaya on the Leh-Manali Highway. With 8.8 km (5.5 mi) length, the tunnel is expected to reduce the distance between Manali and Keylong by about 60 km. Rohtang pass receives heavy snowfall and blizzards during winter months and is open for road traffic only four months in a year. Lying on the Manali-Leh axis, this is one of the two routes to Ladakh. The other route through the Zojila pass on the Srinagar-Drass-Kargil-Leh highway also gets blocked by snow for nearly four months in a year.

Fig. 2a - The southern portal at Rohtang Pass (HT photo)

Fig. 2b - The existing road above the Rohtang Pass

Several tunnels are under planning in Bhutan Himalaya to avoid major landslide areas. These include the Jumbja tunnel along the Phuentsholing-Thimpu highway and the Thimpu-Wangdi road tunnel to reduce the distance between the capital Thimpu and the town of Wangdi. NGI has performed feasibility for both the tunnels. The Jumbja landslide is located at about 42 km from Phuentsholing and has a width of about 400 meters (Fig. 3).

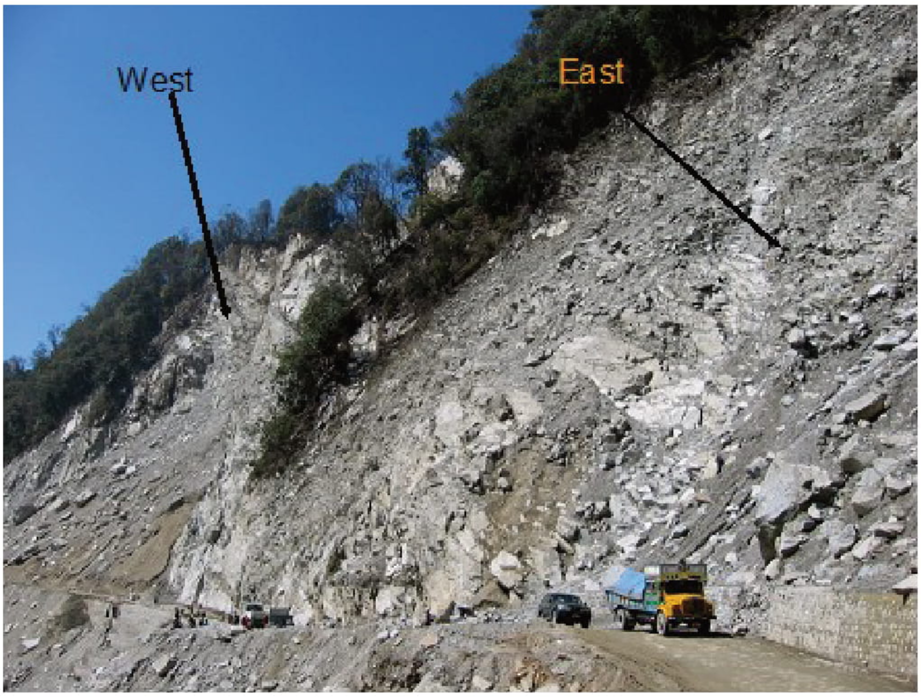

Fig. 3 - The 400 m wide Jumbja slide

The slide, 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 include 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. Flexible wire mesh fences can be constructed on the slope to capture the moving rock blocks. 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 relocated road has sunk several meters, because the road is founded on old scree mixed with soil, which is creeping downhill.

The long-term mitigation measure would be to bypass the slide by constructing a tunnel near the affected area. Satellite images were procured to plan the bypass tunnel (see Fig. 4a). A one km tunnel is planned through a ridge to bypass the slide (Fig. 4b).

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:

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} = \frac{90}{9} \times \frac{1.5}{2} \times \frac{1}{1} = 7.5 \qquad \text{Fair rock quality}$$

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} = \frac{50}{15} \times \frac{1}{6} \times \frac{1}{20} = 0.03 \qquad \text{Extremely poor rock quality}$$

