Innovative Approaches to Rock Tunnelling

ABSTRACT

The Underground Ammunition Facility (UAF) was the first major rock cavern project in Singapore, where principles of rock engineering were applied extensively in its development.

This article introduces the technologies in rock engineering for the construction of the UAF, particularly the adaptation of the Norwegian Tunnelling Technology to the local context. It also discusses innovative approaches to rock cavern development as well as risk management and contracting practice, which have contributed significantly to the successful development of the UAF.

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INTRODUCTION

The Underground Ammunition Facility (UAF) was the first hard-rock cavern project in Singapore where the construction of large underground spaces was relatively new. Due to the limited land space in Singapore, the use of underground space has to be optimised, leaving less room for flexibility when planning the tunnel and cavern layout. Hence, rock engineering was a key part of the development of the UAF.

A mature tunnelling technology known as the Norwegian Tunnelling Technology (NTT) was adapted to the local context. The use and transfer of NTT was an essential part of the strategy to build local capability in rock tunnelling. While adopting the NTT, the project management team (PMT) implemented innovative approaches to rock cavern management as well as risk management and contracting practice.

This article introduces NTT and explains how the innovative approaches have led to the efficient and successful delivery of the UAF project.

ROCK TUNNELLING TECHNOLOGY

The successful completion of tunnel projects relies on the employment of appropriate tunnelling methods and approaches. The NTT was chosen to be adopted for the UAF project, among other tunnelling methods such as the New Austrian Tunnelling Method which is primarily for tunnelling in weak ground using the active design approach. The NTT was assessed to be the most appropriate for the design, construction and support of underground openings in hard rock and it permitted rapid and safe excavation at a low cost (Sekar, Zhou and Zhao, 2010).

The NTT is a system of tunnelling practices and processes that encompasses a complete set of techniques for investigation, design, construction and rock support. It adopts a systematic approach to the different phases of tunnelling and follows principles of the observational method which includes assessment of the variations in ground conditions, observation during construction, and modification of design to suit actual site conditions. The success of this method also depends on close collaboration among the client, contractors, design engineers and engineering geologists (Blindheim, 1997).

The main features of the NTT (Barton et al., 1992) are:

- Use of engineering geology report as basis for cost estimates
- Establishment of unit prices for various rock conditions: client pays according to actual rock conditions
- Use of preliminary design for tendering
- Selection of detailed design during excavation, which is after tunnel mapping
- Close collaboration between contractor and client geologists
- Forum for resolving differences on site
- Emergency power conferred to contractor in the event of adverse conditions

Some of the key processes and techniques in rock tunnelling applied in the UAF project, such as site investigations, design, construction and rock support, are discussed in the following sections.

Site Investigations

Unlike the construction of buildings, rock excavation involves working with uncertain ground conditions as the quality of rock mass cannot be determined until it is excavated. Moreover, cavern construction was relatively new in Singapore. Thus, to ensure that the site was suitable for construction and to obtain reliable data for tunnel design, site investigations had to be carried out. Site investigations were also essential to establish the 3D geological model of the cavern, which included the rock head elevation, major geologicial features and distribution of rock mass properties.

Geotechnical investigations in Norway are usually carried out in two stages (Norwegian Tunnelling Society, 2008) First, investigations are conducted prior to construction works to obtain the base data for the design and planning works. Second, investigations are conducted during construction works (e.g. probe-drilling ahead of tunnel face) to obtain detailed information for on-site decisions.

For the UAF project, extensive site investigations were carried out using a combination of modern geophysical methods and diamond core drilling to assess the site conditions. These activities formed an integral part of the engineering design process, which involved the consideration of the layout plan, rock support design, cost and construction safety. These investigations were overlapping in scope, which reduced variability and uncertainty (Sekar, Zhou and Zhao, 2010) in the data obtained.

A three-stage approach was employed for the UAF project:

a. Preliminary site investigations to establish overall feasibility

b. Main phase investigations based on selected method of tunnelling

c. Supplementary investigations during design and construction

Site investigations for the UAF included specialist geo-physical surveys and rock drilling. In addition to obtaining rock mechanics properties, results from the site investigations were used to establish the geological model and the rock mass classification.

