Active Site Supervision to Enhance Drilling & Blasting

Simon Leung[1*], Elton M Y Ko[2]

[1]AECOM Asia Co., Ltd., Hong Kong, China
[2]Drainage Services Department, HKSARG, Hong Kong, China

*Corresponding author
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ABSTRACT

In Hong Kong, the steep hilly terrain is a significant constraint on surface development but provides good opportunities for underground rock caverns. The systematic use of rock caverns will be the long-termed options to increase the land supply, and drill-and-blast is still the most commonly adopted excavation method in underground. However, the technology adopted in site supervision of drill-and-blast excavation has no significant advancement along the time-tunnel of development in Hong Kong. The checking on the as-built blast holes is not comprehensive enough as only the layout on the blast face and the depth of only reachable blast holes can be checked. The alignment of blast holes behind the blast face is unknown, which is however important. In addition, no qualitative and quantitative review on the geological condition ahead of the blast face can be carried out continuously while drilling.

"The relocation of Sha Tin Sewage Treatment Works to Caverns" is a pioneering project for the cavern development in Hong Kong. It showcases the use of rock cavern to unlock the precious land resources in congested urban area. The project team endeavours in adopting Measure-While-Drilling technique to uplift the current practice of site supervision. Sensors and routers are installed at the drilling jumbos to collect valuable drilling data, including the as-built alignment in three dimensions for 100% blast holes, such that live-monitoring of drilling operations could be carried out anytime and anywhere such as in office as well as on site. In case of any as-built blast holes were found to be significantly deviated from the original alignment, review on the drilling operation and rectification could be carried out immediately. Geo-mechanical data is also live-collected for rock mass analysis while drilling of each blast hole, serving like ground investigation drillholes to reveal the geological condition ahead blast face in a fast and an efficient way. The geological condition is one of the major factors in controlling the overbreak in drill-and-blast excavation as well as the blasting factors. The blast design can be reviewed and can be optimized to cope with the changing geological conditions. The huge volume of data generated will be stored into a Big Data database, which is versioned to share all the data obtained with the local construction industry. In long term, the use of Big Data would be the way in predicting the potential risks and its root cause instead of being traditionally merely responsive to an already happened event.

The site supervision for underground construction under public works projects has become more active than ever before, for which the client departments and Resident Site Supervisors (RSS) actively master the use of live data as to enhancing the safety and quality of drill-and-blast operation. The full adoption of Measure-While-Drilling are leading the site supervision sector towards a more productive, more effectively managed digital age where real time data and reporting will be available for key elements of future tunnel and cavern projects.

Keywords: Active Supervision, Geo-Mechanical Data, Rock Mass Analysis

1 Introduction

In Hong Kong, drill-and-blast excavation is commonly adopted excavation method in rocks considering its low investment cost, high adaptability to very varied ground condition and large flexibility to deal with different shapes and sizes of openings. However, the drill-and-blast excavation method will inevitably damage the peripherical rock mass due to the formation of a network of fine cracks which

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may lead to safety and stability concerns. In case of too large damaged zone, it would endanger the safety of front-line workers and RSS due to the reduction of stand-up time, especially for poor rock mass. It also leads to escalation of time and cost due to the increase in rock fragment being mucked out and larger extent of permanent support. In addition, functionality and post-construction performance of the structures get affected due to the large extent of the damage zone if not taken care in time.

The overbreak/underbreak zone and damaged zone have significant impact on the project cost, construction period, safety and performance of the underground opening. They are mainly influenced by the quality of the rock mass, the validity of the blast design and the workmanship of blast hole drilling. In addition, it is not uncommon encountering that the actual pull length is less than the designed pull length, as a result the project would suffer and require a longer or more round of blasting to mitigate the lost pull length causing an out-of-blasting cycle or programme problem. Such problem is usually attributed, among other geotechnical factors, by the mis-alignment of the inner blast holes as well as the surface blast holes. With such an insight, it is of paramount importance to control the quality of blast holes in a workmanlike manner as similar for the workmanship of other civil engineering works supervised by RSS team. The supervision of drill-and-blast operations by RSS team, who endeavours to uplift the supervision practice by adopting Measure-While-Drilling (MWD), has become more direct and active than ever before.

