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NORWEGIAN METHOD OF TUNNELING (NMT) FOR SUSTAINABLE USE OF UNDERGROUND SPACE

Krishna Kanta Panthi[1]

Abstract: The debate for the minimization of carbon emission through minimized / reduced use of fossil energy sources has been ongoing for some decades now. However, carbon emission is not only limited to fossil energy sources, but a substantial amount of carbon is emitted through the production of cement and cementitious products like, for example concrete. On the other hand, the use of underground space for the development of different transport and utility infrastructures is becoming popular due to limited use of surface area, environmental and health friendly solutions. Nonetheless, how to reduce the use of cementitious products while developing underground space is an important issue that needs to be carefully evaluated so that use of underground space is long-term sustainable and environmentally friendly solution. Hence, the aim of this manuscript is to discuss about Norwegian Method of Tunnelling (NMT), which could serve to minimize the use of cementitious product while developing an underground space. The manuscript aims to highlight on the main principals behind the Norwegian Method of Tunnelling (NMT), the optimized and long-term sustainable solutions it offers by substantially reducing time and costs for underground space development.

Keywords: Norwegian Method of Tunneling (NMT), Design of Underground Space, Rock Support, Sustainability

1. INTRODUCTION

The land in the city area is being used for various purposes such as official, residential and industrial buildings, sports arenas, parks, greenery areas, city transport etc. The surface space in large city areas is always scarce. Populace living in the cities desire to have more open space, greenery areas, parks for external activities. Therefore, it is important that the surface area in the cities should be optimally used. One way to do it is to utilize underground space in a maximum possible way. This can be done through the utilization of underground space for city metro lines, vehicular transportation system, parking arena etc. It is noted here that the use of underground space is not new for mankind. For thousands of years, underground space has been used for various purposes. Most early uses were related to the responses to specific geological events, security concerns and/or climate adaptations (Benser 2017). However, according to Bobylev and Sterling (2016), in the past century or so, the use of underground space has emerged as a broader means of supporting the infrastructure and space needs of the rapidly increasing world population. It is particularly the case in the major cities.

Norway is among the countries that utilizes and will utilize underground space for the transportation network, parking arenas, sports halls in the city areas in a maximum possible way. This is because the use of underground space ascertains availability of freer surface for different social and cultural activities. In addition, the use of underground space helps to reduce pollution and makes city areas environmentally friendly and long-term sustainable. Hence, underground space is prioritized as much as it is viable both with respect to costs and ground conditions. Analyzing the statistics given by Norwegian Tunnelling Society (NFF 2024), a rough estimate indicates that Norway has over 7400 km of tunnels and underground facilities. railway tunnels and caverns built for hydropower roughly cover 4500 km (89.92 million cu.m.), road tunnels cover about 1850 km (101.83 million cu.m.), railway and metro tunnels cover about 650 km (21.76 million cu.m.), water supply tunnels cover almost 350 km (5.85 million cu.m.) and remaining belong to drainage tunnels, sports and storage caverns. All together

[1] Professor Krishna Kanta Panthi, PhD in Rock Engineering, Norwegian University of Science and Technology (NTNU), S. P. Andersen vei 15a, 7491 Trondheim, Norway, e-mail address: krishna.panthi@ntnu.no .

almost 250 million solid cubic meters of underground excavation have been made in Norway excluding the underground excavation that has been made for mineral abstractions.

The tunnels and caverns excavation experience gained over many decades for hydropower, water supply, highways, railways and metros, drainage systems, oil and gas storage, sports arenas, parking arenas etc., Norway has developed its own approach to underground design and construction, which can be defined as Norwegian Method of Tunneling (NM). The manuscript dedicates to highlight on the design and construction approaches used in NMT, which is somewhat different than that practiced by other countries in the world. The aim is to discuss the cost effectiveness and environmental friendliness of the NMT, which is very much needed in the development of underground space to improve transportation networks and other underground space use in the urban areas.

2. NORWEGIAN METHOD OF TUNNELING (NMT)

The excavation method in NMT primarily bases on the Drill and Blast and open hard rock TBM (gripper TBM) Methods (Barton et al. 1992). It is emphasized that NMT acknowledges the fact that in-situ stresses within the rock mass increase confinement to the surrounding rock mass in the periphery of an underground excavation (tunnel, shaft or cavern). The homogeneous and intact rock mass is therefore able to withstand the load exerted to it, i.e. rock mass has self-supporting capacity. In case there exist jointed rock mass, the withstand capacity of the rock mass is enhanced by reinforcing its body mass with the use of rock support consisting of application of rock bolts/rock anchors and steel-fiber shotcrete. The applied thickness of steel fiber shotcrete (Srf) is in general vary between 8 to 15 cm thick. In addition, pre-injection grouting is used for groundwater control. If weakness and fault zones containing swelling clay are met in tunnels that are built to convey water (hydropower, irrigation, water supply and sewage tunnels), the cast-in concrete is applied. On the other hand, if weakness and fault zones are met in road and railway tunnels, the applied rock support consists of systematic bolting and application of Ribs of Reinforced Shotcrete (RRS).