The investigations showed the rock mass to be of good or very good quality for cavern construction. Figure 1 depicts a joint image of the three-layer composite geological profile using results from the electrical resistivity and seismic refraction surveys.

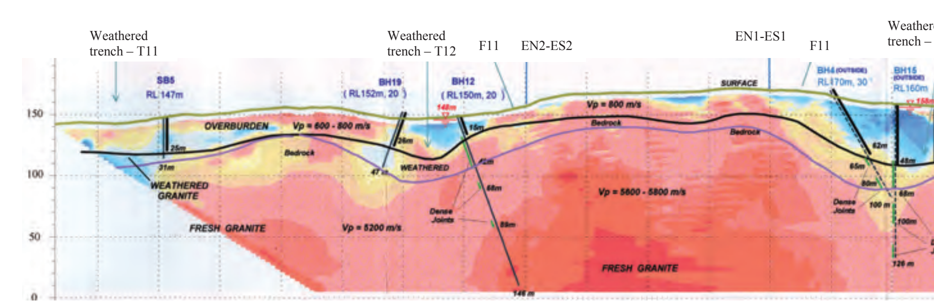

Figure 1. Composite geological profile using results from the electrical resistivity and seismic refraction surveys (Source: Zhou, 2001)

The Use of Q-system for Tunnel Design

A key component of the NTT is the Q-system used for tunnel design. As shown in Figure 2, the Q-system is a design method based on the tunnelling quality index, Q. The tunnelling index Q was developed by the Norwegian Geotechnical Institute in the 1970s (Barton et al., 1974), which was based on the evaluation of a large number of case histories of underground excavation stability. The Q-system is the most commonly used method for rock mass classification in the world.

Based on the site investigation results, the rock mass is classified according to the Q-system for the preliminary support design. The actual support design is determined during construction, after the excavated tunnel surfaces are mapped and a final rock mass classification is done based on the tunnel mapping data.

For the UAF project, the PMT and contractor agreed to adopt the NTT based on the Q-system as a guideline for estimating rock mass conditions and rock support requirements. This arrangement was considered a very important basis for establishing a mutual understanding or a common "tunnelling language" among the PMT, consultant and contractor (Zhou, 2002). The adoption of the Q-system was also critical because local regulations did not have any design code for rock tunnelling work.

Drill and Blast Tunnelling Cycle

Tunnelling can be carried out by mechanical methods, such as tunnel boring machines and road headers, or the conventional drill-and-blast method. The choice of method depends on site geology and project-specific conditions, such as the length and cross-section of the tunnel. The drill-and-blast approach was the only practical method for the UAF project, because of the hard rock and complex geometric layout of the facility.

The drill-and-blast method of construction is a cyclical process. A typical tunnel construction cycle consists of several activities as shown in Figure 3. The cycle begins with surveying, then continues with drilling, charging, blasting, ventilating, removing the muck, scaling and installing the rock support. As these activities are interdependent, proper coordination among different work teams is essential to conduct tunnelling at multiple locations.

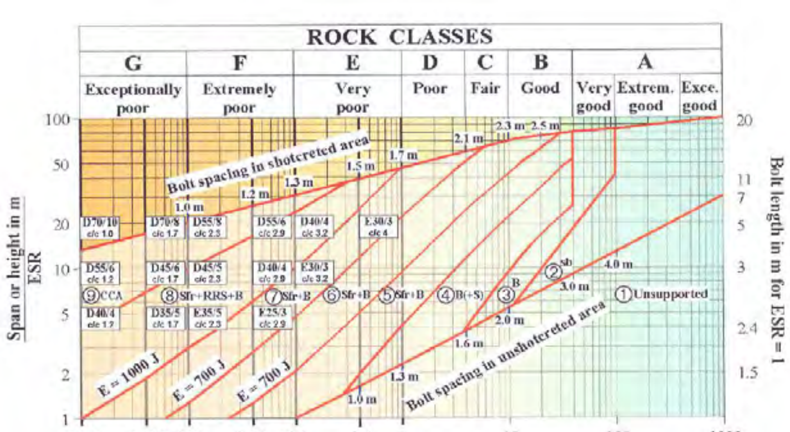

Figure 2. Barton's Q-chart (Source: Barton et al., 1992)

Figure 3. Typical drill-and-blast tunnelling cycle

In the UAF project, the time taken for each tunnel cycle ranged from 12 to 15 hours, depending on the geometry of the tunnel excavated.

