A New Era of Underground Construction in Hong Kong – From Ground Investigation to Construction

Simon C. M. Leung, Bridges Guy D.C. & Franklin K. L. To
AECOM Asia Company Ltd., Hong Kong, China
Michael W.K. Choi
Drainage Services Department, HKSARG, Hong Kong, China

doi: https://doi.org/10.21467/proceedings.171.10

ABSTRACT

In order to support the sustainable development in Hong Kong, the Drainage Services Department (DSD) commenced the project 'Relocation of Sha Tin Sewage Treatment Works to Caverns'. The first stage of construction for Main Access Tunnel was commenced in February 2019 and completed in April 2022 under Contract No. DC/2018/05. The excavation of main caverns to accommodate the sewage treatment facilities is on-going under Contract No. DC/2020/05. The paper first highlights the comprehensive ground investigation in planning stage. Advanced ground investigation techniques, including horizontal directional coring, surface geophysics tests, downhole geophysical logging, over-coring and hydraulic fracturing tests were carried out. The paper also briefly mentions the rock support design of MAT using rock reinforcement approach. The construction phase involves the installation of permanent rock bolts and shotcrete lining, implementation and utilisation of innovative and advanced technologies in drill-and-blast excavation with advanced sensors, surveying data with 3D laser scanner, and real-time monitoring via 5G network. These have allowed the team to conduct study on ground parameters, review of blasting design, continuous monitoring on excavation progress and quality control on site. The MAT construction under Contract No. DC/2018/05 represents a significant milestone in tunnel construction in Hong Kong. It showcases the integration of geotechnical expertise, innovative engineering, and meticulous construction practices. This paper provides an overview and valuable insights in shaping the future and usher in a new era of underground construction in Hong Kong.

1 INTRODUCTION

1.1 The Project and Main Access Tunnel (MAT) completed under Contract No. DC/2018/05

To support sustainable development in Hong Kong, the Development Bureau (DEVB) put forward the initiative to launch strategic planning and technical studies aiming at promoting the enhanced use of rock caverns. The Drainage Services Department (DSD) commenced the project 'Relocation of Sha Tin Sewage Treatment Works to Caverns' as shown in Figure 1. The primary objective of this relocation is to greatly improve the environment of the existing Sha Tin Sewage Treatment Works (STSTW) site and its surroundings. After the relocation, the existing STSTW plants will be demolished to release approximately 28 hectares of land for various beneficial purposes. The relocation plan is being implemented by phases with due consideration of practicality, cost-effectiveness, contract interfacing, and timely delivery of project.

The major geotechnical works include the site formation works at portals, access tunnels and main caverns construction. The stage 1 works (Contract No.: DC/2018/05) for site preparation and MAT construction as demonstrated in Figure 2 was commenced on 28 February 2019 and completed on 10 April 2022. The stage 2 works (Contract No.: DC/2020/05) for main caverns, secondary access tunnel, ventilation adit and ventilation shaft construction commenced on 5 July 2021 and the extensive blasting works on site is currently on-going.

Published by AIJR Publisher in "Proceedings of The HKIE Geotechnical Division 44th Annual Seminar - Elevating Geotechnical Excellence: Novel Practices & Innovative Solutions" (GDAS2024). Organized by the Geotechnical Division, The Hong Kong Institution of Engineers, Hong Kong on May 31, 2024.

Proceedings DOI: 10.21467/proceedings.171; Series: AIJR Proceedings; ISSN: 2582-3922; ISBN: 978-81-970666-7-2

