Application of Norwegian Method of Tunnelling (NMT) principles to bypass landslides in mountainous terrain

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ABSTRACT: Tunnelling to bypass major landslide areas is considered as a good and long-term environmentally friendly solution to reduce an existing hazard. In Norway, hundreds of kilometres of tunnels have been constructed in areas prone to landslides and snow avalanches. Although tunnelling is considered as an expensive mitigation strategy for bypassing landslides, analysis indicate that in some cases the cost of building a tunnel can be repaid by savings in driving costs (fuel) alone over a period of 5-10 years due to reduced driving distances. The other benefits of constructing tunnels in landslide areas include savings in time and increased safety. The Norwegian Method of Tunnelling (NMT) is considered safe, efficient and cost effective compared to other tunnelling techniques. Some aspects of NMT, which are considered safe and cost efficient, are presented. The application of updated rock support techniques, including reinforced ribs of shotctrete (RRS), which is a key component of the Norwegian Method of Tunnelling (NMT), is highlighted.

1. INTRODUCTION

The Norwegian Method of Tunnelling (NMT) was originally coined by a group of reputed engineers from various Norwegian consulting and construction companies to distinguish the tunnelling philosophy of Norway from the New Austrian Tunnelling Method (NATM) (Barton et al. 1992). It was pointed out that NATM appeared more suitable for soft ground where jointing and over break were not dominant and monitoring played an important role in deciding on the timing and type of secondary support. It was also stated that NMT appeared suitable for hard ground where jointing and over-break were dominant and where drilling and blasting or hard rock TBM's were the most common methods of excavation. Over the past two decades, several new tunnels have since been constructed in Norway in relatively weak and poor rock conditions using the NMT method wherein flexible rock support with reinforced ribs of shotcrete (RRS) has been used. This paper describes the application of NMT principles to bypass major landslides in mountain terrain with examples from Norway. Although tunnelling is considered as an expensive mitigation strategy for bypassing landslides, some simple cost-benefit analysis indicate that the advantages of constructing a tunnel outweigh the maintenance costs for keeping the road open to vehicular traffic (Bhasin et al., 2019). These analysis indicate that in some cases the cost of building a tunnel can be repaid by savings in driving costs alone over a period of 5-10 years due to reduced driving distances (Bhasin et al., 2016). The other benefits of constructing tunnels in landslide areas include savings in time and increased safety.

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2. NORWEGIAN METHOD OF TUNNELLING PRINCIPLES

The principles of Norwegian Tunnelling are well documented in a publication by the Norwegian Tunnelling Society (NFF, 2017). In Norway, several thousands of kilometre of tunnels were constructed after the Second World War to transport water for producing hydropower in the country. Tunnels and underground caverns for the hydroelectric power development dominated into the nineteen eighties, which was followed by road and rail tunnels to improve the communication link in the country. Norwegian tunnelers have constructed a number of pioneering projects which includes the World's Largest Man-Made Cavern for public use commonly known as Norway's Olympic Ice Hockey Cavern near the city of Gjovik and the World' longest road tunnel known as Laerdal tunnel which has a length of 24.5 km long.

Some of the key components of NMT, which are considered essential for the design of tunnels to bypass landslides, are described underneath. These include:

- Rock mass characterization using the six *Q*-system parameters
- Rock support design measures using the updated *Q*-support chart
- Site investigations using ground and/or airborne surveys
- Numerical verification of the rock support

3. ROCK MASS CHARACTERIZATION AND DESIGN OF ROCK SUPPORT

In NMT great emphasis is placed on a thorough description of geological and geotechnical aspects of the project (Barton et al., 1992). The Q-system is an empirical method providing a quantitative evaluation of the rock mass based on the structure of the rock mass, its roughness & frictional characteristics and active stress conditions. The rock tunnelling quality *Q* is considered a function of three parameters which are crude measures of:

- Block size $(\frac{RQD}{J_n})$
- Inter block shear strength $(\frac{J_r}{J_a})$
- Active stress $(\frac{J_w}{SRF})$
- The Q-value is expressed by

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \quad (1)$$

The numerical value of *Q* ranges from 0.001 for exceptionally poor quality squeezing ground up to

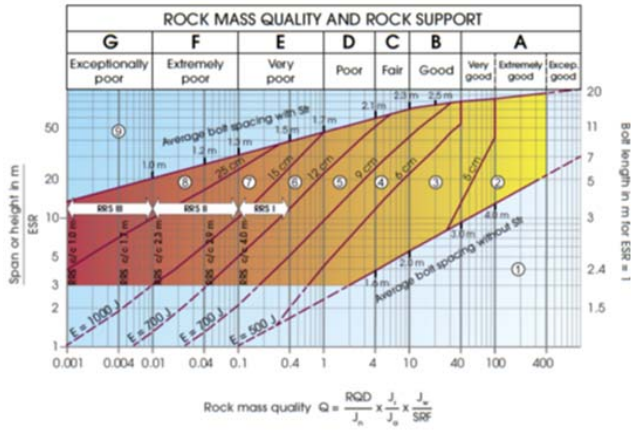

Figure 1. Q-system support chart (Barton and Grimstad 2014 & NGI 2015)