In general, 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. In NMT, it is important to emphasize that the preliminary rock support applied in tunnels and caverns is considered as part of final rock support (Barton et al. 2024)

Hence, the key aspects of NMT include use of in-situ stress information, relationships developed utilizing data from previous tunnelling projects (empirical relations) and numerical modelling for design of tunnels and caverns. In addition, well-organized engineering geological investigations during planning, design and construction phases of underground excavations, well planned tunnelling equipment and well-trained tunnel crew and risk searing approach to construction contracts are key elements for the successful use of NMT. Regarding the construction contracts it is important to minimize disputes through mutual understanding in the responsibility of each party and good coordination (Figure 1).

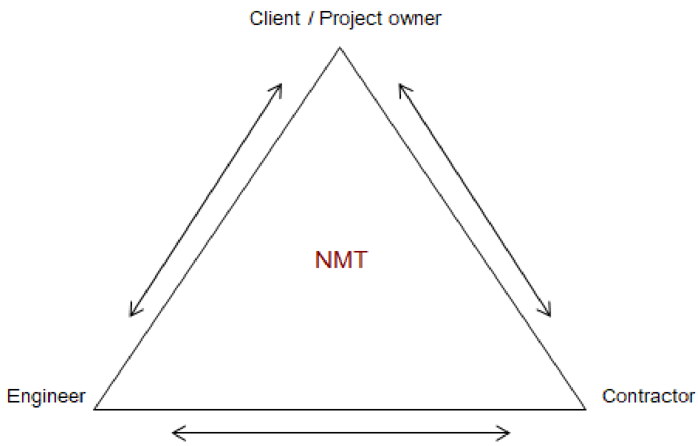

Figure 1. *Triangular communication that NMT adopts in contract management.*

The Client/Project owner is responsible for overall project management. In addition, the client is also responsible for appointing an expert group. The role of an expert group is to make periodic inspections of an underground space under construction, to quality control and to recommend needed design changes by giving improved solutions. The Engineer is responsible for overall design, construction supervision, engineering geological mapping and documentation and rock support decisions. Similarly, the Contractor is responsible for the implementation of the project according to the contract, for excavation and rock support application according to the design and instruction given by the Engineer, for the execution of health, safety and environmental issues set in the construction contract, for construction management. It is important that there is three-way communication between the parties as indicated in Figure 1.

3. PLANNING, DESIGN AND CONSTRUCTION PROCEDURES IN NMT

The main aim of engineering geological design of an underground project is to achieve optimum technical and economic solutions based on engineering geological knowledge gathered during investigation and construction stages. A key requirement for successful planning and design is to ensure that the data and information collected through engineering geological investigations and field mapping are of good quality. In this regard, the description of rock mass quality conditions in both quantitative and qualitative terms is very important. Hence, high quality engineering geological mapping and engineering geological investigations are prerequisites for proper planning, design and construction stages. Furthermore, careful preparation of tender documents explaining clear objectives, bidding process, face mapping and recording of actual ground conditions and follow-ups during construction of underground projects are key essences of NMT. In general, NMT follows the process as given in Figure 2.

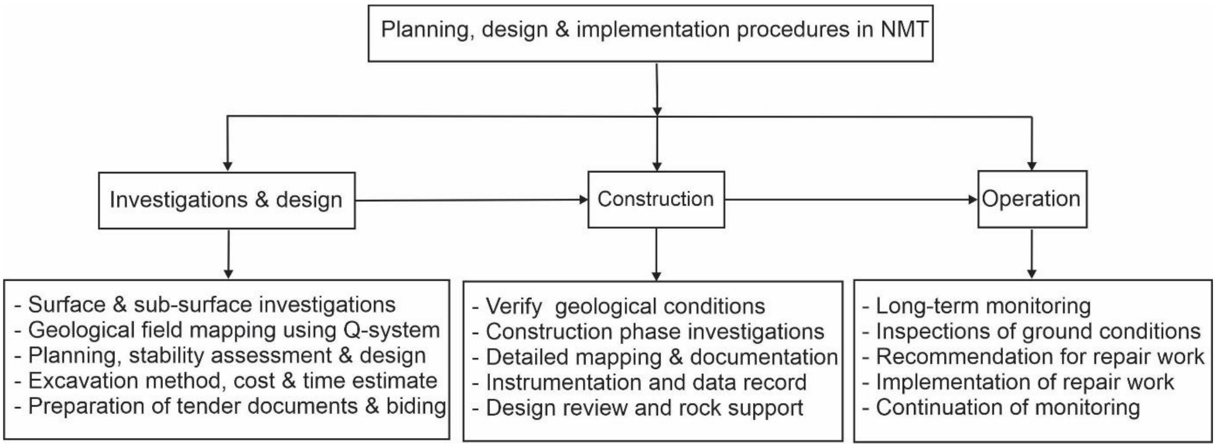

Figure 2. *Steps of planning, design, construction and operation of underground structures in NMT.*

