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NMT for sustainable and environmentally friendly tunnelling in Nepal

Krishna Kanta Panthi

Norwegian University of Science and Technology (NTNU), S. P. Andersen veg 15a, 7491, Trondheim Norway
Corresponding author's email: krishna.panthi@ntnu.no

ABSTRACT

Recent weather pattern in Nepal indicates that there is a considerable impact on the weather system, which is believed to be due to both global and regional warming. The change in weather has started causing serious damage in the Himalayan region and elsewhere. The debate on the minimization of carbon emission through reduced use of fossil fuel has been ongoing for some couple of decades. However, the carbon emission caused by the production of cement and concrete has been less discussed and highlighted. In addition, unnecessarily excessive use of cement and steel is counterproductive due to increased project costs. Therefore, there is a strong need for the reduction in the use of construction material consisting cementitious and steel products while developing the infrastructure and hydropower projects in Nepal where use of underground space will be extensive in near future. Use of Norwegian Method of Tunnelling (NMT) could serve as an alternative to the reduced use of cement, concrete and steel products. This study highlights the principals used in Norwegian Method of Tunnelling (NMT), benefit it gives in the reduced use of concrete and steel, which helps to optimize project costs, contributes to reduce emission and assists to enhance sustainable development of infrastructure and hydropower projects in Nepal.

Keywords: Carbon emission; Hydropower projects; Norwegian method of tunnelling

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INTRODUCTION

Both Nepal and Norway are two mountainous countries searing almost similar topography and geology. Both countries have steep topography and deep valleys where many rivers originate from the top of mountains and follow along valleys before reaching the oceans. It is interesting to note that both countries have rock formations consisting of very young sedimentary, relatively old (older than 250 million years) and very old (over 600 million years) metamorphic and igneous rocks. This is unique. The differences between the two countries are the geo-tectonic environment and glaciation effects. First difference is that Norway has relatively stable tectonic setting with earthquake events that mostly occur with an intensity less than 5 Richter Magnitude (RM). On the other hand, Nepal is located at the tectonically active region where large scale earthquakes (more than 6 in RM) occur periodically. Secondly, Norway went through deglaciation process some 10 000 years ago, which led to wash away top layer of weathered rock material from the Norwegian Mountain Topography. Therefore, one can observe very thin layer of overburden soil in the Norwegian mountains unlike in Nepal (Fig. 1).

Regarding experience in the construction of underground space (tunnelling), Norway is far ahead than Nepal and has over 100 years of experience in modern tunnelling. Until present, Norway has constructed tunnels and underground caverns consisting over 7000 km length. Regarding underground space use for hydropower in Norway, almost 97 % tunnels and shafts are unlined or partly shotcrete lined. Optimized rock support consisting of shotcrete and bolting in road and railway tunnels and almost no concrete lining excluding few in urban areas having low rock cover. Norway is excavating over 60 km length of tunnels every year for last 60 years. On the other hand, though the modern tunnelling history in Nepal goes back to 1917 when excavation of Churiyamai tunnel (first transport tunnel in Nepal) was made, modern era of underground space development started after the construction of 1 MW Tinau Hydropower Project in 1970s. Tinau is the first hydropower project that has all components underground excluding the diversion dam. Til date, Nepal has managed to construct about 325 km length of tunnels and shafts for hydropower, irrigation, water supply and road infrastructures.

NORWEGIAN METHOD OF TUNNELLING (NMT)