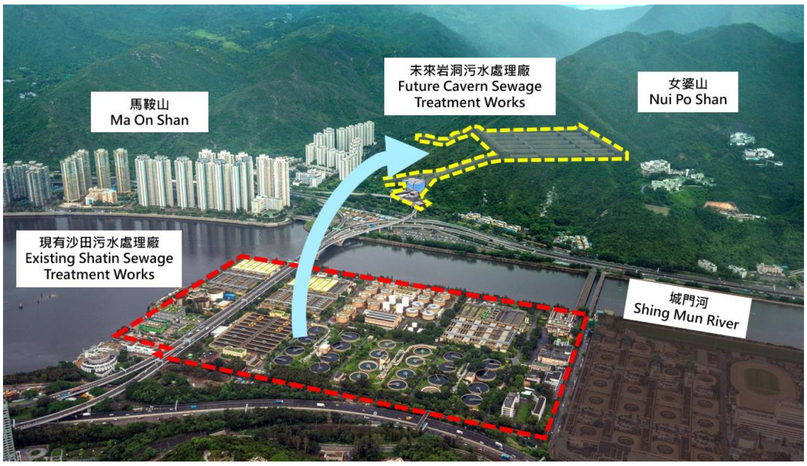

Figure 1: Relocation of Sha Tin Sewage Treatment Works to Caverns

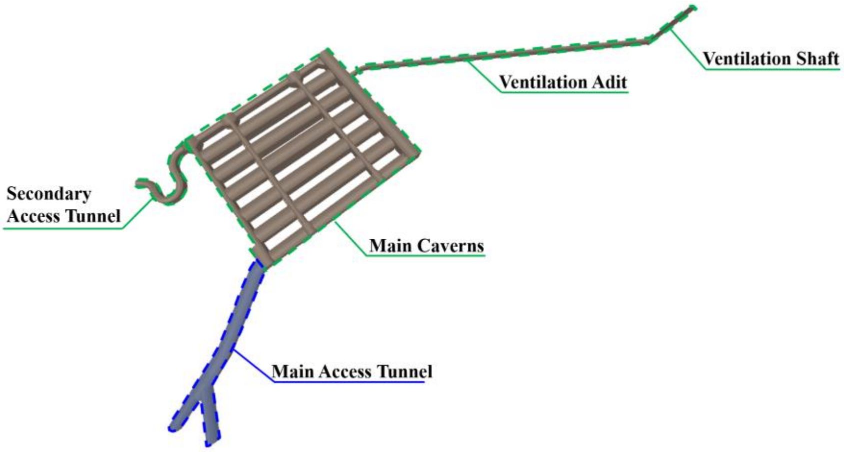

Figure 2: Main Access Tunnel (MAT) and main caverns

2 GROUND INVESTIGATION WITH ADVANCED METHODS

2.1 Horizontal Directional Coring (HDC)

HDC is used to obtain targeted core samples and field testing at specific locations of interest. It allows crossing sub-vertical geological features/faults and provide improved information compared to conventional vertical inclined boreholes. The technique involves “steerable” drilling and continuous core sampling along a planned trajectory. The drilling trajectory including the direction and curvature are controlled by rolling and bending angles. The coring survey is continuously conducted using a miniature electronic multishot (EMS) instrument to ensure the as-built borehole trajectory aligns within the tolerance envelope as per proposed coring alignment.

A total 2 nos. of HDC with approximately total length of 1.85 km were drilled for the project. The drill rig was set up at the base of the hillside with a large working area to accommodate rods of 1 km length. Photos for core barrels and drill rig for HDC are shown in Figure 3 and Figure 4.

Figure 3: Core barrels for HDC

Figure 4: Drill rig set up for HDC

An example of collected information from HDC along MAT is shown in Figure 5, including the Total Core Recovery (TCR) and Rock Quality Designation (RQD). There is a great flexibility in longitudinal gradient to suit the MAT alignment and allows the collection of continuous geological information.

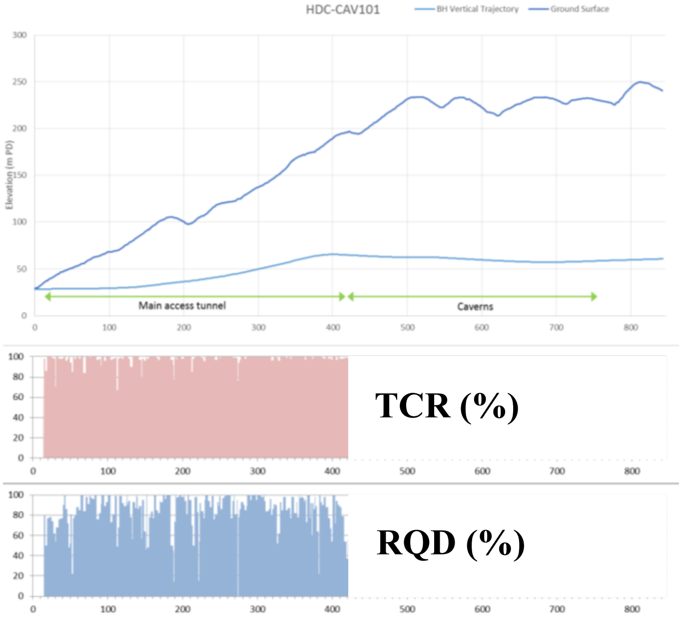

Figure 5: Alignment of HDC-CAV101 along MAT

When cores are retrieved from boreholes, it is difficult to determine the rock joint planes orientation. This project is the very first one in Hong Kong to conduct televiewer tests in HDC. Special equipment with overseas specialist geophysical contractor was employed. Optical televiewer (OTV) was used in upwards inclined hole which cannot retain water; while acoustic televiewer (ATV) was used in downwards inclined hole.

Figure 6a & 6b: OTV tool in end of drill string (left) and cable threaded through 1km long drill rod (right) for HDC

2.2 Surface Geophysics Tests

Seismic refraction tests were conducted to identify rockhead and rock quality at portal areas. It measures the time for seismic waves to travel through different subsurface layers. By analysing the travel times and waves velocities, the subsurface layers and their properties were determined. Geophones were set up along the seismic lines on ground surface and connected to computer. The trained workers then hit the ground with a hammer to induce a seismic wave (Figure 7a). Signals from the geophones were then recorded by the data logger. Analysis of signals for multiple hammer blows can determine seismic velocity through the ground (Figure 7b).

