Norwegian Method of Tunnelling – A Singapore Experience

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1.0 Introduction

Tunnelling is a complex process encompassing many work activities. Tunnelling needs a multi-disciplinary effort and involves many professions. The Norwegian Method of Tunnelling (NMT) originated in Norway, where the tunneling industry has played an important role for more than a century [8]; first for hydropower development, then for transport and water supply, and later for oil development. The term NMT was introduced by Barton et al (1992) [2] and they considered that this method, which permits rapid and safe excavation at low cost, as the most appropriate for the design, construction and support of underground openings in rock.

In Singapore, the use of NMT and technology transfer, though not widespread, was an essential part of the strategy behind the successful development of the Mandai Rock Caverns Facility. With increasing work and demand for expertise in rock tunnelling and development of underground rock cavern space in Singapore, it is important and timely for regulators, planners, developers and other stakeholders to have a more comprehensive understanding of what the NMT encompasses. This paper aims to present and discuss the main features of the Norwegian Tunnelling Technology (NTT), as it is lately known and its practice world-wide, based on the experiences gathered from the Singapore project and gives the local perspectives of NMT practices.

2.0 Norwegian Method of Tunnelling

The NMT is a form of tunnelling system and process that outlines a complete set of techniques, for investigations, design, construction and rock support [2]. It adopts a systematic approach to the different phases of tunnelling. The NMT follows the principles of the observational method [8] which includes assessment of the variations in ground conditions, observations during construction and modification of design to suit the actual conditions.

Norwegian tunnelling leverages on close cooperation between tunnellers, contractors, design engineers and engineering geologists [5] and this is important for developments in tunnel design, excavation methods and rock supporting measures. The “hard rock regime of NMT” is based on the self-standing capacity, impermeable nature and the stress-induced confinement of the tunnels [6]. In general, the main features of Norwegian Method of Tunnelling, as outlined by Barton et al (1992) [2], encompass the following:

- Engineering geology report used as basis for cost estimates
- Unit prices for various rock conditions; client pays according to actual rock conditions;
- Preliminary design used for tendering
- Detailed design decided during excavation after tunnel mapping
- Close collaboration between geologists of contractor and client
- Forum for resolving differences on site
- Emergency power conferred to contractor in the event of adverse conditions

The utilization of high strength and highly ductile fibre-reinforced micro silica shotcrete is another speciality of NMT [5] which removes the need for mesh reinforcement and has sufficient early strength to replace steel and cast concrete arches under a wide-range of tunnelling conditions. The use of wet-mix shotcrete has been increasing over the years, both for temporary support and permanent support [2]. The combination of rock bolting and
shotcrete used for rock support is widespread. It should be further added that numerical modeling and monitoring during construction supplement the empirical design and should be considered a part of the NMT.

3.0 Development of an Underground Cavern Storage Facility

The use of NMT and technology transfer were essential parts of the strategy contributing to the successful development of the Mandai Underground Storage Facility, the first such hard-rock caverns project in Singapore. The project site is located in the central region of the island in the Bukit Timah Granite formation which is about 220 million years old. The rock excavation works which commenced in the year 1999 employed the drill and blast method. The works were carried out in 2 phases and completed in the year 2003. In the following sections, the NMT and its adaptation for use in key aspects of this project are discussed.

3.1 Geotechnical Investigations

Geotechnical investigations are done with the aim of collecting all ground properties [6] to establish (a) a geological model for the design and (b) a basis for predictions for time scheduling, cost assessments, tunnel prognosis, rock support and grout estimates. Geotechnical investigations in Norway are mainly carried out in 2 stages [8]. Pre-investigations are done prior to construction works to provide the base data for the design and planning works whilst investigations done during construction such as probe-drilling ahead of tunnel phase are instrumental in providing detailed information as a basis for site decisions. Such investigations are aimed at determining the variability of the rock mass.