Following the steps highlighted in Figure 2 left and center, it is possible to identify the features like rock mass quality condition, rock mass mechanical properties, topographical and in-situ stress conditions, complexity of the underground structures, construction methods, cost and time required for the construction.

4. DESIGN CONSIDERATION FOR UNDERGROUND STRUCTURES

Norwegian tunnelling community has gained over 100 years of experience in the construction and operation of underground space, which gave possibility to gather large amount of data, which made it possible to develop several "rules-of thumb" that are being used for planning and design purposes. It is emphasized here that NMT recognizes the value of proper engineering geological documentation using Q-system of rock mass classification (Barton et al. 1974 and Grimstad and Barton 1993) for regulating the description of rock mass conditions and initial support recommendations. In addition, observation of site conditions and numerical modelling approaches are used to verify the stability conditions and final rock support needs.

The design of underground structures should be made in such a way that the design provides cost effective, long-term stable and sustainable solutions. This can be achieved by considering rock mass as the part of a structural element that counteracts any load or pressure exerted by unloaded rock mass after excavation. Therefore, any design considerations should be based on the results from comprehensive engineering geological investigations. The aim of the design should be to achieve stability and long-term functionality of an underground structure in consideration (Panthi and Broch, 2022). This can be achieved through proper consideration regarding placement design, orientation and shape & size of an underground structure under consideration.

4.1. Location design of underground structures

For a successful design, it is important to find out the best location for the underground structure in consideration so that it is placed in a best quality of rock mass available in the given topography. According to Hudson and Harrison (1993), an underground excavation may face mainly two modes of failure. The first one is the block failure when pre-existing blocks in the roof and side walls of an underground opening become free to move after the excavation has been made. The second one is stress failure when induced stress around the excavation exceeds the rock mass strength. In this regard, it is mentioned here that near the surface, in-situ stresses are in general an-isotropic, and discontinuities mainly control stability. On the opposite, deep into the rock mass, the in-situ stress magnitudes are increased, and frequency of discontinuity occurrence are reduced due to enhanced confinement (Panthi 2023; Panthi and Broch 2022). Hence, stability is controlled by induced stresses in deep cited underground structure. Therefore, the stability challenges vary greatly depending upon the way an underground scheme is located.

The underground structures that are located at shallow overburden have low gravitational vertical stress, which may cause higher level of stress anisotropy. Similarly, at low overburden areas (near surface) the rock mass is prone to high degree of weathering. In such a situation, the rock mass may have low level of interlocking effect between the rock blocks that may cause reduction in arching effect leading to potential block falls from the roof and side walls of an underground opening. The stability assessment should therefore be associated with potential block fall (Figure 3).