Figure 7a & 7b: Hammar hitting along the seismic lines (left) and signals analysis (right)

In general, the elevated ridges are commonly underlain by thicker layer of soil; whereas the stream cut channels showed a higher bedrock profile according to the tomographic seismic velocities from the refractive waves. The layout plan for the interpreted rockhead depth is presented in Figure 8.

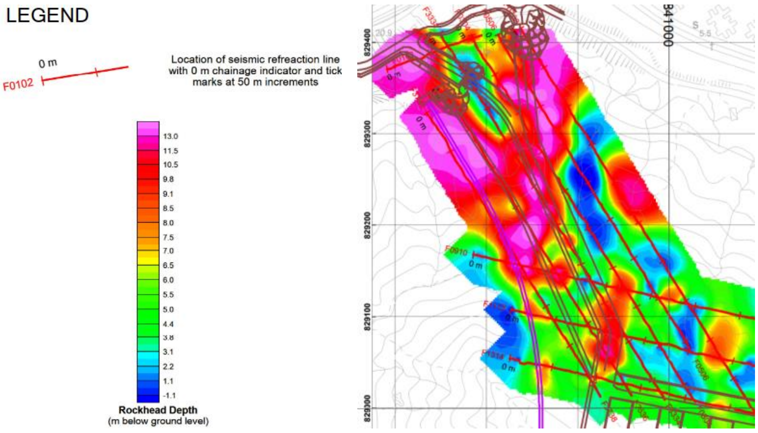

Figure 8: Layout plan for interpreted rockhead depth along MAT by seismic refraction traverses

Surface gravity surveys were conducted to identify any potential deep geological features. The strength of Earth's gravitational field, affected by the density of ground, was measured on a grid across the site to detect areas of differing densities, such as variations in rockhead levels in Figure 9, which may be indicative of faults or structural features, as well as man-made or natural cavities or the compaction of soil at ground surface.

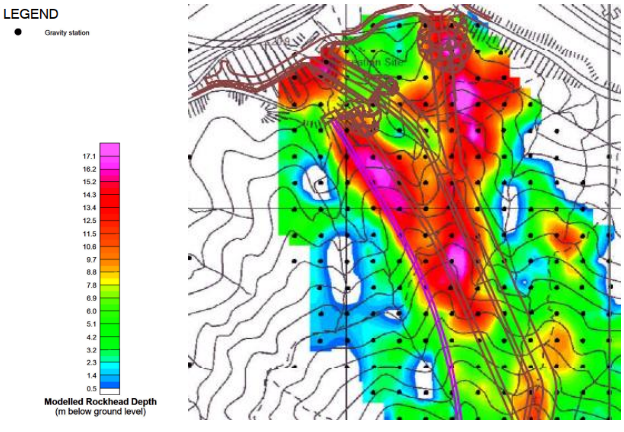

Figure 9: Microgravity survey modelled rockhead depth

2.1.3 Downhole Geophysical Logging

Downhole geophysical logging aims to obtain quantitative data from a drilled borehole, such as the mineralogy and geotechnical properties. It is relatively cheap and fast to obtain information on the borehole conditions. Surveys can cover up to 150m of hole in less than 1 day, with instant availability of the findings. In vertical / inclined boreholes and HDC, uncommon tests in Hong Kong were carried out for the project, including ultrasonic P and S wave velocity measurement, resistivity measurements and gamma logging.

The measurement of P and S wave velocity was able to evaluate the quality of rock. An example is extracted in Figure 10b. With the wave velocities and measured rock density, the elastic modulus and rock mass quality were evaluated based on empirical relationships.

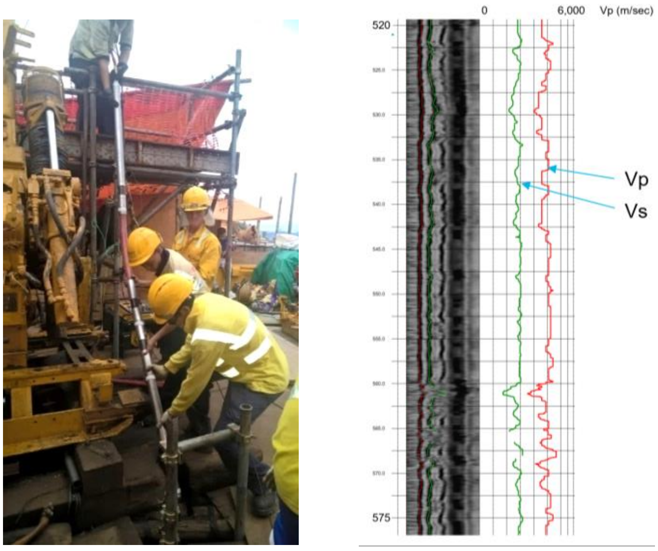

Figure 10a & 10b: Downhole geophysical logging (left) with ultrasonic wave velocity measurement (right)

Downhole resistivity (ohm-m) measures the inverse of the conductivity of the rock between a receiver and a transmitter as the tool was being raised through the borehole, which is mostly affected by water content of rock mass. Therefore, the resistivity appears to be highlighting the more fractured and weathered rock mass with a slightly higher water content (i.e. higher conductivity and lower resistivity). The resistivity could also be correlated to the logged weathering decomposition grade of granite as shown in Figure 11.