As the construction of tunnels and large underground caverns in rock was relatively new in Singapore, extensive site investigations were carried out using a combination of modern geophysical methods and diamond core drilling to assess suitability of the site for construction and to obtain reliable data for tunnel design [15]. The site characterization works for the Mandai Project formed an integral part of the engineering design process involving the layout planning, support design, costing and construction safety. The overlapping scope of such investigative works limits variability and uncertainty thus giving better resolution of results. The main strategies adopted for the site characterization works for the Mandai Project were:

- Preliminary site investigations to establish overall feasibility
- Main phase investigations based on selected method of tunnelling (NMT)
- Supplementary investigations during design and construction

Figure 3.1 depicts a joint image of the 3-layered composite geological profile using the electrical resistivity and seismic refraction surveys (Source: Mandai Rock Caverns Project)

Figure 3.1 – Composite Geological Profile using the electrical resistivity and seismic refraction surveys (Source: Mandai Rock Caverns Project)

In the Mandai Rock Caverns Project, in-situ rock stress measurements were carried out before excavation, followed by rock stress control and deformation measurements during and after excavation. Extensive site investigations have shown the rock mass to be of good to very good quality for cavern construction. Key geological features include deep weathering trenches, intermittent vertical strips of fractured zones, and a relatively high horizontal stress field [14].
Investigation programs should be cost effective. A cost comparison of the site investigations for the Mandai Rock Caverns project with the Norwegian tunnelling recommendations was made. The Norwegian tunnelling recommendations estimates 2-10% of excavation cost for road tunnels [9] whereas the experience from the Mandai Rock Caverns project show that the investigative works amounted to about 1% of rock excavation cost or about 0.25 equivalent ratio of borehole length to tunnel length. This relatively low cost was attributed to the concentration of the tunnels and caverns within a small land area.

3.2 Empirical Design Using the Q-system

The primary objective of the use of rock mass classification system is to qualify the various engineering properties of the rock mass. The classification system predominantly used in NMT is the Q-system, whilst others used RMR and GSI. The Q-system was developed as a rock tunnelling quality index by the Norwegian Geotechnical Institute (NGI) in the 1970s and was extensively used in the empirical design of tunnel reinforcement and support [1]. In Norway, the Q-system has gained popularity as a useful tool, particularly at the planning stage in connection with the estimates of rock mass qualities and the expected volume of support [7].

Rock mass classification using the Q-system was used in Mandai Rock Caverns Project as a basis for the design and estimation of the rock support and groundwater control measures. Based on the site investigation results, the rock mass were classified according to the Q-system for the preliminary support design in the project. The support design was re-evaluated during construction to determine the adequacy and appropriateness. The statistical distribution of Q-values served a very useful function of providing the necessary information for the cost estimates during tendering. During the construction, the results obtained from tunnel mapping yielded slightly different results, with a higher concentration of the Q values in the Fair to Good category (Figure 3.2). This could be partly attributed to the “uniform” damages on the tunnel surface that were created due to blasting [16].

For the Mandai Rock Caverns project, the owner and contractor agreed to adopt the NMT based on the Q-system as a guideline for estimating rock mass conditions and rock support requirements. This was considered a very important basis for establishing a common understanding and indeed a common “tunnelling language” amongst the owner, consultant, and contractor [16]. As a standard practice, the geology at the tunnel face was mapped and the rock mass quality classified immediately following the blasting of a new round. The conditions were then discussed with the representative responsible for construction on the face in question and the type and extent of construction support needed were agreed upon by the parties concerned. The need for modifications to the excavation procedure such as having short blast rounds or for exploratory drilling and grouting was handled in the same manner. The post-investigations and especially the tunnel mapping were important parts in the process of building up engineering geological experience [15].
3.3 Numerical Modelling and Monitoring

During the detailed design phase of the Mandai project, numerical modeling using the discontinuum model, Universal Distinct Element Code (UDEC), was used to verify the support design and changes were made as construction progressed. UDEC models were also created to study the effects of jointing on excavation stability and identify potential instability mechanisms [16]. The variation of input parameters to the models yielded valuable information regarding the sensitivity of the design to the variation of the in-situ conditions. The evaluation of rock condition and initial or permanent support were based on detailed rock mass description, ground investigation, in-situ observation during excavation, analytical or numerical calculation and monitoring of deformation.