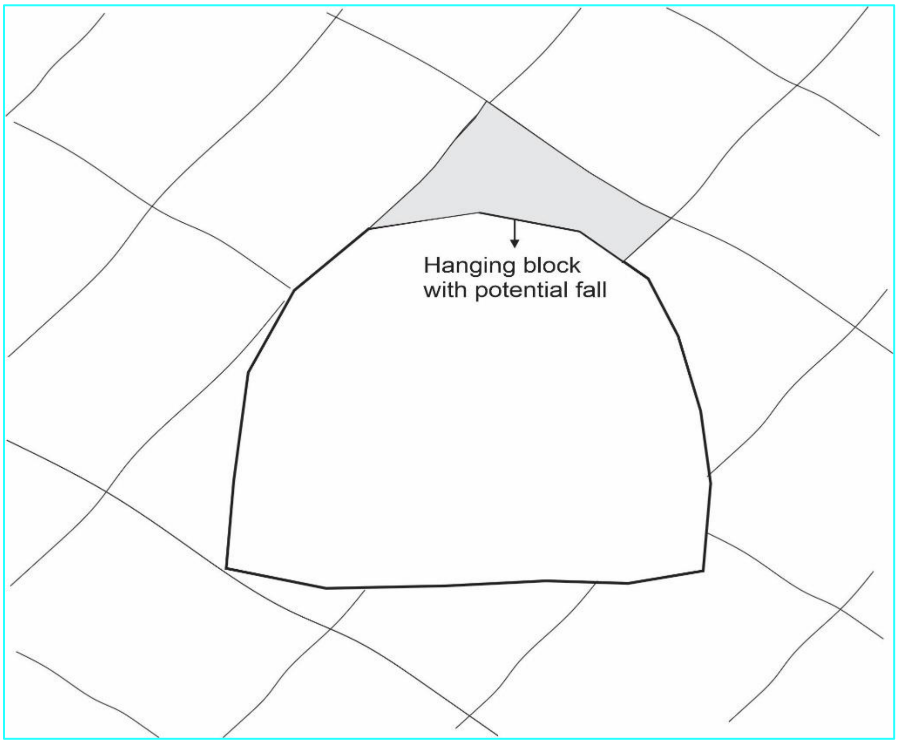

Figure 3. *Potential block fall from the roof of an underground structure located at shallow overburden*

The underground structures that are located at great depth with high overburden may face stability challenges associated with the high in-situ rock stresses. In one hand, increased in-situ rock stresses increase the confinement in the rock mass and in the other hand, high in-situ rock stresses may cause rock burst/rock spalling or squeezing conditions if rock mass strength is less than the induced stresses (Panthi 1012). Therefore, the placement of the underground structure should be made in such a way that it achieves favorable stress condition. If the topographic condition does not give possibility for such location, in-depth stability assessment should be made using empirical, analytical and numerical modelling approaches. One of the rules of thumbs that is being used in Norway is expressed in Figure 4. In addition, the strength reduction factor (SRF) of Q-system also provides a qualitative assessment for the placement design of the underground structures.

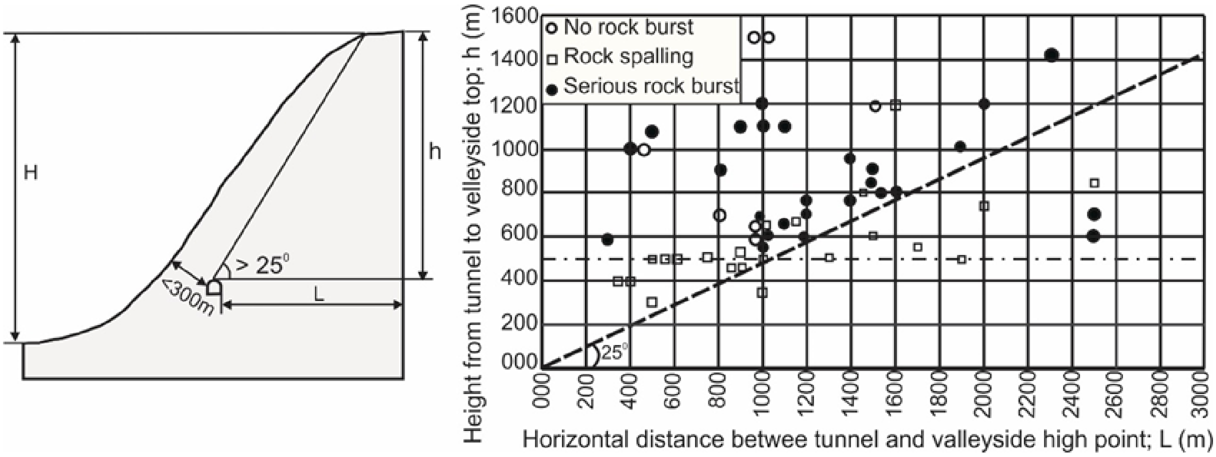

Figure 4. *Location of underground openings in relation to topographic conditions (left), and plot of rock burst/spalling in relation to height (h) from the tunnel roof to the top of valley-side and horizontal distance from an underground opening to the top of valley side (L) (Panthi 2018* based on *Selmer-Olsen 1965).*

Figure 4 shows tunnel cases that were passing through a topography where vertical rock cover directly above the tunnel is relatively small in comparison to the vertical height between the tunnel and the top of the valley-side slope (the plateau). Similarly, these tunnels are relatively short distance (mostly not exceeding 300 m) from the valley surface. This Norwegian rule of thumb is very useful to make placement design of underground structures, which should also be supplemented by numerical modelling.

4.2. Fixing orientation of underground structures

Correct and optimum alignment of an underground structure is very important to minimize instability. In this regard, fixing orientation with respect to mapped data of major and systematic joints and discontinuity systems is a decision-making factor for an underground structure. Therefore, it is vital that detailed discontinuity mapping is made, congregated, and systematized. During planning phase mapping, the major discontinuity systems such as bedding / foliation planes, cross joints, major fault/weakness zones present in the locality should be identified. The basic rule that should be adopted is to orient the length axis of an underground opening along the bisection line of the maximum intersection angle between the two predominant joint systems (Figure 5) and parallelism with other minor joint systems should be avoided as possible (Panthi and Broch 2022). The optimization also includes the prevention of adverse cavern orientation relative to the orientation of weakness zones and major principal stress.