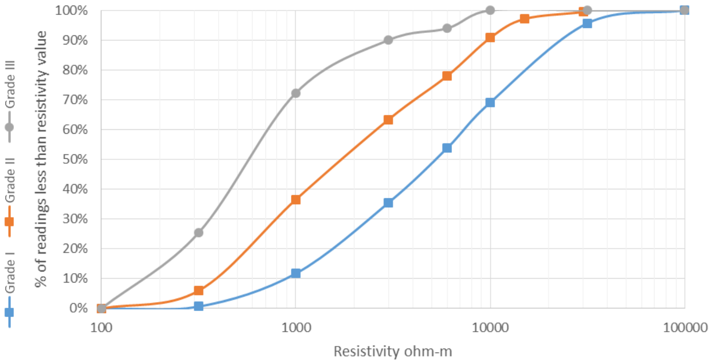

Figure 11: Correlation of resistivity and logged decomposition grade

Granite is known to emit relatively high levels of gamma rays due to the potassium (K) in the feldspars and trace amounts of elements such as uranium (U) and thorium (Th) typically found in granite. The gamma logging tool (Figure 12) was used to measure the natural radiation emitted by rocks down a borehole to determine the chemical and physical properties. The number of gamma rays striking the instrument per second was measured and converted into API (American Petroleum Institute) units.

Figure 12: Gamma tool being extracted from drill rods after testing in a borehole

For Shui Chuen O Granite, the K content is approximately 5%, uranium is only 7ppm and thorium is 43ppm. Unlike measurement for resistivity, there is no difference in gamma count between grade I / II granite, but a possible increase for grade III granite. In general, basalt dykes have a significantly lower gamma count due to lower K, U and Th content. For faulted rock, it had a wide range of gamma count based on minerals redistribution during faulting in related to hydrothermal alteration. An example is presented in Figure 13b.

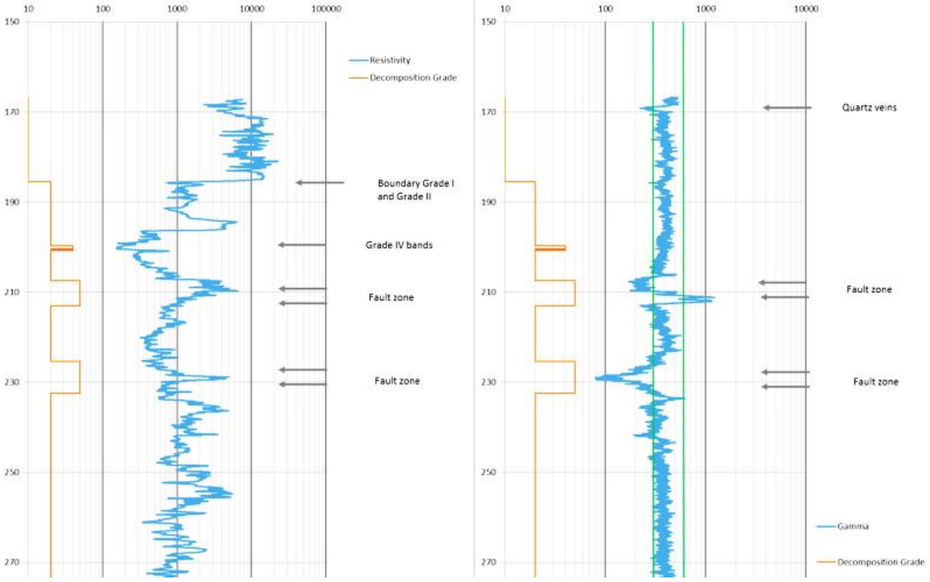

Figure 13a & 13b: Results of resistivity (left) and gamma count (right) along a borehole

2.1.4 In-situ Stress Measurement

Stress-controlled failure is one of the main failure modes for rock tunnels/caverns stability. In order to study the in-situ stress conditions, two field tests named over-coring and hydraulic fracturing were conducted.

Over-coring involved drilling of a borehole (101mm diameter) to a designated depth with a flattened hole bottom by a special drill bit, and further drilled a 38mm dia. smaller pilot concentric hole as shown in Figure 14a. A triaxial measuring cell (Figure 14b) was then inserted and fixed inside the smaller concentric hole.