The performance of the tunnels and caverns were monitored during construction by deformation, convergence, rock bolt loads, as well as 3-D stress measurements. Deformation results from numerical analyses and monitoring have shown the possibility of reducing the number of rock bolts without compromising on tunnel stability due to the high horizontal stresses [15]. Further optimization of the cavern height is possible which will reduce the overall excavation cost. Zhou (2002) [15] made a comparison of rock bolt load measurements between the Mandai Rock Caverns and the Gjovic Stadium in Norway to further justify the above findings. Numerical modelling and instrumentation of deformation and bolt loads have shown that the relatively high horizontal stresses are favorable to tunnel stability. These findings were used to optimize the dimension and support design in later parts of the project.

3.4 Water Control in Tunnelling

Water control should be applied to avoid negative impacts caused by tunnelling. Environmental problems due to lowering of the ground water table, inflows of water stopping or slowing down tunnel advance rates or problems with durability of tunnel lining systems due to wet conditions in tunnels are common in tunnel projects. Therefore, The Norwegian concept of water control in tunnelling is based on dry and safe tunnels and hydro-dynamic confinement [4] and as a standard practice, pre-grouting of the rock mass is performed to achieve the required water tightness. The allowable amount of water inflow is determined by the actual circumstances. Eivind (2009) [6] mentions that probe-drilling ahead of tunneling and rock mass grouting form an integral part of the Norwegian tunneling process, where the dual grouting strategies adopted are leakage control and rock improvement.

The permeability of the rock mass at Mandai site consisting of competent rock and joints is in the favourable range of $10^{-6}$ m/sec. The most conductive zones in the rock mass were identified and treated. The main target was to construct a tunnel that is tight enough, in terms of fulfilling the project specific target on allowable water inflow. Ground water during construction was very mild and occurred only in isolated places near the weathering trenches. In the isolated cases where seepage water became excessive, exploratory or probe drilling ahead of the tunnel face was done to locate leakage zones and followed by pre-grouting using cement grout. This was sufficient to control the water inflow in the tunnels.

3.5 Norwegian Contract System and Risk Sharing

The contract system used in Norway which has a 20-year track record of low costs and few disputes is based on tender documents that reflect the unit prices for the equipment, methods and materials most likely to be needed for tunneling [5]. Figure 3.3 illustrates where the Norwegian practice lies in terms of their risk sharing according to type of contract and assumed influence on project cost [9]. The proven success of Norwegian tunnel contract system hinges on the use of experienced engineering geologists by the owners [6].

The management of geological risks was given high priority for the Mandai Rock Caverns project. This included a comprehensive site investigation program and various contractual arrangements aimed at minimising geological risks [16]. In managing the geological risks for the project, rock excavation works were divided into pilot phase and main phases. The pilot phase formed a small portion of the overall rock excavation work but was chosen to represent
the worst expected geological conditions. The pilot phase was created with the following objectives:

- Appreciation of geological conditions and rock mass quality
- Evaluate effectiveness of excavation method and rock support
- Establish data on cost, unit rates, and time
- Verification of design assumptions and cavern performance through instrumentation
- Feedback for modifications of design and technical specifications
- Facilitate Norwegian tunnelling technology transfer and competency build-up

The NMT’s concept for addressing geological risks is focused on risk sharing. Under the Norwegian risk sharing concept, the owner is responsible for the ground conditions, the site investigation results and the overall design concept whilst the contractor is mainly responsible for the construction performance in accordance with specifications [8]. The Mandai project went smoothly without any disputes on the geology and payment for rock excavations [16].

Every effort was made to ensure that the geological risks to the Mandai Caverns Project were properly managed and minimized [16]. A comprehensive Engineering Geological Report (EGR), similar to that of a Geotechnical Baseline Report (GBR) was used in the project. The Mandai Rock Caverns EGR contained specific information on the geological setting, structural geology, geological profiles, ground water and rock mass permeability, in situ stresses, basic rock mechanics data, rock mass classifications as well as anticipated rock mass behaviour for the intended design. Input parameters in the EGR such as the strength and deformation characteristics of the intact rock as well as the in-situ stress magnitudes were essential for the design of the underground openings in the Mandai project. The NMT adopts similar EGR as a basis for cost estimating for tunnel projects.