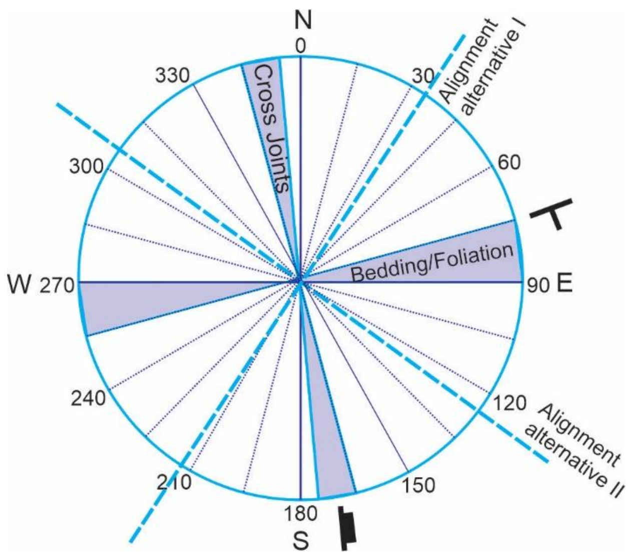

Figure 5. *Rosette of joint systems and possible orientation alternatives of length axis of an underground opening.*

4.3. Design of size and shape of underground structures

The shape and size of an underground opening depends on its function. Most of the tunnels in Norway have an inverted D shape in cases if tunnels are excavated using drill and blast method. Similarly, the caverns are also of inverted D shape with deep walls since these have been excavated using drill and blast method. The size of tunnels and caverns are mainly dependent on the purpose of construction and needed space requirement. For example, the road tunnels in Norway are inverted D-shaped and are mainly excavated by fully mechanized drill and blast (D&B) method. The size of road tunnels depends on Annual Average Daily Traffic (AADT) and size vary from T4 (4 m wide) to T14 (14 m wide). Similarly, the railway tunnels are either inverted D shaped or circular depending on the excavation method used, i.e., excavated with drill and blast method or excavated using TBM, however, mostly dominated by inverted D shapes.

5. ROCK SUPPORT DECISION FOR UNDERGROUND STRUCTURES IN NMT

Fully mechanized Drill and Blast (D&B) method is the essence of NMT. Norwegian tunneling community believes the principal that the rock mass has its own capacity to self-support, which means substantial load is carried by the rock mass itself. A key requirement for NMT is that it is important to consistently carry out mapping rock mass quality and record the actual ground conditions in both quantitative and qualitative terms. In this regard, Q-system of rock mass classification plays an important role. In addition, the main principle of rock support should be to strengthen existing rock mass surrounding the periphery of an underground opening. Priority is given to the use of flexible support.

5.1. Rock support in normal ground conditions

In NMT, the immediate rock support measures right after excavation and mucking include mechanical scaling and immediate application of end-anchored rock bolts, as spot bolts, to strengthen loosened rock blocks. Additional rock support is applied after face mapping and assessment of rock mass quality conditions by detailed observation and application of Q-system of rock mass classification. In general, rock support consisting of a combination of systematic rock bolts (B) and steel fiber shotcrete (Sfr) is a preferred choice in NMT as both temporary and permanent rock support (Figure 6). The rock support chart of Q-system updated in 1993 by Grimstad and Barton (1993) has been further updated by NGI (2015) that helps to recommend preliminary rock support (Figure 7).

Figure 6. *An under-construction road tunnel supported by systematic bolting and fiber reinforced shotcrete.*

In addition, pre-excavation grouting is carried out to control groundwater depletion and water inflow (seepage). The grouting pressure applied varies from 10 to 80 bars depending upon where an underground opening is constructed. If an underground opening is constructed in the city area, it is important not only to control water inflow but also it is necessary to restrict groundwater depletion from the surface requiring much stricter regulations.