Norwegian Method of Tunnelling (NMT) bases on the fact that in-situ stresses increase confinement in the rock mass and the rock mass can withstand load exerted to it. For jointed rock mass, withstand capacity is enhanced using rock support that consists of bolting / anchoring and application of steel-fiber shotcrete (in general less than 15 cm thick). Pre-excavation grouting is used for groundwater control. If weakness and fault zones with swelling clay are met in tunnels built for water convenience like headrace and tailrace tunnels, cast-in concrete is applied. Whereas, if weakness and fault zones are met in road and railway tunnels, combination of systematic bolting and RRS (Ribs of Reinforced Shotcrete) are applied. NMT uses in-situ stress information, empirical relations and numerical modelling in the design of tunnels and caverns (Panthi, 2024). Q-system (Barton et al. 1974; Grimstad and Barton 1993) is used for rock mass characterization, documentation of engineering geological information, estimation of rock support requirement during planning and design phases and preliminary rock support decision during construction. Preliminary rock support applied in tunnels and caverns is considered as part of final rock support (Barton et al. 2024) where addition of rock support is decided based on stability assessment using observational experience, empirical equations and numerical modelling. The successful application of NMT requires well-organized engineering geological investigations during planning, design and construction phases of underground excavations, well planned tunnelling equipment and well-trained tunnelling crew and risk searing approach to construction contracts (Panthi, 2025).

PLANNING AND DESIGN CONSIDERATIONS

Planning and design of underground structures should be made in such a way that the placement design of underground structures must provide cost effective, long-term stable and sustainable solutions. In NMT, this is achieved by considering rock mass as part of a structural element that counteracts any load exerted by either unloaded rock mass after excavation or hydrostatic water head acting during operation of hydropower plants. Any planning and design considerations should be based on the results from comprehensive engineering geological investigations. It is important that the aim of any design must be to achieve stability and long-term functionality of the underground structures (Panthi and Broch, 2022). There are four main aspects of planning and design of underground structures that govern the extent of cost and time optimization, total need of rock support and long-term stability. These planning and design aspects are location, orientation, size and shape of the underground structures under consideration. However, these aspects are dependent on for what purpose these underground structures are developed.

Location design

Finding the best location for an underground structure is the most important part of planning and design. For this a proper engineering geological investigation that defines the quality of rock mass prevailing in the topographic area where planned underground structures should be located is a prerequisite. There are mainly two modes of failure that occur in an underground excavation, which are block failure when pre-existing blocks in the roof and side walls are free to move after the excavation and stress failure when induced stresses around the excavation exceed the rock mass strength. This means, most of the instabilities in underground excavation are depth dependent. Near the surface, the in-situ stresses are an-isotropic, and discontinuities mainly control stability. On the other hand, in-situ stress magnitudes are increased at depth, and frequency of discontinuity occurrence are reduced due to enhanced confinement. Hence, the stability of an underground structure at greater depth is controlled by induced stresses. This means the stability conditions vary depending upon how and where an underground structure is located. In addition, the location of an underground structure is also dependent upon the functional requirement such as road and railway tunnels, tunnels and underground caverns for hydropower, water supply and irrigation as well as other utility uses. The Norwegian experience of development of unlined pressure tunnels and shafts paved good basis for location design of waterway system of hydropower, irrigation and water supply projects, which is recognized as Norwegian confinement criteria (NCC). In addition, there have been updates in the criteria based on both Norwegian and International experience. The following four equations (Broch 1982; Panthi and Broch 2022) are the basis for the placement design of the underground waterway system of hydropower plants.

$$h > \frac{P_w}{\gamma_r \times \cos\alpha} \quad (1)$$

$$L > \frac{P_w}{\gamma_r \times \cos\beta} \quad (2)$$

$$L > f_g \times \frac{P_w}{\gamma_r \times \cos\beta} \quad (3)$$

$$\sigma_3 > \rho_w \quad (4)$$

Where, h is the vertical height (m) from a given point of the waterway system, p_w is the hydrostatic water pressure (MPa) for a given point of the waterway system, γ_r is the specific weight of rock (MN/m3), β is the inclination angle of valley side slope (degrees), f_g is the factor of safety for multiple valleys and σ_3 is the minor principal stress (MPa). Fig. 2 below explains the conditions of waterway location.

Fig. 1: Steep topographic condition of both countries and differences in surface weathering.