### 3.6 Contractual Arrangements

Norwegian companies have devised a special system to tailor bids to suit customer needs and expectations and to account for all contingencies [6]. Developed over the last 20 years, the Norwegian Tunnelling Contract System aims to minimize costs and avoid disputes by stating specifications and unit prices for the entire range of potential modifications necessary to adapt to actual rock conditions [8]. Such flexibility allows both contractor and client to make sound economic decisions on the spot. Based on the contract, the parties can work constructively as a team during all phases of construction.

The rock support work is of fundamental importance to the excavation works. The support work re-establishes the stability of the rock as quickly and effectively and as such, it is crucial for the safety of the tunnel facility under operation and also the safety of the tunnel crew during construction. Thus, the contract must be flexible enough to address almost every possible eventuality or occurrence of changing geological conditions.

A design-bid-build contractual approach, with appropriate risk sharing, provides the basis for optimization of cost while minimizing project risks. In this instance, the contractor prices for the risk and the owner absorbs it. Various types of incentives inclusive of bonuses for early completion and meeting safety goals are given to Norwegian contractors to encourage increased productivity and efficient but safe tunneling [9].
From a risk management point of view, there are two main aspects in deciding the contractual arrangement. The first is the contractual arrangement with respect to how geological risks are shared. The second aspect concerns how the design and rock excavation are managed. For both the pilot phase and main phase excavation work, the owner design contract type was adopted for the Mandai Rock Caverns project. This type of contract allowed more flexibility in dealing with the geological risks during excavation. In this arrangement, selection of consultants and approval of design and specifications, overall control of the project remained with the DSTA (owner), while the consultant carries out the detailed design [15]. For this purpose, DSTA planned and built the necessary in-house engineering capability.

Upon completion of the pilot phase, the client and contractor established a common understanding of the expected geological conditions and references for the various cost components [15]. The main phase excavation was based on a lump sum Design-Bid-Build contract with unit rates. The use of cost-plus contract for the pilot phase was due to:

- Lack of local expertise and experience
- Technology transfer
- Provide basis for rates for excavation work in main phase

Under the cost-plus or cost-reimbursable contract for the pilot phase, the contractor was paid for the costs incurred for the works. Under this contract, the cost for the management, overheads and profits was paid on a fixed percentage of the value of work done.

3.7 Construction Practice

Utilization of high capacity equipment, allowing fast progress and short construction time [6] characterizes the practical performance of the tunneling work activities carried out under the Norwegian construction practice. The workers at tunnel face are multi-skilled and well-paid and they are organized in autonomous work teams, led by experienced shift-managers [8]. Traditionally, they have the right expertise delivering projects at high production levels. The experience and organization of the personnel and the choice of equipment allow the flexible and efficient switching between work activities. This means that the adaptation to varying ground conditions can be done without any time loss. The permanent support is selected to suit the ground conditions and the use of the tunnel. Supports are selected from the full range of available measures: scaling, bolting, sprayed concrete, and in-situ cast concrete lining [8]. Experienced geologists participate in the decision making at the tunnel face thus enabling adaptability to the actual ground conditions by carefully following-up of the encountered rock mass through mapping and classification to obtain a best fit for the rock support measures [6].

Unlike the Norwegian construction, the experience in Mandai pilot phase showed that having meeting tight timelines could result in more over-breaks, lesser accuracy and higher powder factor [15]. The local contractors tended to be more specialized but less educated and lower paid. Much of the decision making close to the tunnel face was relatively slow due to lack of experience of the local tunnel crew.

4.0 Discussion

As Barton et al (1992) [2] maintain, the three most essential components of NMT are the systematic bolting, robotically applied fibre-reinforced shotcrete and the Q-value rock characterization. The NMT has several advantages over other tunneling methods. The emphasis given to geotechnical and contractual aspects confers flexibility to NMT for dealing with varying ground conditions and avoidance of disputes. The permanent rock support, consisting mainly of shotcrete and rock bolts, an essential feature of the NMT, is a key factor for fast progress in poor ground. The predicted rock support can be checked using advanced numerical techniques [6] as demonstrated in the Mandai project and adjusted during tunnelling after geotechnical monitoring and geological mapping.