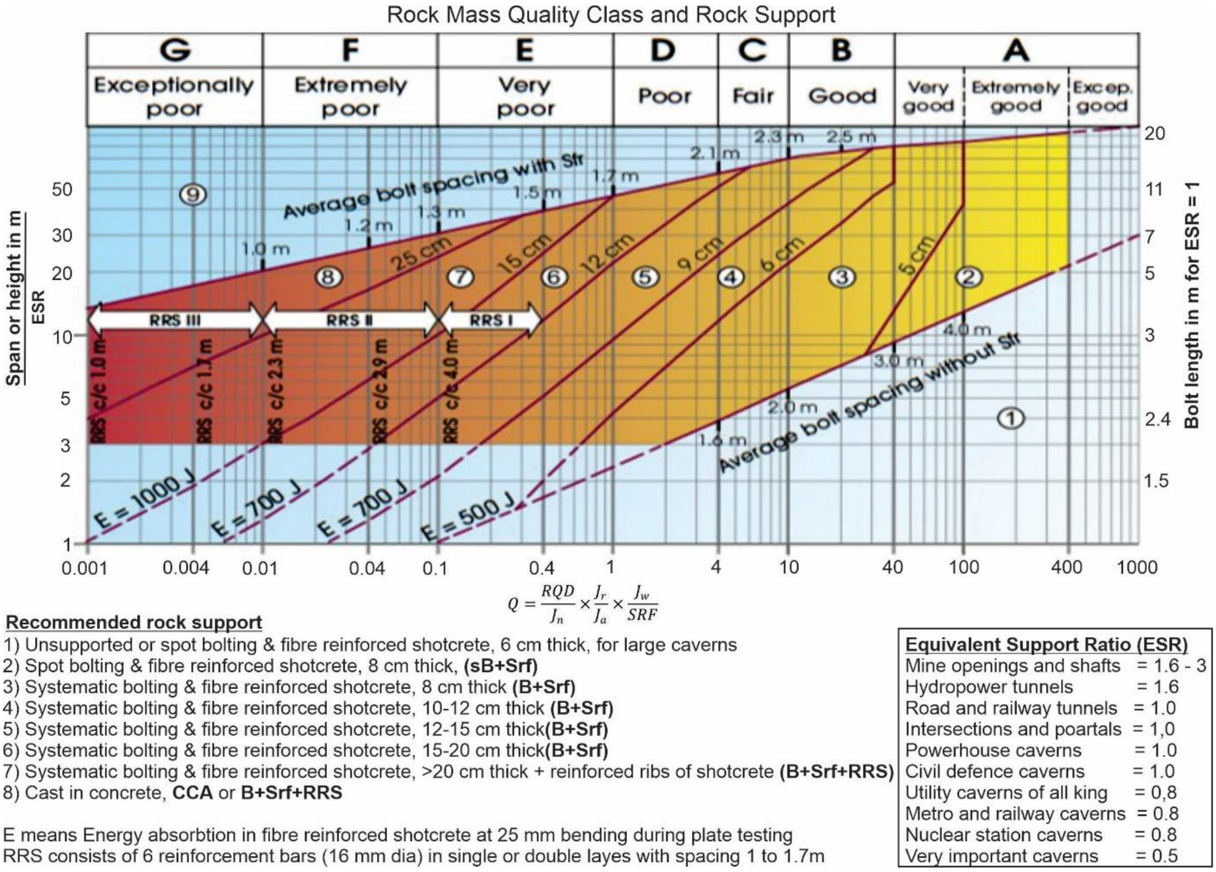

Figure 7. *Support chart according to rock mass class (NGI 2015), updated to suit urban underground structures.*

It is emphasized here that the blocky rock mass where joints and discontinuities are clay-filled, rock support in combination with systematic bolting (B) and steel fiber shotcrete (Sfr), as seen in Figure 6, is used. Barton et al (1992) state with some certainty that B+Sfr are the two most versatile tunnel support methods yet devised, because they can be applied to any profile as temporary or as permanent support, just by changing bolt spacing and thickness of steel fiber shotcrete. Although the high level of experience in the Norwegian tunnelling community has allowed "rules-of thumb" and much "previous experience" to dictate a lot of the support estimates, more and more companies are realizing the value of a documentation method such as the Q-system for regulating the description of rock mass conditions and support recommendations.

5.2. Rock support in difficult ground conditions

In general Norway is a hard rock province where intact rock strength is more than 40 MPa, which provides possibility to achieve good underground excavation progress in normal ground conditions. However, these hard rock mass often constitute faults and weakness zones. Underground excavation through faults and weakness zones poses challenges and difficulties since these zones represent very poor to extremely poor rock mass quality, which are unable to self-support. To address this challenge, NMT favors using a thick load bearing ring that constitutes spiling bolts, circumferential bolts and reinforced rib of shotcrete (RRS) (Figure 7 and Figure 8-right). The beauty of the application of RRS is that it can form and match an uneven underground excavation profile (Figure 8-left), which is very difficult to achieve with the application of lattice girder or steel ribs. In addition, installation of spiling bolts, systematic circumferential bolts and reinforced ribs of shotcrete is straight forward and relatively quick, which immediately helps to control difficult ground against collapses.