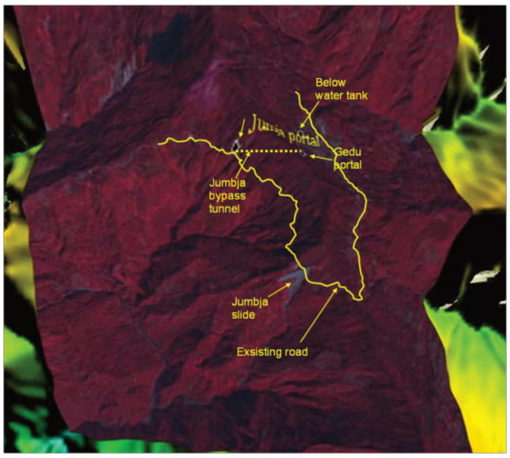

Fig. 4a - Satellite image of the area showing the Jumbja slide

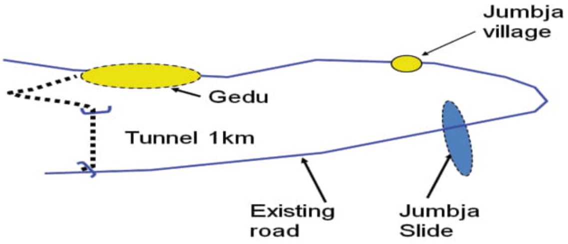

Fig. 4b - Sketch of the area around the Jumbja slide

With the above rock mass quality, tunnelling is feasible with appropriate tunnel support measures using the Q-system support chart. 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 is estimated to be Nu or ₹ 20/km
- There are about 1500 vehicles that pass each day through the landslide affected area
- The number of kilometers saved if one drives through a proposed tunnel is estimated to be 7 km
- The cost saving per day for all the vehicles ≈ 1500 ×20 × 7 ≈ ₹ 210,000
- The cost saving/year ≈ ₹ 7.7 crore or ₹ 77 million

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 ₹ 700,000 per meter i.e. 7.0 lakh ₹ /meter. This means that a one km long tunnel would cost approximately ₹ 700 million or Nu 70 crore.

From the above analysis, it was concluded that in less than ten years savings in driving cost alone would repay the construction cost of tunnel. There are some additional savings from constructing a tunnel that have not been highlighted above.

Another example of a planned road tunnel in Bhutan is the Thimpu-Wangdi tunnel for which NGI has carried out a detailed feasibility study. The case study involves the planning of a new road tunnel in the Bhutan Himalaya between the capital, Thimpu, and Wangdue (Fig. 5). Both cities are fast growing areas in Bhutan and the existing 70 km long road between Thimpu and Wangdue is not well suited for this increased traffic. The road is steep, winding, narrow, and goes over the Dochu La pass at about 3100 m. In addition, there exists ice and snow in winter, and unstable road cuttings and slopes during the rainy season, which have caused repeated problems. The improvement of the old road is not considered relevant and a new road link was proposed. This new road would reduce the traveling distance by 36 km. It would, depending on the options, include either a 10.5 or 14.5km long tunnel. The construction of the tunnel, including the choice of the most favorable route and the design of the rock support, was studied using a broad range of methods, from geological surveys to geophysical investigations, including also numerical simulations and cost analyses. Details concerning this example were presented in the Indorock conference in 2016 (Bhasin et al., 2016). Advanced airborne electromagnetic AEM surveys were performed along the tunnel corridor to provide information on the rock mass quality along the potential tunnel alignment and for visualizing the existing sub-surface geological conditions (Fig. 6). Specifically, high resistivity areas i.e. competent bedrock was distinguished from low resistivity areas i.e. incompetent or weathered rock. The Airborne Resistivity method (AEM) is based on the physical effect of electromagnetic induction where an electrical current is induced in the ground and thus a secondary magnetic field is created. This secondary magnetic field is governed by the electrical resistivity of the ground. AEM systems measure the EM time decay or frequency response and the related resistivity distribution is subsequently obtained by inverse modelling. Time-domain systems (TEM) measure an EM step response decaying with time. They are generally well suited for deeper investigations due to the higher transmitter moment. Some TEM systems can provide highly accurate and well calibrated data.

AEM data provides a powerful tool for geotechnical projects due to coverage and survey speed. Significant cost reductions can be achieved by planning geotechnical drillings based on the preliminary geological model derived from AEM. Integrated with AEM, limited drilling sites can be linked and combined to a model covering the complete area of interest (for details see Bhasin et al., 2016).