Equation 1 and Equation 2 are valid for the conditions Fig. 2 left and Fig. 2 right top (1) whereas Equation 3 is valid for the conditions in Fig. 2 right (2 and 3). In addition, it is important that an underground waterway system should fulfil the requirement given by Equation 4 where the minor principal stress is always greater than the hydrostatic water head. If the waterway tunnels cross faults and shear planes, which attenuate the magnitude and orientation of in-situ stress situation, there is a need for a valid numerical modelling assessment.

The experience gained in Norway has also provided possibility to roughly locate long traversing tunnels of all kinds against potential rock burst / rock spalling situations in strong and homogeneous rock mass (rocks having strength exceeding 75 MPa). Figure 3 below is one of the empirical approaches that can be used for this purpose.

In addition, the increased computing capacity of computers in recent years makes it possible to do complicated 3D numerical modelling to assess in-situ stress condition. The numerical modelling assessment is important not only to assess the location but also the stability condition of all kinds of tunnels and underground caverns built for all kinds of infrastructures that involve use of underground space.

Fixing orientation

Fixing orientation is another important issue in planning and design of underground structures. It is necessary to optimize orientation of underground structure relative to the orientation of major discontinuities including weakness and fault zones. It is preferred to orient the length axis of underground structure along the bisection line of the maximum angle between two major joint systems orientation as indicated in Fig. 4. It is important to avoid orientation or an underground structure parallel with the orientation of any major joint set. In addition, one should have knowledge about the orientation of maximum horizontal principal stress with which an underground structure should orient with an angle between 15 to 40 degrees.

Moreover, during planning and design it is important to also evaluate the character of discontinuity surfaces which control the frictional properties. An underground opening with relatively high walls should have an angle of at least 25 degrees to steeply dipping planner joints or joints system filled with clay material.

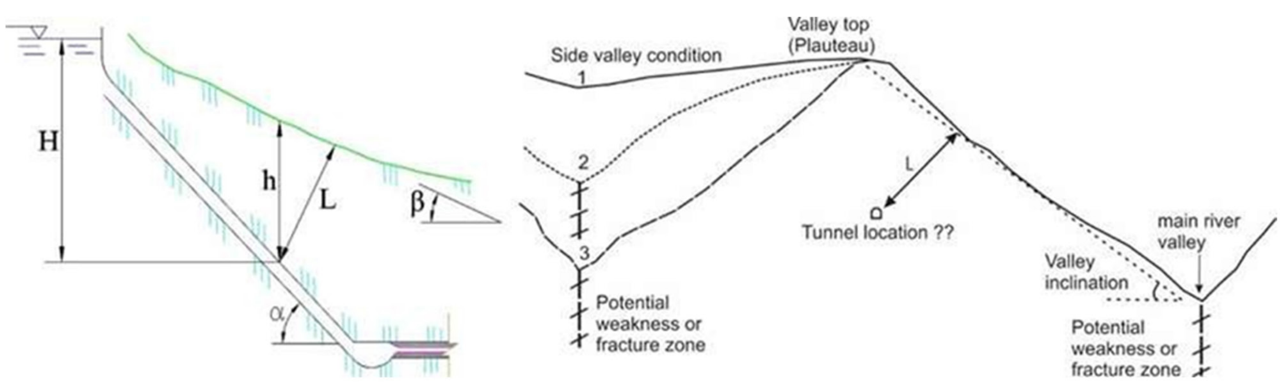

Fig. 2: Topographic condition for Eq 1 and Eq 2 (left) and for Eq 3 (right) (Panthi and Broch 2022).