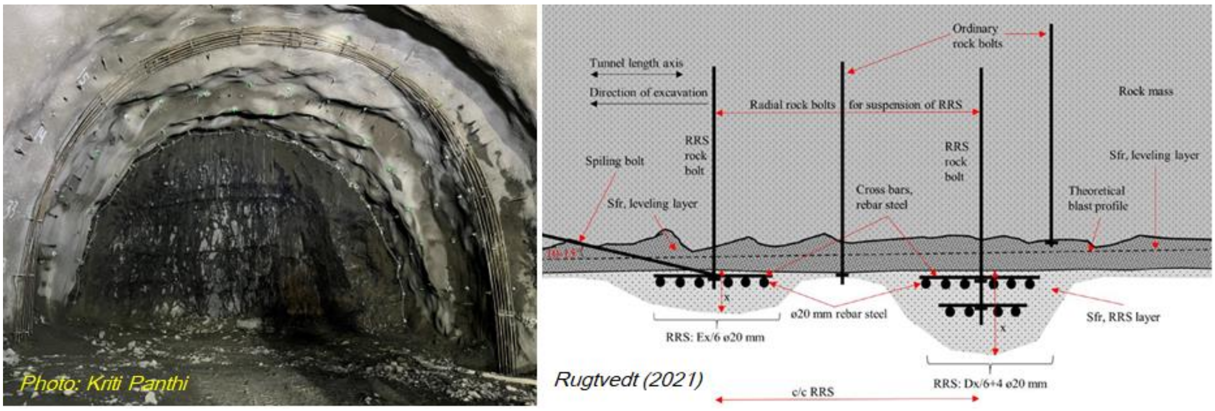

Figure 8. *Photo showing RRS application in difficult ground (left) and schematic arrangement of RRS with bolts.*

As seen in Figure 8-right, RRS can be designed with different configurations. The main parameters influencing the configuration and load bearing capacity depend on the use of single layer or double layers of reinforcement bars (generally 6 numbers 16 mm diameter reinforcement bars are used), spacing between RRS, quality and thickness of steel fiber shotcrete, length & spacing of rock bolts and spiling bolts. Spiling bolts are rock bolts that are mounted at an angle between 5 to 10 degrees from the tunnel face contour towards the direction of excavation.

5.3. Groundwater and frost control (water shielding)

Among the important features of the Norwegian Method of Tunneling (NMT) is the use of rock support in combination of pre-injection grouting, systematic bolting and application of steel fiber shotcrete, which is not fully waterproof. This means, the underground structures are considered as drained structures. 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 (Hognestad et al. 2005). The remaining water seepage should drain through the drainage system built in the side walls of tunnel invert, which implies drainage of groundwater from immediate surrounding rock mass of the underground structures. Many under the sea (subsea) road tunnels in rock mass have been successfully designed and constructed according to the drained structures principle since 1982 (Nilsen and Henning 2009). The flexible rock support solutions however require an inner lining structure, which collects and drains seeped groundwater from the rock mass down to the drain structures located side wall of the tunnel invert. In areas where a tunnel is exposed to freezing, thermal insulation is also needed to prevent formation of ice. The principal sketch of water shielding system that is being used for road and railway tunnels is shown in Figure 9.

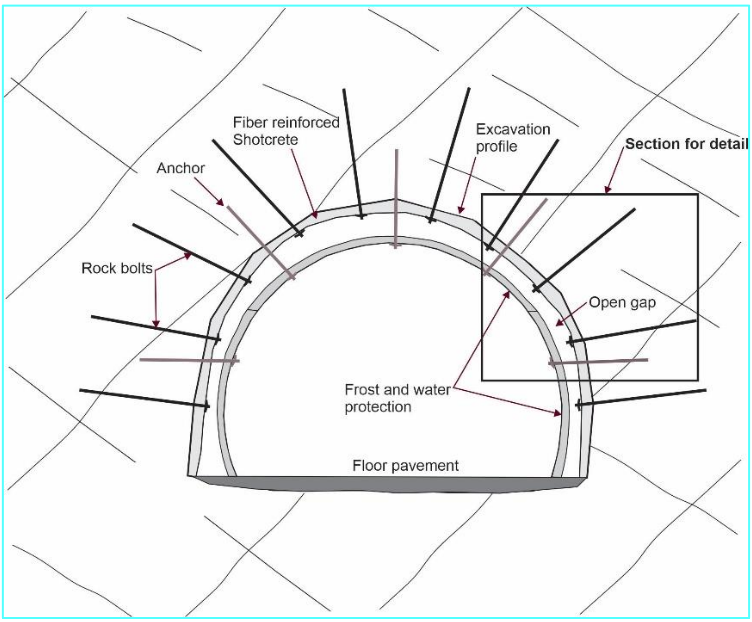

Figure 9. *Schematic principal arrangement of water shielding and frost insulation system in use in Norway.*

The water shielding systems have main functions consisting of waterproofing, drainage of seeped water and thermal insulation to avoid formation of ice near portal areas. In general, there are mainly two types of shielding that are in use in tunnels in urban areas (Figure 10). The first one is a combination of shotcrete and polyurethan foam (PE-foam) as shown in Figure 10a and the second one is a combination of concrete elements and waterproofing membrane as shown in Figure 10b.