Highly mechanised processes were introduced to the drill-and-blast works which reduced heavy manual work, improving productivity and enhancing safety as a result. These mechanised processes included using automated, robotic and specialised equipment in the excavation area. Further mechanisation was carried out for the support infrastructure services in the excavated area.

Fully computerised drilling jumbos (see Figure 4) were used to drill holes in the rock face for more accurate blasting results. Thereafter, the holes were filled with explosives and detonated. Next, the excavated area was ventilated to remove any toxic fumes created from the blasting, and the tunnel muck was cleared away. After scaling the loose rocks, rock supports were installed for the walls and crown of the tunnel. This process was repeated until the tunnel was fully excavated.

Figure 4. State-of-the-art drilling jumbos in operation

The rock supports helped to prevent the rock mass from caving in. For the UAF, the rock support system used consisted of steel-fibre reinforced sprayed concrete (known as shotcrete) and cement-grouted rock bolts (see Figure 5). Rock bolts have a "stitching" function that is used mainly to support larger rock blocks, while shotcrete helps to contain the smaller blocks in between the rock bolts. The versatility and adaptability of the NTT have been demonstrated through this project and its ability to make use of either shotcrete or rock bolts for the initial and final rock support.

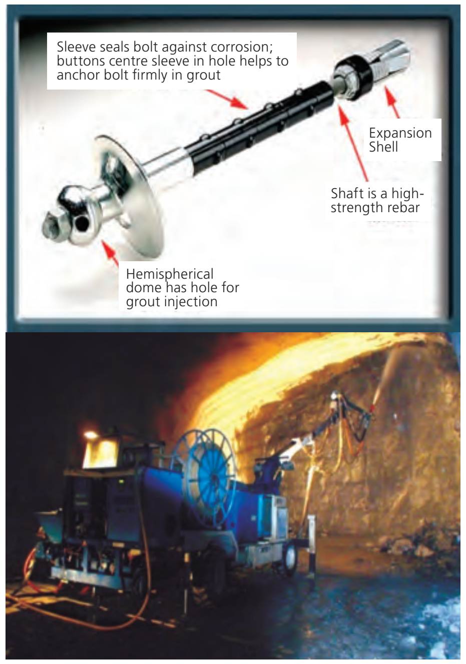

Figure 5. End anchored rock bolt (Top) and application of shotcrete (Bottom)

INNOVATIONS IN ROCK ENGINEERING

While adapting the NTT to the local context, the PMT had to address several unique challenges of the project through innovation.

The lack of local expertise in hard rock tunnelling meant that the PMT had to rely on foreign expertise and the subsequent transfer of technology. Thus, the PMT established collaboration with the contractor to manage these risks innovatively. While constructing the UAF, the Housing Development Board (HDB) was operating within the quarry and its quarrying operations could have had an impact on the UAF's rock space requirements. This situation led to another partnership which allowed both agencies to meet their requirements.

Stringent regulations and control in Singapore on the handling, transportation and storage of explosives, as well as work and safety conditions, posed challenges related to the blasting works of the UAF. To ensure safety requirements were met, the PMT searched for new technologies in the market. The limited resources in Singapore spurred the PMT to come up with sustainable initiatives that addressed the need for environmental protection. Thus, the innovative reuse of tunnel muck, excavated rocks and pond water was explored. The PMT also challenged the conventional methods in rock engineering design to maximise land use for the UAF development.

The following section explains how these innovations were applied to overcome challenges as well as to achieve cost savings and higher productivity.

Winning Through Collaboration

> Risk Management and Contracting Practice

The management of geological risks was given high priority for the UAF project. This included a comprehensive site investigation programme and various contractual arrangements aimed at minimising geological risks (Zhou and Cai, 2007). Emphasis was also placed on facilitating technology transfer, as competency build-up within the local community was essential to minimise geological and security risks.