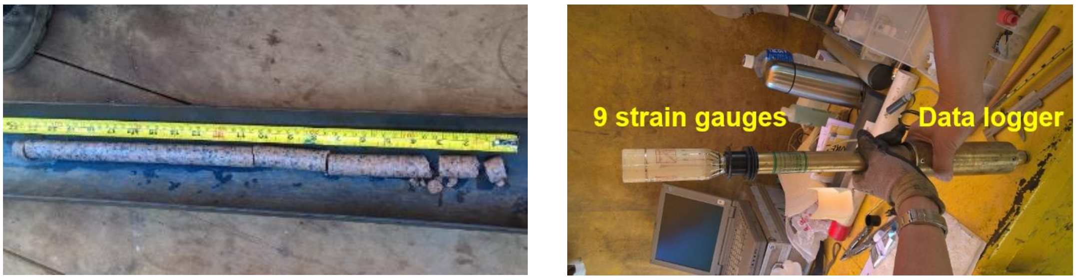

Figure 14a & 14b: Pilot concentric hole (left) and triaxial measuring cell (right)

The small hole with cell and data logger fixed inside was then slowly overcored by the larger diameter bit and retrieve from borehole as demonstrated in Figure 15a. The stress acting on the rock core is relieved and the corresponding strains before, during, and after overcoring were recorded by the strain gauge rosettes. The in-situ stress states can then be evaluated based on the strain difference elastic properties of the rock.

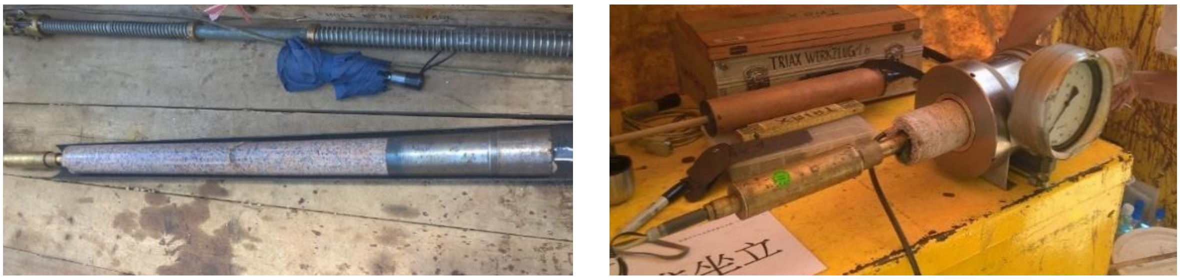

Figure 15a & 15b: Overcored rock with measuring cell (left) and field measurement for elastic properties (right)

Hydraulic fracturing test as presented in Figure 16 involved injecting water or other fluid at high pressures into a test section isolated by packers in a borehole, until the rock failed in tension and induced controlled fractures. The fluid pressure for inducing, propagating, sustaining and re-opening the tensile fractures were constantly recorded as a function of time. The orientation of the hydraulically induced fracture plane coinciding with the orientation of the maximum horizontal principal stress was then determined by the impression packer test; while the orientation of the minimum horizontal principal stress is perpendicular to the fracture plane.

Figure 16: Site establishment for hydraulic fracturing test

2.1.5 Rock Core Samples Logging as Grade I – Fresh Granite

As a conservative approach, local GI contractors have been avoiding to assign grade I – fresh granite to core samples. Therefore, there is a high chance that some excellent rock cores were conservatively classified as grade II rock. For this project, the AECOM team has carefully checked and logged grade I for granite as shown in Figure 17. Differentiating grade I from grade II granite (Figure 18) has not been a usual practice in Hong Kong.

Figure 17: Core samples logged as grade I granite (i.e. fresh)


Grade I granite **Grade II (almost grade I) granite**

Figure 18: Differentiating Grade I from Grade II granite

3 ROCK SUPPORT DESIGN

3.1 Geological Model and Rock Mass Quality

The solid geology is predominantly Shui Chuen O Granite. Based on the extensive GI data, a three-dimensional geological model (Figure 19) was developed. No major faults were identified crossing the MAT. The identified geological features/photolineaments could result in slightly lowered rockhead and fractured altered rocks.

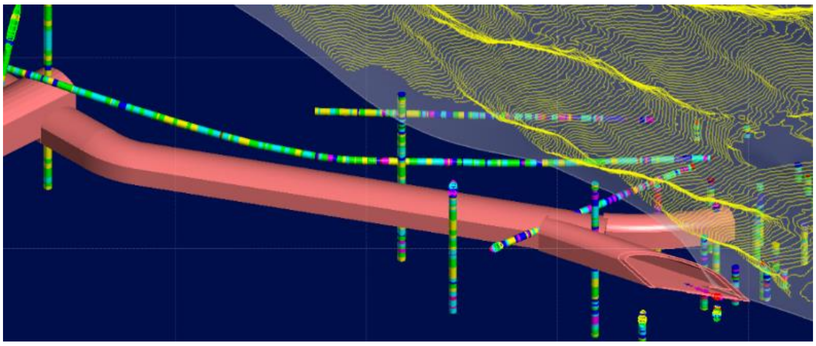
Figure 19: Three-dimensional geological model for MAT

The NGI Q-system first developed by Barton et al. (1974) and updated by Grimstad & Barton (1993) was used for rock mass classification. It describes the stability of an underground opening in jointed rock masses. The Q-value is formulated by the multiplier of six different rock mass parameters as presented in Equation 1:

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

A high Q-value indicates good stability, and vice versa. It has been commonly used in Hong Kong to assess the rock mass quality and determine support classes for hard rock tunnels. For a given combination of Q-value and cavern configurations, the shotcrete and rock bolt support requirements for a given rock support class can be obtained. However, the limitations include the appropriateness for large-span and multiple parallel caverns.