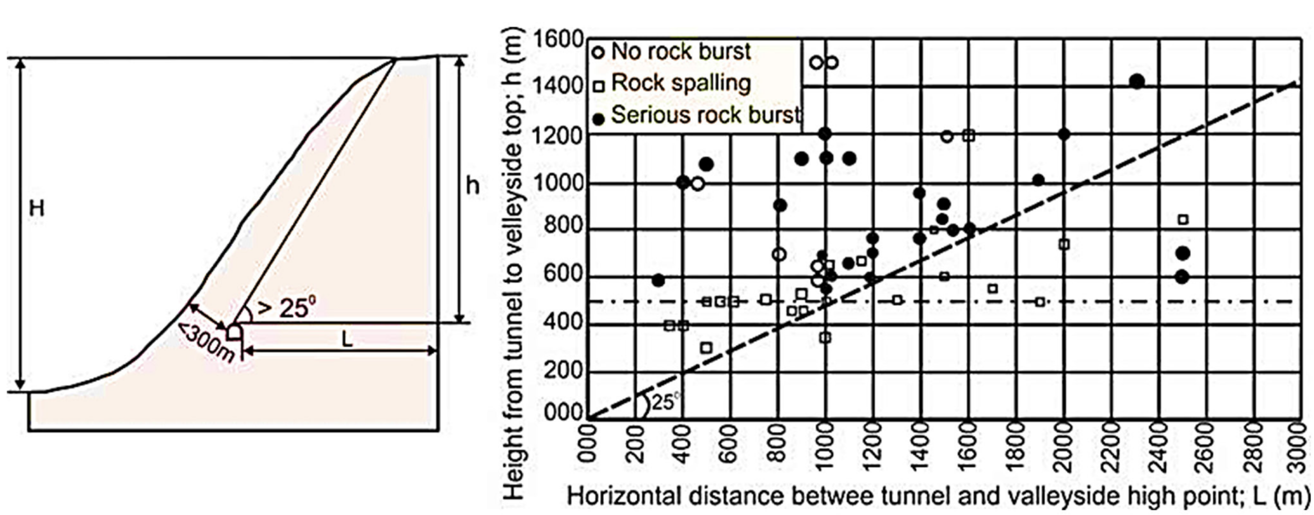

Fig. 3: Horizontal distance from tunnel to valley-side top (left), and rock burst/spalling in relation to height from tunnel roof to top of valley-side (right). The figure is formulated by Panthi and Broch (2022) based on Selmer-Olsen (1965).

Shape and size of an underground opening

The Norwegian Method of Tunneling (NMT) recommends having tunnels and underground caverns with inverted D-shaped if drill and blast meth of excavation is used and if it is practical regarding its functional requirement. This will ease in planning construction equipment and excavation works. On the other hand, the size of underground openings is dependent on the purpose of construction and therefore should be optimally designed to fulfil the requirement. It is also important to optimize the width (span) of an underground opening since the probability of occurrence of instability conditions increases with an increasing span. Unnecessarily large width (span) of an underground opening often exposes hidden discontinuities that amplifies instability potential compared to shorter and optimized width. This is because the narrower the opening width the better it will be the confinement. Reduction in confinement increases the risk of wedges sliding during excavation.

CONSTRUCTION AND ROCK SUPPORT

In Norway, Drill and Blast (DandB) method of excavation is the dominating one. The TBM excavated tunnels account for less than 5 % (about 300 km in length) of the total excavation of underground structures. Hence, fully mechanized Drill and Blast (DandB) method is an essence to NMT. Rock mass has its own capacity and utilization of rock mass capacity as self-support, meaning substantial load is carried by the rock mass itself, is part of rock support philosophy in NMT. Organized mechanical scaling and spot bolting (Figure 5a and b) are the first steps of rock support, which helps to improve the working environment at the tunnel face. After that, the main goal of rock support is to reinforce the rock mass and improve stability condition of an underground opening.

As indicated in Fig. 5 c and d, the application of combination of systematic rock bolting and steel fiber shotcrete will reinforce the surrounding rock mass by forming a pressure arch, which is a flexible approach to rock support. Moreover, an underground opening at shallow depth is exposed to low in-situ rock stresses where joint systems may be prominent, and block failure may likely occur. The aim of rock support is to avoid potentially fall of loosened rock blocks. When overburden increases the in-situ stress condition will improve, which enhances confinement. The aim of the rock support in this condition is to reinforce the surrounding rock mass. It is emphasized in NMT that the flexible rock support consisting of rock bolts and steel fiber shotcrete applied during construction to achieve a safe working environment is considered as part of the permanent support.