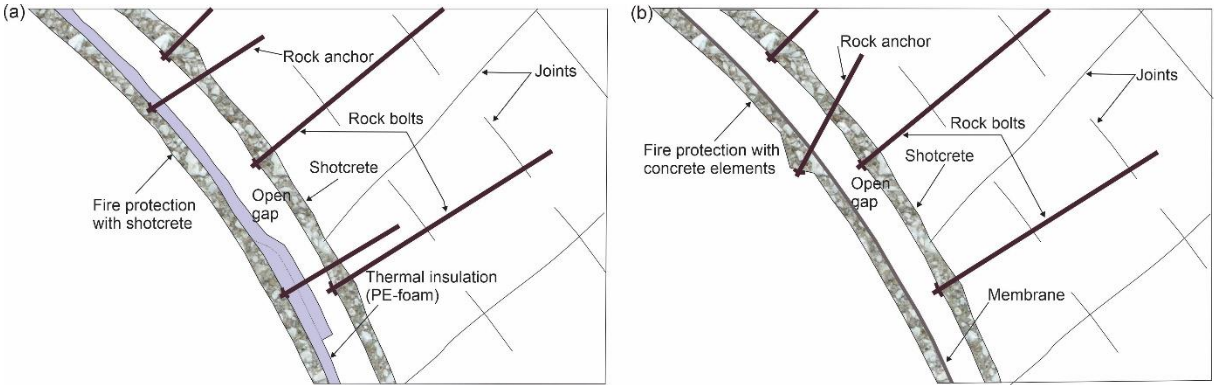

Figure 10. *Details of water shielding and frost insulation arrangement in Norway. a) Water shielding arrangements with shotcrete and PE-foam; b) Water shielding arrangements with concrete elements and waterproof membrane.*

An open gap that is left between water shield and tunnel rock support applied in combination of bolting and shotcrete gives possibility to carry out periodic inspections on the condition of installed rock support, periodic repair work of the rock support without losing any space required for the vehicular and train movements. This flexibility is very important for the long-term sustainability of underground space use. In addition, the solution provides the possibility to reduce unnecessary concrete use.

6. ISSUE OF SUSTAINABILITY

The 17 UN Sustainable Development Goals (SDGs) recognize that ending poverty and other deprivations must go together with strategies that improve health and education, reduce inequality, and achieve sustainable economic growth and at the same time addresses climate change issues and preserve earth's oceans and forests. Hence, sustainability is directly linked to the interconnections between social equity, economic growth and environmental issues. This means, the sustainable development of underground space should meet the needs of the present without compromising the environment and need for the future. The Norwegian tunneling industry is proactive in this regard and actively recommends needed changes in regulations regarding construction processes and material use (NFF 2022) to achieve both sustainable and environmentally friendly underground solutions.

The use of life cycle assessment (LCA) in NMT to evaluate tunnel construction projects is an essential part and the contractors, material producers, and the project owners actively use process and results from the LCA. The LCA studies performed have indicated that the construction phase of a tunnel contributes to about 50 to 60 percentages of greenhouse gas (GHG) emissions, which are mainly related to the use of material and energy sources. The emissions are mainly from the use of cement associated to rock support and tunnel lining and to some degree tunnelling process itself (Huang et al 2015). NMT always aims to reduce the quantity of concrete, cement and steel as rock support and rock grouting considering rock mass as self-supporting element. It is important to decrease the use of resources and the most important task of NMT is to become more sustainable tunneling. Small reductions in each material resource can contribute to enhance sustainability.

Sustainable use of materials means using the lowest possible volume of materials with the longest service life and quality. Many different materials are used in the construction of underground space. However, among the most important resource materials are cement and concrete. It is a well-known fact that cement is among the major contributors to GHG emission in the construction of underground space. The production of one ton Portland cement emits 900 kg of $CO2$, which accounts for 88% of the emissions associated with the production of concrete mix. Hence, reduction in the use of cement plays a key role in the reduction of GHG. This is because, following to Khaiyum et al (2023), cement industry is responsible for 5–8% of global GHG emissions.

7. CONCLUSION

Sustainable development of underground space should meet the needs of the present without compromising the environment and need for the future. The Norwegian Method of Tunneling (NMT) takes in account the rock mass as self-supporting material. NMT prioritizes the use of rock support consisting of systematic bolting, steel fiber shotcrete and pre-excavation grouting as both preliminary and final support, which contributes to considerably reduce the use of concrete products. The Norwegian tunneling industry is proactive, which collaborates with the government authorities and actively recommends needed changes in regulations regarding construction processes and material use to achieve both sustainable and environmentally friendly underground solutions.

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