2 Incomprehensive Current Practice on Supervision of Blast Holes Drilling

The current practice for the quality supervision of the blast hole drilling is not comprehensive enough and remains much rooms for improvement without evolving with the fast-developing tunnel technology. The layout of as-built blast holes on the blast face can only be checked briefly by visual inspection to an approximate extent. No qualitative checking of the deviation of as-built blast holes from the designed layout is carried out. There was no way to check the correctness of the alignment of as-built blast holes behind the blast surface, i.e., the inner blast holes. During drilling, drilling error may be caused by collaring, alignment and trajectory deviation. However, the blast hole deviation changes the burden, spacing and plane of holes, which is particularly critical for the contour holes. This results in overbreak/underbreak at the perimeter of the opening, for which it induces significant direct and indirect cost to the project. However, the RSS team is compelled to ignore the checking of the alignment of the as-built blast holes due to the time and practical constraints. In addition, the depth of the blast holes is important to check to ensure that the actual depth conforms with the design and no internal collapse subsequent to drilling, thereby affecting the quantity of explosive. The depth of blast holes is checked manually by a worker inserting a rod into the as-built blast holes sometimes with the aid of a cherry picker, and then measure the inserted length by a ruler **(Photo 1)**. The checking is time consuming and is also limited to those reachable blast holes. In view of this, the RSS could only conduct spot checks on the depth of as-built blast holes at easily accessible locations and the checking covers very low percentage of the total blast holes per round **(Photo 2)**. The checking is however considered not effective as a higher possibility of significant deviation is anticipated to occur at blast holes having difficulties to access, e.g. the perimeter holes at the crown level, which usually got skipped during checking. Furthermore, the checking of as-built blast holes by RSS was usually carried out after the whole round of drilling and right before the blasting in regard of the tight blasting cycle to facilitate the completion of the project on time. Sometimes the explosive has already been ordered and being delivered on the way to the site while the drilling of blast holes is still in progress. Therefore, it is considered too late for the checking and implementing any corrective action to rectify the largely deviated blast holes. The overall quality of the blast hole drilling is somehow deemed to be self-controlled by the contractor and RSS had been difficult to provide input on the quality supervision of the blast hole drilling before.

Photo 1: Depth Checking of As-built Blast Holes by Inserting a Ruler Manually

Photo 2: Depth Checking Covers Few As-built Blast Holes Only

3 Limited Geological Information

For civil engineers, dealing with the drill & blast activities can be an extraordinary task. There are so many known and unknown geological details that must be observed, understood and act upon by RSS in order to achieve a qualitative supervision. There are no two blasts having exactly the same geotechnical conditions and so are the challenges and concerns. The level and extent of these challenges and concerns can vary substantially for each blast. Even in a situation where an experienced RSS may have a profound knowledge on the drill and blast, there are still many unpredictable risks arising from the known and unknown geological details behind the blast face. In view of this, we should not only rely heavily on the mapping information appears visually on the surface, but should be explored as to how we can obtain those geological conditions exist behind the blast face and be aware of those associated potential risks, then stay vigilant during our supervision.

The underground project is normally started with a site investigation to determine the in-situ rock mass condition and it provides the basis for the tunnel and the blast design. However, the site investigation is often based on limited information such as surface mapping, geophysical profile, few drill holes, etc. The estimation of the rock mass conditions may contain inaccuracies, resulting in inappropriate designs. During the excavation, the predicted rock mass conditions is verified by observational method (Peck 1969). Geological mapping is conducted on the blast surface after each round of blasting at 3m to 5m interval normally. The determination of rock mass condition is based on the mapped sections discretely. An assumption has been made that the rock mass condition beyond the blast face could be represented by the blast face, which may not be applicable to some locations with complex geological setting. In addition, the geological mapping is recorded individually for each blast face, which is inconvenient for geotechnical engineers who try to understand the trend of changing rock mass condition over a tunnel portion. As the information of geological mapping report is not digitalized, it hinders the sharing and utilization of the information by other future underground projects in Hong Kong.