The rock excavation work was divided into two phases: the pilot phase and the main phase. The pilot phase was a small portion of the overall rock excavation work, but the site chosen for this phase represented the worst expected geological conditions.

The pilot phase was conducted with the following objectives:

- Facilitate technology transfer and competency build-up
- Understand geological conditions and rock mass quality
- Evaluate effectiveness of excavation method and rock support
- Collate data on cost, unit rates and time
- Verify design assumptions and cavern performance through instrumentation
- Gather feedback for improving the design and technical specifications of the tunnel

From a risk management point of view, there are two main aspects to consider in the contractual arrangement. First, parties involved in the contract have to decide how the geological risks will be shared. Second, they have to plan how the design and rock excavation will be managed.

The NTT's concept for addressing geological risks is focused on risk sharing. Under the Norwegian risk sharing concept (see Figure 6), the PMT is responsible for the ground conditions, the site investigation results and the overall design concept while the contractor is mainly responsible for the construction performance in accordance with specifications (Norwegian Tunnelling Society, 2008).

For the pilot phase and main phase of the excavation work, the traditional Design-Bid-Build contract was adopted for the UAF project. This type of contract allowed more flexibility in dealing with the geological risks during excavation. In this arrangement, the selection of consultants, approval of design and specifications, and the overall control of the project remained with DSTA (client), while the consultant carried out the detailed design (Zhou, 2002).

Unlike the main phase, the pilot phase was based on a cost-plus or cost-reimbursable contract. Under the cost-plus contract, the

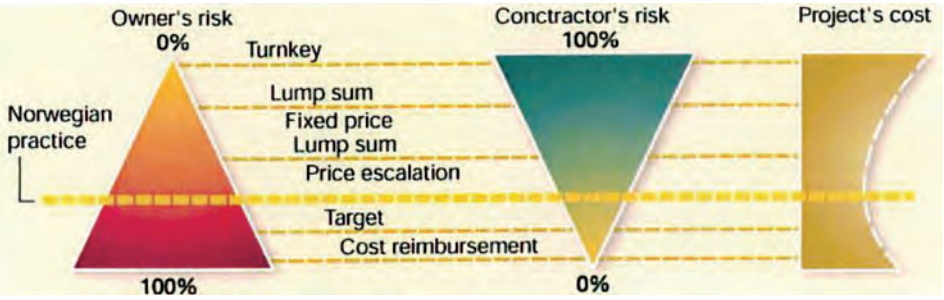

Figure 6. Norwegian concept of risk sharing for different contracts (Source: Norwegian Tunnelling Society, 2008)

contractor is paid for the costs incurred for the works, plus a fixed percentage of the value of work done – covering overhead costs, management fees and the profit margin. The cost-plus contract was used for the pilot phase due to the lack of local expertise and experience. This form of contracting also facilitated technology transfer and provided the basis for excavation work charges in the main phase. Using a cost-plus contract required very tight management and deep technical involvement by DSTA, as well as close collaboration among all parties working on the project.

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. The main phase of the excavation was based on a lump sum Design-Bid-Build contract with unit rates. The advantage of the high flexibility in drill-and-blast tunnelling was fully realised with corresponding contracts that specified a fair risk sharing between the client and the contractor. As a result, the rock excavation work went smoothly without any disputes while achieving very competitive cost rates for rock excavation (Zhou and Cai, 2007).

> Combining Aggregate Mining and Quarry Shaping

Shaping the Mandai quarry was an essential part of the design to ensure facility protection and external safety. With nearly 30 hectares of surface area covering the construction site, the Mandai quarry required substantial rock excavation.

During the early stages of the UAF construction, HDB was operating within the existing quarry which provided building materials for its housing projects. Thus, HDB wanted to continue its quarrying operations for as long as possible. The PMT worked with the HDB Quarry Office to devise a plan that would allow quarrying operations to continue, while the quarry was shaped according to the requirements of the UAF project.

Previous quarry operations had left the quarry wall heavily damaged which required additional works for quarry wall protection. Based on the PMT's input, controlled blasting was incorporated into HDB's quarry blasting, resulting in minimal rock damage to the final quarry walls. This inter-agency collaboration was a win-win approach that helped the project to save more than S$2 million in rock excavation and quarry wall protection works, as well as to reduce the construction lead time.