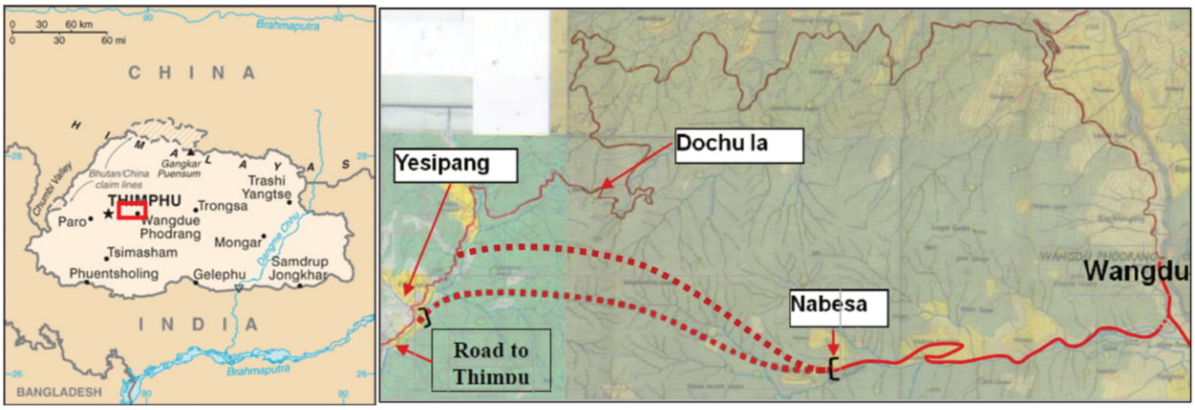

Fig. 5 - Location of the 70 km long old road over Dochu La pass (3100 m) and the two new road tunnel options (red doted lines) from Yesipang to Nabesa

Fig. 6 - Preparation for AEM survey (left) and performing AEM survey along tunnel alignment

## 3. MITIGATING LANDSLIDES IN SIKKIM HIMALAYA

Detailed engineering geological investigations were performed on landslides in the Sikkim Himalaya in connection with NGI's institutional cooperation project with the Central Soil and Materials Research Station in New Delhi (Bhasin et al., 2002). Emphasis was placed on investigating the four landslides that caused significant damage to life and property in Sikkim, namely Chanmari landslide, Tathangchen landslide, Six-mile landslide and Burdang landslide.

For the Burdang landslide, it was suggested by the authors in 2002 that a 300-m-long rock tunnel should be constructed beneath the landslide to keep highway open between the capital Gangtok and the lower elevation throughout the year. This would provide a long-term solution to the slope problem along this route. 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 $m^3$. The entire landslide covers an area of approximately 100,000 $m^2$. Recently the first author visited the site and saw that a relatively short tunnel about 50 m in length has been constructed along the route whereas the rest of the slope has been stabilized through plantation and by construction of a retaining wall (Figs. 7a and 5b).

Figs. 7 a & b - The Burdang slide adjacent to the river Tista in Sikkim and the recent construction of a tunnel and retaining wall for mitigation of the landslide

## 4. 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 and Kvale, 1999). Some recent examples of tunnels constructed in rugged Norwegian topography are presented below.

### 4.1 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 year connectivity between the two largest cities Oslo and Bergen through the European highway E16. 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 (Grimstad and Kvale, 1999). During the excavation, spalling and rock burst were observed in large parts of the tunnel. 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 (about 8 billion Rupees). 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).

Fig. 8 - Photos showing the summer road above the Laerdal tunnel (commons.wikimedia.org/wiki)

Fig. 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 (Grimstad, 1999),

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

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

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

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 Bjorkaastunnel was recently 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.

Fig. 10 - Bjorkaastunnel bypassing hazardous rock fall areas along the coast

In the Himalaya 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 Bjørkåstunnel.

Another example in Norway is the E6 Nordnes-Skardal tunnel to avoid rock fall along the coastal road. This tunnel is close to the city of Tromso, 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. Figure 13 shows the constructed portal of the tunnel to bypass rock fall areas.

Fig. 11 - Half tunnels in Himachal Pradesh

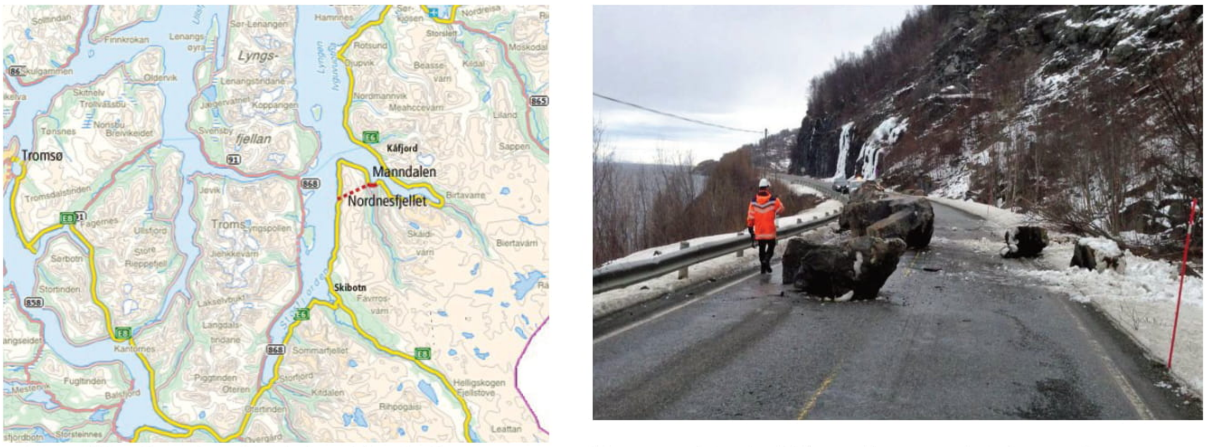

Fig. 12 - Nordnesfjellet in North Norway near Tromsø, Rock fall on the road (Tatensveivesen, Kåfjord commune)