Rock support in difficult ground condition

Even though, Norway is considered as hard rock province with rocks having high rock strength (strength exceeding 75 MPa), this is not always the case. The highly schistose rocks like black sale, phyllite, schists and rocks with layers of pyroclastic sediments are abundant. In addition to the schistose rocks, numerous weakness and fault zones are found in all geological formations. Excavation of underground openings through highly schistose rocks and through weakness and faults zones poses great stability challenges since these zones represent very poor to extremely poor rock mass quality and cannot fully self-support. To address this challenge NMT favors using a thick load bearing ring structure that constitutes spiling bolts, circumferential bolts and reinforced rib of shotcrete (RRS) (Fig. 6).

As shown in Fig. 6 (left), spilling bolts are mounted at close spacing (generally less than 40 cm spacing) with an angle

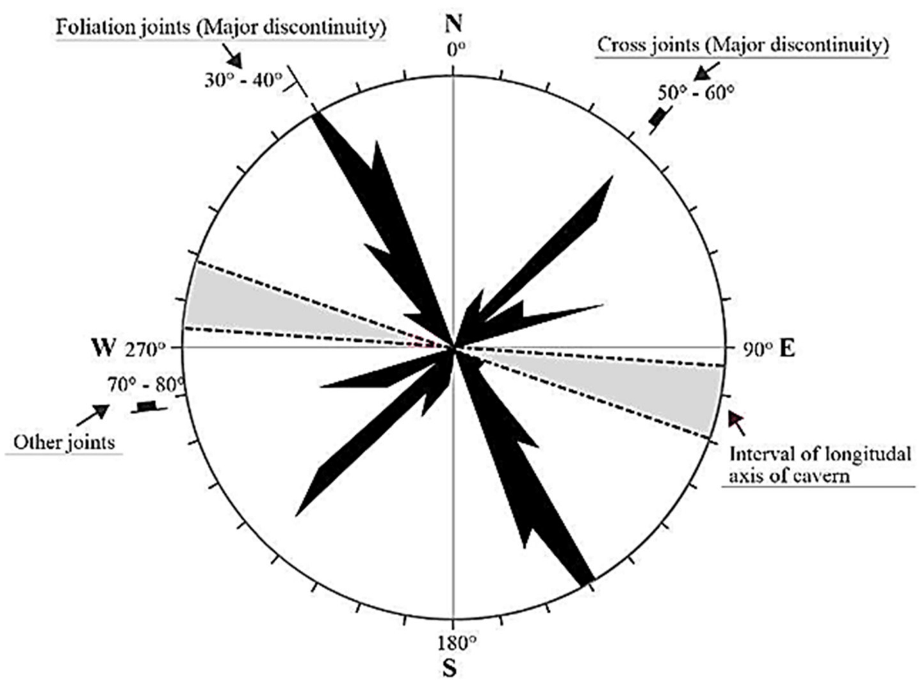

Fig. 4: Joint rosette illustrating orientation of major joint sets and potential orientation of an underground structure (Based on Nilsen and Thidemann, 1993).

of 3 to 5 degrees from the tunnel contour in the direction of excavation. The main purpose of spiling bolts is to maintain the theoretical profile of an underground opening until rock support consisting of RRS is installed. Therefore, the spilling bolts are not considered as part of the permanent rock support. Similarly, reinforced ribs of shotcrete (Fig. 6-right) consist of transversing rebars, radial rock bolts and steel fiber shotcrete. RRS is used in very poor to exceptionally poor-quality rock mass since it has insufficient capacity to sustain itself. RRS can be designed with different configurations depending upon quality of rock mass. RRS can have either single or double layers of transverse rebars (Fig. 6-right), varying spacing between RRS, varying shotcrete thickness and bolting pattern and length. Depending on the geological conditions, RRS can be mounted at face or behind face.