Norwegian tunnelling is highly mechanized with extensive use of self-moving units for all processes [6]. This means that the heavy and partly dangerous manual work that used to characterize tunnelling is strongly reduced. The typical Norwegian tunnel worker is multi-skilled and the crew is organized as an autonomous work group, led by qualified shift foremen. The employer and crews usually negotiate a bonus system based on production achievements.
enhancing motivation geared towards production and reward [9]. The Norwegian experience over the last few years shows that this system can be well combined with high emphasis on health and safety [6]. Safety and contingency planning in Norway are based upon responsibility, equality and the proximity principle [9]. Similarly, safety always had the highest priority in the Mandai Project. Co-operation and coordination of safety matters have worked extremely well for the joint venture and the client. Safety measures on the ground were good and well executed.

In the Singapore case study, the primary support for the tunnels is a combination of rock bolts and steel-fire reinforced shotcrete, the design of which was based on the Q-system and combined with numerical modelling for special design cases. Numerical modelling and instrumentation of deformation and bolt loads have shown that the relatively high horizontal stress is very favorable to tunnel stability [14]. This is attested to by the fact that since construction began in 1999, no tunnel stability problems have been encountered.

A number of literature reviews show that generally there are great uncertainties related to the characterization of the ground features as well as the inability of the Q-system to cover peculiar ground conditions. Pells and Bertuzzi (2008) [13] drew evidence from their case-studies that the support deduced from the Barton’s Q-system might be substantially non-conservative and as a result, the final design support employed is usually substantially heavier than that indicated by the Q-system. Palmstrøm and Stille (2006) [11] acknowledged that classification systems require the user to be experienced with the systems and the tunnelling ground conditions. They also agree with Palmstrøm et al (2006) [12] that “the Q support chart gives only an indication of the support to be applied, and it should be tempered by sound and practical engineering judgment.”

Though the Q-system was very useful in the support design and in the tendering process for the Mandai Rock Caverns Project, the following shortcomings were found by Zhou (2002) [15]:

a) The Q-rating did not take into consideration the effects of joint orientation. The engineering geologist had to adjust the support design based on his perception during tunnel mapping, making the design process somewhat ‘arbitrary’.
b) The resolution in the SRF value in the Q-rating was insufficient to allow the designer to take into account the favorable high horizontal stresses, which had been identified and proven as the primary factor for tunnel stability.
c) Different geologists using different combinations of rock parameters arrived at different Q-values for exactly the same rock mass conditions.
d) There was no information in the Q-chart on the safety margin.

Generally, classification systems such as Q-system should not be used as the primary tool for the design of primary support [12]. The use of rock mass classification schemes need to be updated and used in conjunction with site specific analyses when access to more detailed information on in-situ stresses and rock mass properties are available.

5.0 Conclusion

The NMT has proven to be an effective tunnelling system as it provides a complete set of techniques for investigations, design, excavation and rock support. Generally, with proper implementation, NMT provides cost effective tunnelling. The Norwegian contractual arrangement provides the necessary framework for risk sharing and for adaptation to ground conditions. This risk management tool allows the owner the control of the final product and gives the Contractor an incentive to adopt the best methods and develop them further.

In land scarce Singapore, the need to construct underground excavations at varying depths is providing many challenges and the same time opens new frontiers. Careful engineering is required to lower the risk to acceptable levels both in terms of safety and economy. With NMT, the ability to preview designs and visualize complex technical issues upfront led to better design coordination, a crucial element in a project of such nature, magnitude and complexity.

In conclusion, this paper has outlined the key features of NMT including its applications and short comings. For the Singapore project, the adaption of NMT system including the active approach for the design phase, use of Q-system for the rock classification, use of rock support
measures like steel fibre-reinforced shotcrete, adopting a total risk management approach and contracting methods, have been successful and have been dealt with in detail. This paper hopes to pave the way and provide a platform for others to successfully adopt and implement NMT practices in tunnelling projects in the near future.

References