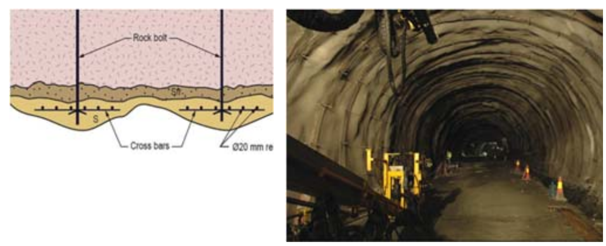

Figure 2. Section showing RRS and the execution of RRS in a tunnel in Oslo (Grimstad et al. 2003 and NPRA. 2010)

1000 for exceptionally good quality rock, which is practically unjointed (Barton et al. 1974). Based on the *Q*-value and dimensions of the opening, the rock support in a tunnel can be selected using the *Q*-system support chart as shown in Fig. 1.

One of the key feature of the rock support chart is the recommendation of reinforced ribs of shotcrete (RRS) which has practically replaced relatively expensive rock support techniques such as lattice girders, steel ribs and cast concrete arches. Fig. 2 shows a section of RRS and its execution in a tunnel in Oslo.

The arrangement of the 16 mm diameter reinforcing bars on a preliminary and smoothing shotcrete is shown in Fig. 3 before being covered by another layer of shotcrete, which may be 30 cm thick. This rock support structure is quite flexible. The RRS is bolted approximately at 1 m interval around the arch. The spacing of RRS along the tunnel length is dependent on the value of *Q* and the support chart shown in Fig. 1. provides guidelines for its spacing.

The execution of RRS is described by Grimstad et al. (2003) and in NPRA Technology Report No. 2538 (2010). NGI has instrumented several sections

Figure 3. Set-up of RRS comprising of six 16 mm diameter-reinforcing bars.

Figure 5. Finshed product showing tunnel support with RRS in a tunnel in Oslo (NPRA, 2010)

Figure 4. RRS along the tunnel length prior to shotcrete spraying

Figure 6. Performing geophysical surveys (AEM) along the tunnel alignment in hilly terrain in Bhutan

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). Fig. 4 shows the RRS along the tunnel length prior to shotcrete spraying. Fig. 5 shows the finished RRS product.

4. SITE INVESTIGATIONS

In the past few years, NGI has been utilizing airborne electromagnetic (AEM) surveys for carrying out site investigations for aligning the tunnel corridor. Advanced airborne electromagnetic AEM surveys are 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 can be distinguished from low resistivity areas i.e. incompetent or weathered rock (Fig. 7). The Airborne Electromagnetic (AEM) method 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.

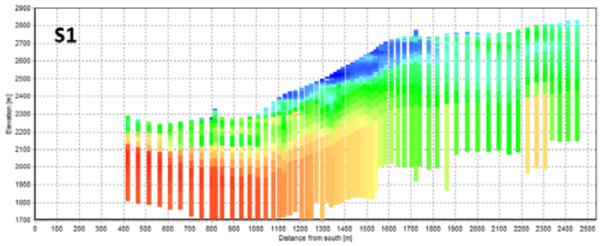

Figure 7. Results from AEM survey showing resistivity in a vertical section along a tunnel alignment, red is conductive (incompetent rock) while blue is resistive (competent rock)

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.

5. NUMERICAL VERIFICATION OF ROCK SUPPORT

Numerical verification of rock support is increasingly carried out to optimize the rock support selected using the *Q*-support chart in Fig. 1. The use of numerical codes for predicting rock reinforcement requirements in underground excavations in both static and dynamic conditions have proved to highly useful, especially in mountainous terrain (see e.g. Bhasin and Pabst, 2013; Bhasin et al., 2017). Complimentary analysis using both finite and distinct element techniques are usually performed to understand the rock mass deformation and verification of rock support selected using the *Q*-system. Dynamic and pseudo-static analysis may also be conducted to assess the behavior of the tunnel subjected to dynamic loads (earthquake).

Fig. 8 shows an example of the displacements around the periphery of the tunnel using the distinct element code UDEC. The numerical modelling results shown in this figure are for very poor to extremely poor rock qualities (*Q*-values from 0.4 - 0.04) for a planned road tunnel in the Himalayas.