Water leakage control

Rock mass permeability is controlled by the degree of jointing and the characteristics of joints such as spacing, persistence, roughness, aperture, infilling conditions. The extent of ground water inflow in the tunnels and caverns is controlled by rock mass permeability (degree of jointing

Fig. 5: Application of rock support in NMT; a) Mechanical scaling, b) Spot bolting to hold loosened rock block, c) Application of steel fiber shotcrete and d) A tunnel reinforced with the application of systematic bolting and steel fiber shotcrete as final rock support.

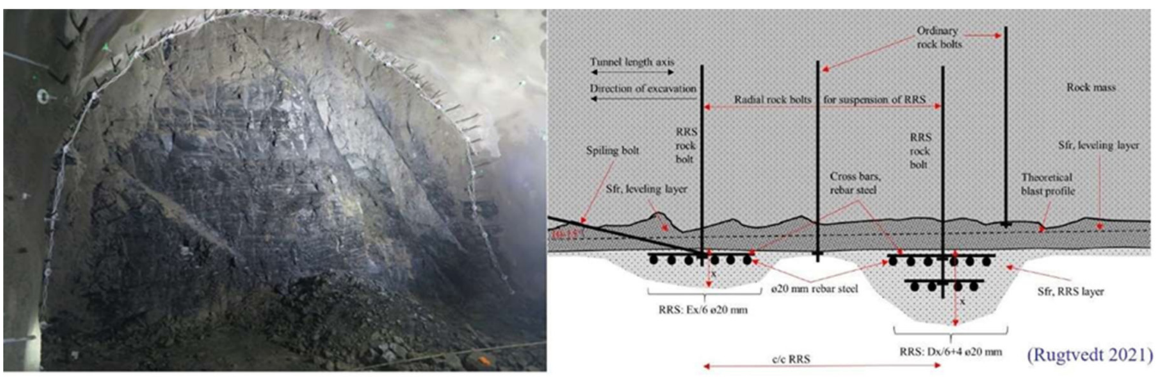

Fig. 6: Installed spilling bolts and schematic arrangement of RRS with rock bolts.

and their character), ground water table and at what depth the tunnels and underground structures are located (Panthi 2014). Excavation of underground space in the rock mass exposes joint systems. If the joint systems are long persisting and filled with permeable material, these joint systems hold considerable amount of ground water, which leaks to the excavated underground space. The inflow of groundwater in the excavated underground opening may lead to the reduction of working environment, may increase instability, may deplete groundwater table increasing risk of ground settlement and damage to the surface structures.

There exist very strict regulations in Norway against drawdown of ground water table and limitation criterion. Since no water inflow exciding the limiting criteria should occur in underground opening during construction, the full concrete lining is not a solution. It is well known fact that the purpose of full concrete lining is mainly associated with long-term stability and functionality. However, the long-term stability and functionality can also be achieved using systematic pre-injection grouting (Fig. 7), application of rock support discussed above and application of water shielding mechanism that will be discussed in the next chapter.

As Fig. 7 shows, the overlap between the pre-injection rounds varies between 6 and 12 meters. Stricter is the water inflow requirement, longer will be the overlap between the rounds. The injection procedure is adjusted depending upon tightness requirement, mapped geological condition and joint systems characteristics.

Since chemical grouting is not favored in Norway due to strict environment regulation, preinjection grouting with the use of both industry and micro cement are preferred solutions. The pre-injection grouting pressure varies from 10 – 80 bars depending on type and location of underground opening as well as the water tightness requirement set by government regulatory body. Different stopping pressures for injection grouting are used depending on the tightness requirement. In general, the injection grouting velocity is limited to a maximum of up to 30 liters per minute. If desired pressure is not achieved until 400 kg cement slurry with water-cement ration one (W/C = 1), the W/C-ratio is reduced to 0.5. Figure 7 shows a principal sketch that shows the length of grout holes, overlapping distance and blasting rounds.