Fig. 13 - The entrance to Nordnestunnel from the Mandalen side (*Photo*: Jan Arild Hansen)

## 5. SPECIAL FEATURES OF NORWEGIAN TUNNELLING TECHNOLOGY

One of the key feature 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 tunnelling. There are no contributions or considerations 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 good workmanship (Fig. 14). The execution of RRS is described by Grimstad et al., 2003 and in NPRA Technology Report No. 2538 (2012). 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.

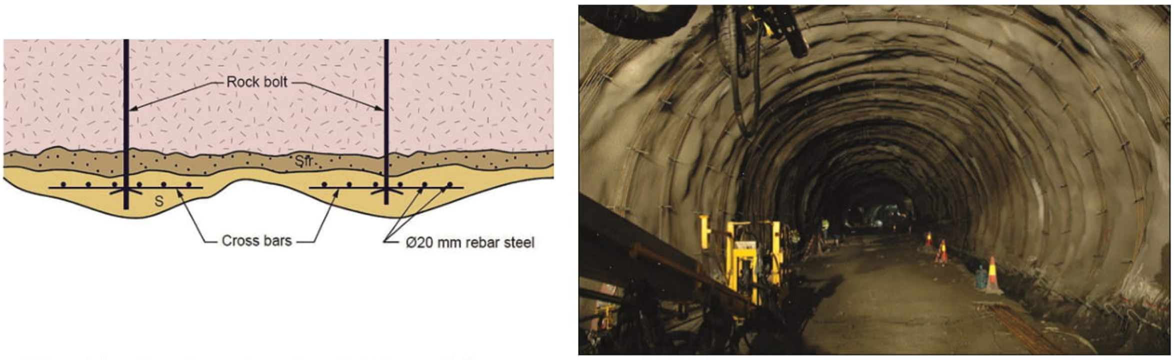

Fig. 14 - Section showing RRS and the execution of RRS in a tunnel in Oslo (Grimstad et al., 2003 and NPRA, 2010)

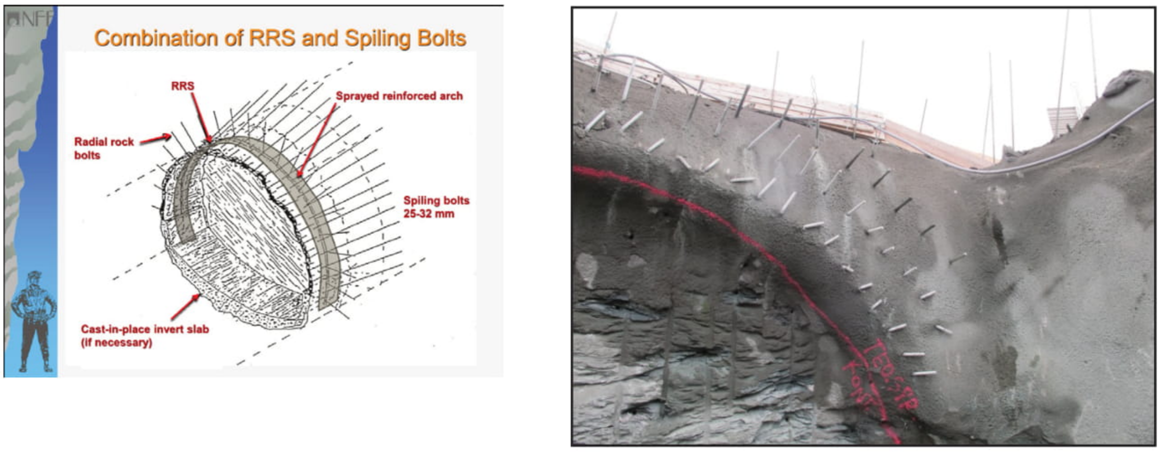

Fig. 15 Principle of combined RRS and spiling bolts (NPRA 2010) (left), spiling bolts and sprayed concrete in a tunnel in Norway (right)

## 6. CONCLUSIONS

This paper has provided some examples of tunnelling to bypass major landslide areas in both in the Himalaya and in Norway. It is experienced that tunnelling is a long-term environmentally 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 over a period of 5-10 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 kilometers 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 shotctrete (RRS) has replaced the use of passive steel sets in underground support in Norway. 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 Himalaya.

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