The strength of a jointed rock mass depends on the behavior of both intact rock and rock blocks. For rock mass properties in finite element modelling, the Generalized Hoek-Brown (GHB) failure criterion by Hoek et al. (2022) was adopted. It estimates the deformation and strength characteristic of rock mass based on the interlocking effect and discontinuity conditions. The rock support class defined by the Q-value was correlated to Geological Strength Index (GSI), which is a input parameter for GHB failure criterion, using Equation 2:

$$GSI = 9 \ln Q' + 44 \qquad (2)$$

3.2 Permanent Support System with Rock Reinforcement Approach (RRA)

The span of MAT is ~26m underlain by strong granite with uniaxial compressive strength of 65 to 165 MPa, which is much greater than structural concrete. With an arched roof to utilize the arching-effect/hoop stress, the rock support design using RRA as sketched in Figure 20 offered a practical method to consider the hard rock as a structural material to self-support itself. The inherent strength of rock mass is utilised by applying confining pressure from bolts. Permanent rock bolts were installed as primary supports for forming the reinforced rock arch, while permanent shotcrete is the secondary support for the smaller rock wedges between adjacent bolts.

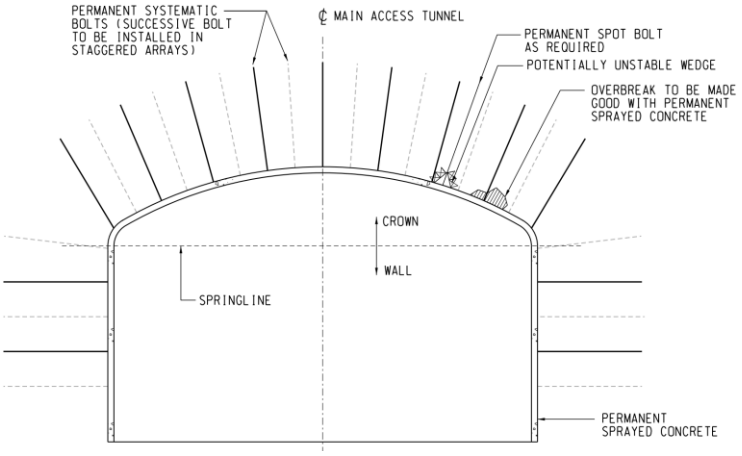

Figure 20: Excavation Profile and Permanent Rock Reinforcement of MAT

Design verification of permanent rock reinforcements estimated by empirical methods and RRA was carried out using numerical analysis, including 2D and 3D finite element modelling (FEM) as shown in Figure 21 and Figure 22, as well as discrete element modelling. The systematic rock bolts and shotcrete lining were designed to withstand the induced rock supporting pressure re-distributed from the surrounding ground after excavation; while permanent spot bolts to support individual rock wedges were determined by the geologist on site.