Water shielding mechanism

Following the Norwegian tunneling experience, pre-injection grouting enables to achieve water tightness down up to 1-2 liters per minute per 100 m tunnel length (0.01-0.02 lt/min/m tunnel). The remaining seepage water should be drained through a drainage system built in the side walls of an underground opening. This implies that the underground structures are drained structures and require an inner lining structure in road and railway tunnels and in the caverns. This will allow us to collect seeped groundwater from the rock mass down to the drainage structures (Fig. 8).

In areas where an underground opening is exposed to freezing, thermal insulation is applied to prevent the formation of ice. It is emphasized here that many under the sea (subsea) tunnels (road and cable tunnels) in rock mass have also been successfully designed and constructed according to the drained structure principle shown in Fig. 8. The water shielding systems function as waterproofing, drainage of seeped water and thermal insulation. The two types of shielding are commonly used in underground openings in Norway. The first type is a combination of shotcrete and polyurethan foam (PE-foam) to the roof and concrete elements in the walls (Fig. 9-left) and the second type is a combination of concrete elements and waterproofing membrane (Fig. 9-right).

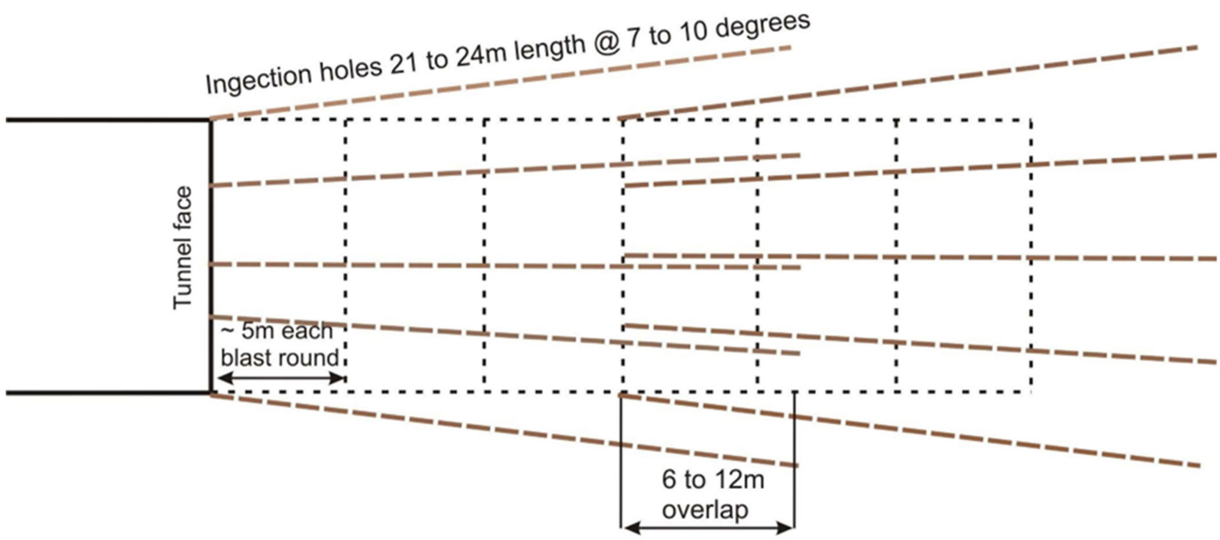

Figure 7: A principal sketch that shows pre-injection grouting pattern used in Norway (Panthi 2014).

NECESSITY OF NMT IN NEPAL

Use of steel rib or lattice girder and shotcrete to contain deformation is not a cost effective and optimal rock support. The practice made in the use of steel ribs, welded reinforcement rods connecting two steel ribs, stone packing behind (Fig. 10) and only application of shotcrete is a dangerous way of supporting the tunnels.

The support provided in Fig. 10 is not able to interact with the surrounding rock mass and the support must take all loads coming from the rock mass. In addition, if the tunnel is built for water convenience like hydropower, irrigation and water supply tunnels, one must seal all the packed stones with grout material, which is tedious, time consuming and costly. Hence, this type of support demands concrete lining as final support, which is cost intensive, time consuming and environmentally unsustainable. We should remember that time is money and unnecessary use of resources not only increases the project costs but also damages the environment.