In the above example, the failure of rock bolts and tunnel lining was modelled for providing a better insight into the behavior of the tunnel support with overburden. Thus, one can become better prepared to tackle the situation through extra reinforcements in the tunnel. Fig. 9 shows the bolts failure (in %) for various *Q*-values and overburden, under static and dynamic (earthquake or EQ) loadings. It can be clearly seen in this Figure that

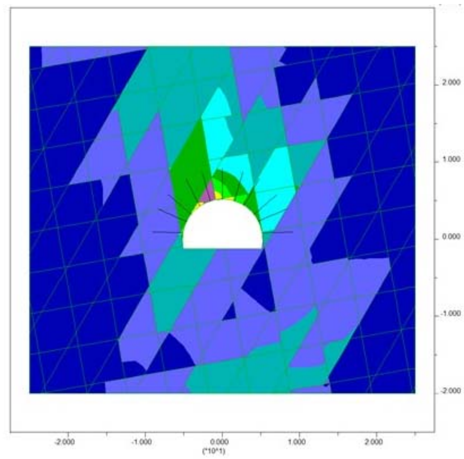

Figure 8. Example of results obtained with UDEC models showing displacements around the tunnel (Bhasin et al. 2017)

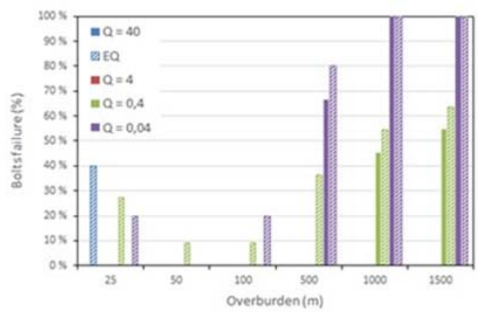

Figure 9. Bolts failure (in %) for various *Q*-values and overburden, under static and dynamic (earthquake or EQ) loadings (Bhasin et al. 2017)

with low *Q*-values and increased overburden there is an increased risk of bolt failure requiring a strengthening of the bolt-system. Similarly, the tunnel lining (RRS. etc.) can also be modelled for verifying different tunnel supports.

6. NORWEGIAN EXAMPLES OF ROAD TUNNELS BYPASSING UNSTABLE SLOPING AREAS

In areas of difficult topography in Norway, hundreds of kilometres 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.

6.1 South Kjostunnel project

This is a recent tunnel project, completed in 2018, to bypass an area exposed to unstable slopes with

Figure 10. Map of the area showing the existing road and the new tunnel alignment

Figure 11. Portal of the South Kjos tunnel

Figure 12. A 5.8 km long road tunnel has reduced the distance along the European Highway E6 by 8 km and has increased the safety along the road

frequent rock and snow avalanches. Fig. 10 shows a map of the area in the north of Norway beyond the Arctic Circle where the road tunnel has been constructed. Fig. 11 shows the portal of the tunnel.

The principles of NMT were utilized for constructing the 4.5 km long tunnel where the average cost of the tunnel per meter was estimated to be about 9,700 Euros.

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 also beyond the Arctic Circle. Fig. 12 shows a map of the area where frequent rock falls have occurred on the road.

The constructed tunnel, which opened in November 2019, is 5.8 km long and has reduced the distance of the European highway E6 by 8 km.

6.2 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, (see Fig. 13) 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

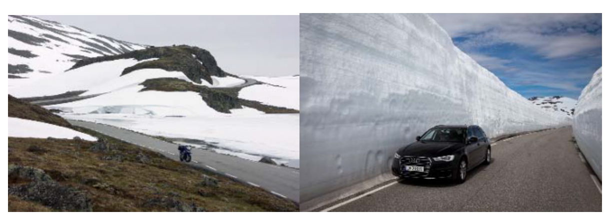

Figure 13. Photos showing the summer road above the Laerdal tunnel (commons.wikimedia.org/wiki)

Figure 14. Entrance to Laerdal tunnel (left) and a safety cavern inside World's longest road tunnel (right)

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. Fig. 14 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).

Typical recorded rock mass qualities from the tunnel were:

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

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

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} = \frac{80-100}{6} \times \frac{1.5}{1-2} \times \frac{1}{1-5} = 2.0 - 2.5$$

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.

7. CONCLUSIONS

This paper has provided some examples of tunnelling to bypass major landslide areas using the Norwegian Method of Tunnelling. 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 kilometres of road and rail tunnels have been built in Norway to combat major landslide and rock fall areas. The benefits of constructing tunnels in landslide areas include savings in time and increased safety. More than 5000 kilometres 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. 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 Vietnam especially along some parts of the Ho Chi Minh Highway, which is prone to frequent landslides.

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