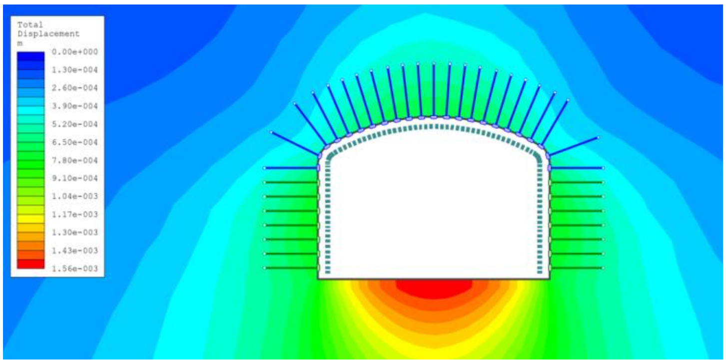

Figure 21: 2D FEM Analysis for Permanent Rock Reinforecment at MAT

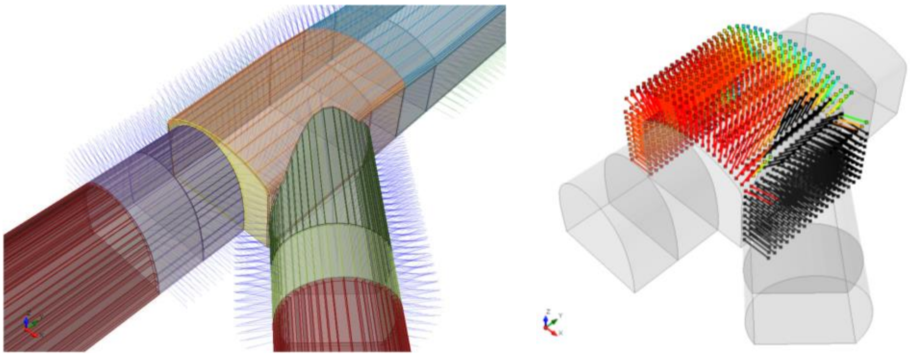

Figure 22: 3D FEM Analysis for Permanent Rock Reinforecment at MAT Junction

4 CONSTRUCTION

4.1 Installation of Permanent Rock Bolts and Shotcrete Lining

Rock bolts and with temporary shotcrete provides immediate support to the excavated rock, which allowed safe and efficient continuation of MAT blasting activities. The proprietary rock bolts with specific corrosion protection measures (Figure 23a) and expansion shell at far end (Figure 23b) provided immediate support through mechanical anchorage and were fully grouted to ensure bond strength and durability prior to next blast. The permanent shotcrete lining was applied in later stage to facilitate blasting and excavation activities. Without the need of heavy steel shutter for cast-in-situ lining, the rapid installation significantly saved time and cost.

Figure 23a & 23b: Permanent rock bolts with specific corrosion protection (left) and expansion shell at end (right)

4.2 Drilling Jumbo with Advanced Sensors

Computerized drilling jumbo was used to carry out probing ahead, drilling blast holes and drilling rock bolt holes. With the use of advanced Measure-While-Drilling (MWD) system which comprised sets of sensors on the jumbo booms, real-time monitoring of the drilling performance data was recorded. The as-built blast holes with actual drilled locations and depth were controlled and checked as demonstrated in Figure 24. The MWD system also provided a complementary tool for rock mass characterization which enabled further optimization of blast design for tunnel and cavern excavation works. Examples are indicated in Figure 25a and Figure 25b.

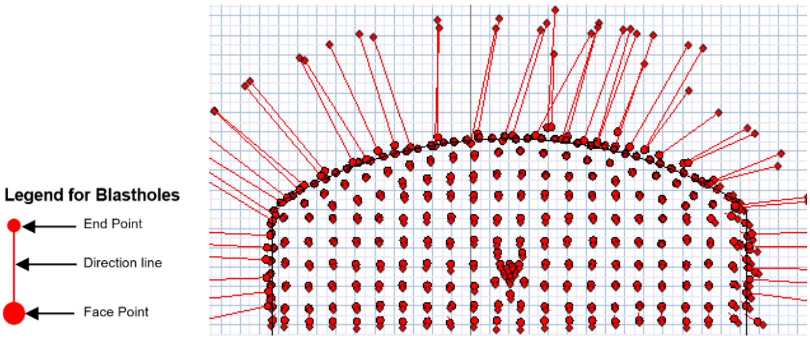

Figure 24: As-built blast holes with actual drilled locations and depth

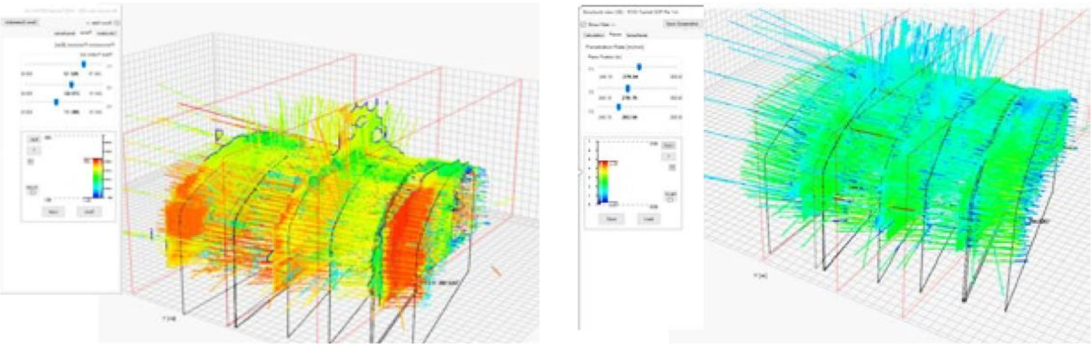

Figure 25a & 25b: Real-time monitoring of percussion pressure (left) and penetration rate (right) using the MWD system

4.3 Surveying of Excavated Profile with 3D Laser Scanner

The three-dimensional tunnel profile after excavation, as shown in Figure 26, was surveyed using a 3D laser scanner with LIDAR technology to generate point cloud data. This data was used to estimate the volume of rock excavation, identify underbreak/overbreak, and immediately assess the thickness of temporary shotcrete after each round of excavation, as demonstrated in Figure 27. The high data intensity significantly improved the precision of surveying data compared to conventional method using total stations. It ensured faster and more efficient checking and monitoring of construction progress, site safety and quality control in tunnel excavations.