Excavating More for Higher Productivity

The drill-and-blast method is cyclical in nature and it is a slow process with the average blasting cycle advancing at a rate of five metres in length. For optimal resource utilisation and shorter overall excavation time, it is advantageous to excavate concurrently on multiple working faces.

Based on the facility layout, the contractor had to excavate the long access tunnel leading to the storage area, as the storage level was where multiple faces could be opened for excavating a major volume of rock. However, this approach to construction would result in longer excavation time and lower productivity.

To gain direct access to the storage area and open up multiple working faces, the PMT instructed the contractor to excavate a separate construction access tunnel (see Figure 7) with a steeper gradient. This construction access tunnel required the PMT to work around the tight tunnel layout.

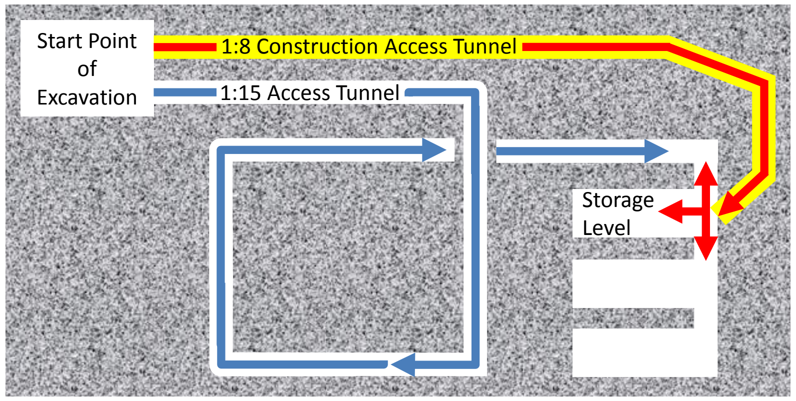

Figure 7. Sketch of construction access tunnel

With the excavation of this tunnel, the contractor was able to reach the caverns in half the time required and this ramped up the production rate by opening multiple working faces. The time for clearing the muck away was also reduced because of shorter travelling distance for the vehicles. This solution helped the project to save four months of construction time and resulted in overall savings of S$1 million although more excavation works were done.

Harnessing New Technologies

The blasting work for the UAF excavation required more than 4,000 tonnes of explosives. Storing and handling the necessary explosives posed major challenges during the construction planning stage, due to the stringent safety regulation of explosives in Singapore. The daily transportation of explosives for blasting work would also mean additional risks to public safety.

A new commercial explosive product called bulk emulsion was selected for use in the project. This product was introduced for the first time in Singapore. The bulk emulsion is classified as a Class 5.1 Hazard Division chemical (non-explosive) and can be stored safely on site (see Figure 8). The emulsion only becomes "live" when it is pumped into the drill-hole together with an oxidising agent.

Figure 8. On-site storage of bulky emulsion

With the use of bulk emulsion, the only high explosives required for the blasting work were the detonators and the booster charges. To address the safety and logistic issues, the idea of an on-site storage was conceived. Approval was sought from various agencies to construct and operate a temporary magazine (see Figure 9) within Mandai Quarry, in a rock cavern excavated specifically for this purpose. This

Figure 9. On-site storage magazine (Source: UAF Project)

on-site magazine was the first of its kind to be built locally in a rock cavern to store construction explosives. With the on-site magazine, transportation of high explosives on public roads was reduced significantly from a daily to a monthly basis. The on-site magazine also provided better safety and security, and more importantly improved site productivity.

The combined use of bulk emulsion and on-site storage of detonators and booster charges solved a major safety issue, and resulted in better productivity. It also helped to reduce ventilation time and air pollution as there were less toxic fumes emitted from the blasting. The total estimated cost savings was about S$10 million. The introduction of bulk emulsion to the UAF project was such a success that the Norwegian Road Authority requested a visit to the UAF site to learn more about this new technology for their own evaluation process.

Turning Waste into Assets

> Recycling Tunnel Muck for Road Base Products

The excavation of the underground space generated about 6.5 million metric tonnes of excavated rocks, also known as muck or waste material. This large volume of excavated material had to be disposed of at a cost.