It is emphasized here that Cementous products are among the materials that cover almost 15 percent of the CO_2 emission in the world. The production of concrete is directly proportional to the cement content used in the concrete mix. It should be remembered that 900 kg CO_2 is emitted while producing 1000 kg (one ton) cement. Therefore, limiting the use of concrete is very important not only to protect the environment but also to make cost effective and sustainable tunneling in Nepal. The use of NMT plays a key role in this respect.

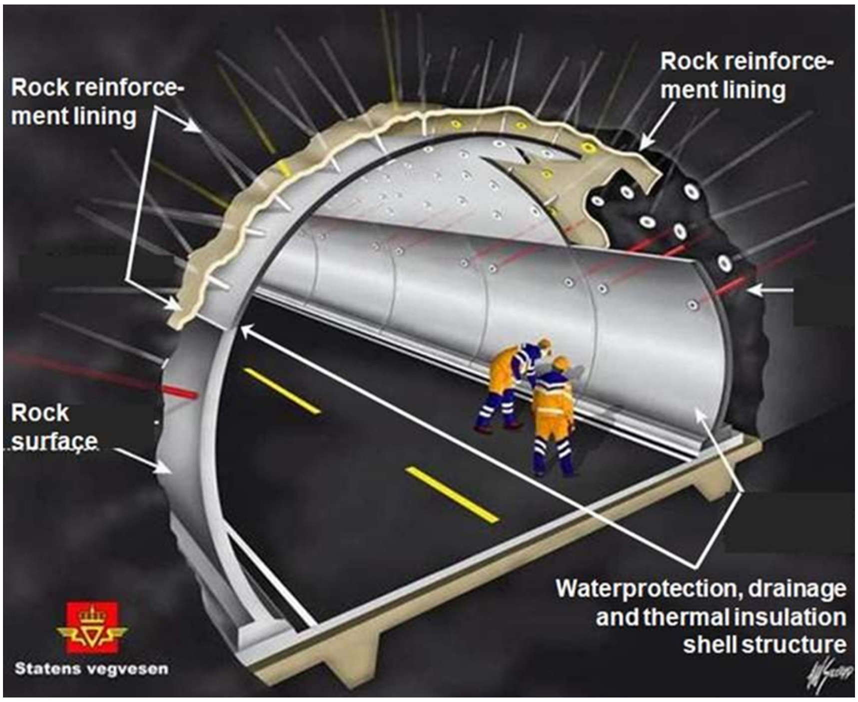

Fig. 8: Principal sketch of water shielding system for road and railway tunnels (www.statensvegvesen.no)

Fig. 9: Water shielding. Left: combination of shotcrete and polyurethan foam (PE-foam) on the roof and concrete elements in the walls and right: combination of concrete elements and waterproofing membrane.

Fig. 10: Practiced support system in fracture rock mass in Nepal. Left: A worker is busy welding the reinforcement bars to connect with applied steel ribs. Right: The workers are stone packing behind bars.

CONCLUSIONS

The experience gained from the development of unlined/ partially shotcrete lined tunnels in Norway gave possibility to develop Q-system of rock mass classification, which integrates support system chart and is being updated periodically. Today, Q-system of rock mass classification has got worldwide acceptance. The design criteria and principles developed for stability assessment and location design in consideration of engineering geological, in-situ stress and topographic environment are useful tools and are part of essences in NMT. The pre-injection grouting is good not only for water leakage control but also for enhancing quality of the rock mass. The optimized use of rock bolts, steel fiber shotcrete and RRS as rock reinforcement are very effective rock support measures that help to reduce rock support costs and enhance sustainability. Therefore, NMT is a cost effective, sustainable tunneling solution and is an important means in the reduction of carbon emission and to protect the environment.

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