Figure 26: Three-dimensional excavtaed profile formed by point cloud data

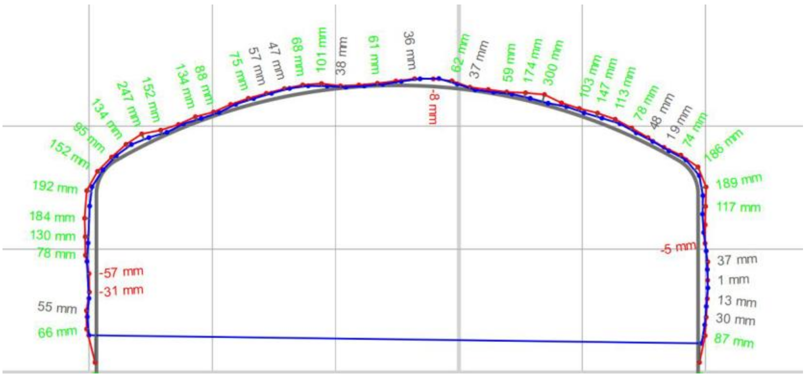

Figure 27: Checking of temporary shotcrete thickness and overbreak/underbreak

4.4 Rock Mass Quality Encountered at MAT

During the MAT excavation, grade II/III granite was encountered. The summary of mapped Q-value along the MAT tunnel is plotted in Figure 28. The Q-value within the shallow rock cover section ranged from 0.06 to 0.65 due to unfavorable conditions for RQD, J_n, J_a and SRF. For hard rock portion, only localised weak seam and intrusion were encountered with Q-value ranged from 3.25 to 5. The mapped Q-value indicated that the rock quality was generally good. Site photos were extracted in Figure 29a and Figure 29b.

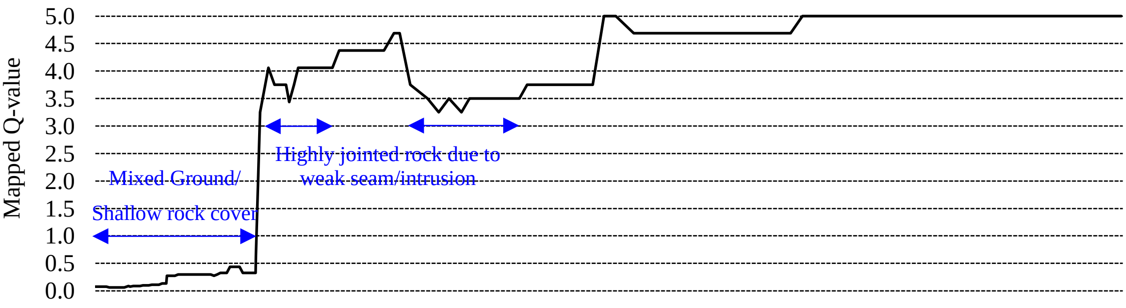

Figure 28: Mapped Q-value along MAT (Top-heading)

Figure 29a & 29b: Example of top-heading (left) and bench (right) at MAT both with mapped Q=5

4.5 First Site Specific 5G Network for Tunnel Construction in Hong Kong

The project is the first construction site in Hong Kong to establish a site specific 5G network in tunnel as indicated in Figure 30. With the advantages from 5G network of low latency, high-speed transmission and high device capacity, together with the development and implementation of various innovative technologies, the efficiency of project management, construction safety and site progress monitoring were significantly improved. With the 5G network, real-time air monitoring and UWB positioning watch were used to monitor the air, temperature, gas and health status of all site staffs and workers in the confined space environment.

Figure 30: First site-specific 5G base stations in Hong Kong construction site

4 CONCLUSIONS

The paper has discussed the comprehensive ground investigation in planning stage, as well as briefly mentioned the rock support design of MAT using rock reinforcement approach. Also, the construction stage of MAT involved the implementation and utilisation of advanced technologies, which showcases the integration of geotechnical expertise, innovative engineering, and meticulous construction practices. This paper provided valuable insights in shaping the future and usher in a new era of underground construction in Hong Kong.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the Drainage Services Department, the Government of the Hong Kong Special Administrative Region, for permission to publish this paper.

PUBLISHER'S NOTE

AIJR remains neutral with regard to jurisdictional claims in published maps & institutional affiliations.

HOW TO CITE

Leung *et al.* (2024). A New Era of Underground Construction in Hong Kong – From Ground Investigation to Construction. *AIJR Proceedings*, 103-115. https://doi.org/10.21467/proceedings.171.10

REFERENCES

Barton N., Lien R. and Lunde J. 1974. *Engineering Classification of Rock Masses for the Design of Tunnel Support*. Rock Mechanics, vol. 6, pp 189-236.

Grimstad E., and Barton N. 1993. *Updating of the Q-system for NMT*. Proceedings of the International Symposium on Sprayed Concrete, Fagernes, Oslo. pp46-66.

Hoek, E., Carranza-Torres, C. & Corkum, B. 2002. *Hoek-Brown Failure Criterion – 2002 Edition*. Rocscience.

AECOM. 2017. *Ground Investigation Report (Final), Geotechnical Engineering Report,* Relocation of Sha Tin Sewage Treatment Works to Caverns – Investigation, Design and Construction.

Leung S. C. M. & Ko E. M. Y. 2022. Active Site Supervision to Enhance Drilling & Blasting. Proceedings of The HKIE Geotechnical Division 42nd Annual Seminar 2022, Hong Kong.