The PMT came up with the idea to reuse this natural resource as a material replacement for graded stones, which were required for constructing pavements. The granite muck from the rock excavation was sieved on site to obtain a material similar to graded stones. The sieved muck was then assessed by the consultant to be technically feasible for road base construction. The recycling of sieved muck for road base construction achieved overall cost savings of S$860,000.

> Using Rocks for Building Products

Besides recycling the sieved muck for the project, there was a potential use of these excavated rocks in the local construction industry. After consulting various agencies, the PMT performed a market survey and assessed that there was a demand for these excavated rocks in the building industry.

Through an open tender approach, the final rock disposal option was to sell the excavated rocks to a contractor. The selected contractor processed the excavated rocks by crushing them into various building and road construction products (i.e. graded stones, crusher-run stones, aggregates and granite fines). The rock disposal contract generated revenue of S$17 million for the government, while saving the UAF project the cost of rock disposal.

> Tapping Pond Water for Tunnel Construction

In rock blasting, a large volume of water was needed for various tunnel activities such as drilling, scaling, shotcreting and wetting the muck pile for dust control. Using water from the Public Utilities Board means that a higher cost would be incurred for portable water and the additional water infrastructure required.

After exploring various solutions, the PMT came up with the initiative to harness water from the nearby Gali Batu pond which was more than 30 metres deep. As part of the safety design, the pond had to be pumped out to prevent flooding of the UAF. Overland pipes were laid to pump water from the pond to a holding basin above the tunnel site, before the water was drawn for construction use. This environmentally friendly solution tapped about 1.5 million cubic metres of pond water, which saved the UAF project more than S$1 million.

Challenging the Norm

With the need to minimise land use for UAF development, one of the challenges faced during the planning stage of the facility was to configure the underground space within a limited footprint. To minimise the overall land use, it was important to obtain the optimal separated distance between tunnels. There was also the challenge to ensure that excavation of the tunnels at close proximity would be safe and stable. However, the data for tunnel separation was not available in the literature at that time. In general, designers followed the rule of thumb for rock engineering design, which was a conservative route.

For the UAF project, there was a tunnel directly above another tunnel. The specialist consultant had proposed a minimum separation of 15 metres between the two tunnels. The separation would require deeper storage chambers, a larger footprint, and longer access tunnels resulting in higher construction cost and longer vehicle travel time for operations.

The PMT conducted a joint research project with Nanyang Technological University and collaborated closely with the consultant to assess the optimal separated distance. The following procedures were undertaken:

- Extensive numerical modelling of the tunnel configuration
- Consideration of the unique conditions of the granite in Bukit Timah which had a relatively high horizontal stress (see Figure 10)
- Rock stability instrumentation inside the tunnels
- Monitoring tunnel stability during construction

As a result, the PMT proposed a reduction of the separation distance from 15 metres to eight metres. The proposal also took into account the unique conditions of a relatively high horizontal stress. This solution led to the excavation of a shorter tunnel, achieved cost savings of about S$9.3 million, and reduced the travelling time during user operations.

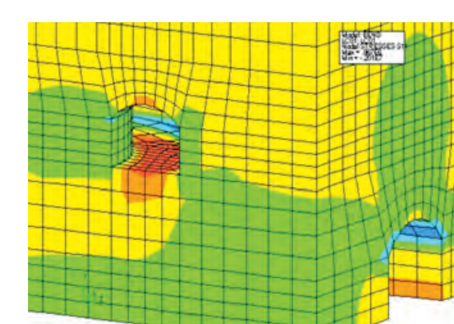

Figure 10. Typical numerical model

CONCLUSION

The UAF project provided a platform for the PMT to learn and innovate through the adaptation of the NTT. The use of the tunnel technology with a planned technology transfer and capability build-up, as well as the innovations in rock engineering collectively contributed to the successful development of the UAF project.

The challenges faced in this project were multi-faceted due to the scale and complexity of the project, with numerous stakeholders involved. Being new to this field, the PMT took a holistic approach to rock engineering and focused on the big picture. Opportunities for overall improvements in efficiency and process optimisation were seized through innovation, as well as active collaboration and partnership established among stakeholders of the project.

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BIOGRAPHY

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