4 A Pioneer Project with Pioneer Supervision Skills

The Relocation of Sha Tin Sewage Treatment Works (STSTW) to Caverns is a showcase cavern project in Hong Kong commenced in 2019. The aerial photo the project site is shown in **Photo 3**. After its completion, the cavern hall is around 380m x 350m with span up to 32m. It consists of five parallel caverns along the longitudinal axis of the cavern complex. The future cavern complex for the relocated STSTW will be the largest of its type ever built in Hong Kong and it needs to be implemented in stages. BIM model of future cavern complex is shown in **Figure 1**. The first stage of the project involved construction of 260m long Main Access Tunnel (MAT) and 90m Main Access Tunnel West (MAT-W). The MAT and MAT-W are formed as a horseshoe shape with approximate excavated span 18m and cross section area around 270m2. The majority of the tunnels and caverns are in rock with more than half span of rock cover above the tunnel crown and will be formed using the drill-and-blast method and the general view inside MAT is shown in **Photo 4**.

Photo 3: Aerial Photo of the Project Site

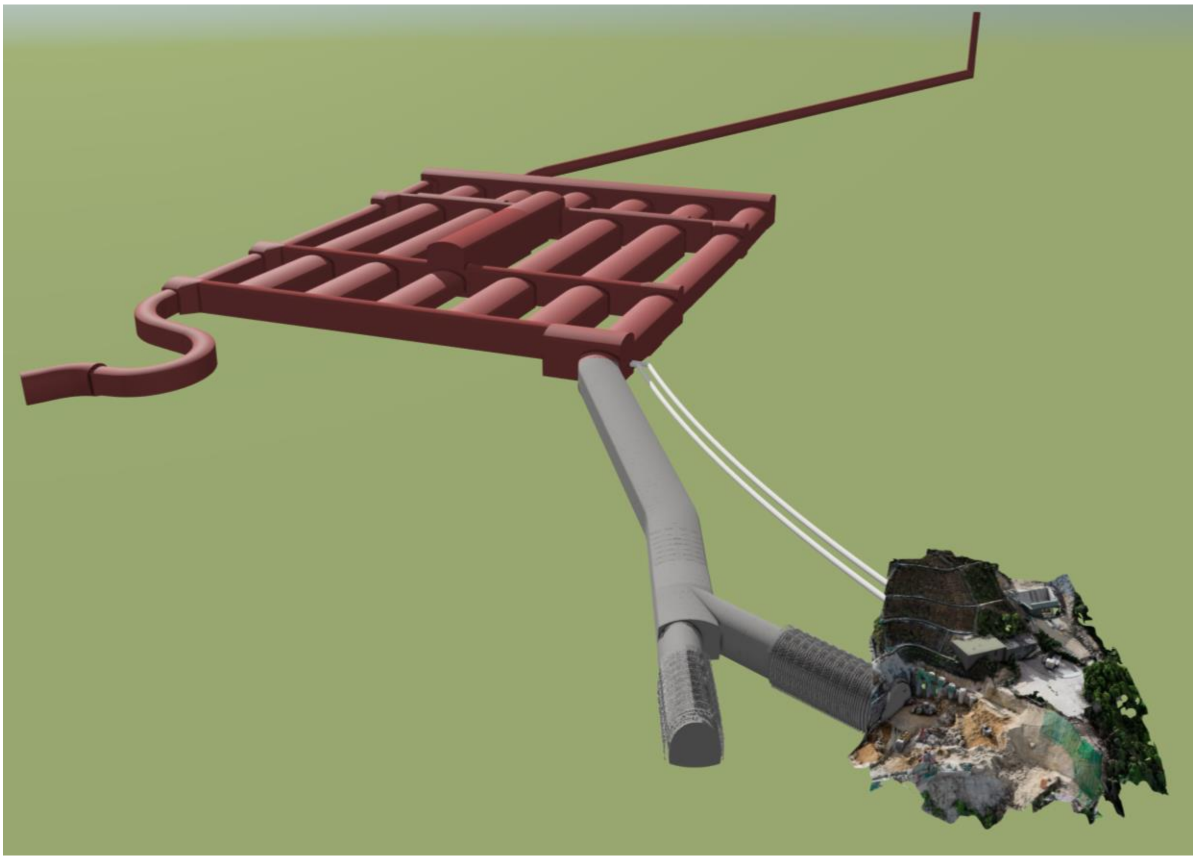


Figure 1: BIM Model of Future Cavern Complex

Photo 4: General View inside MAT

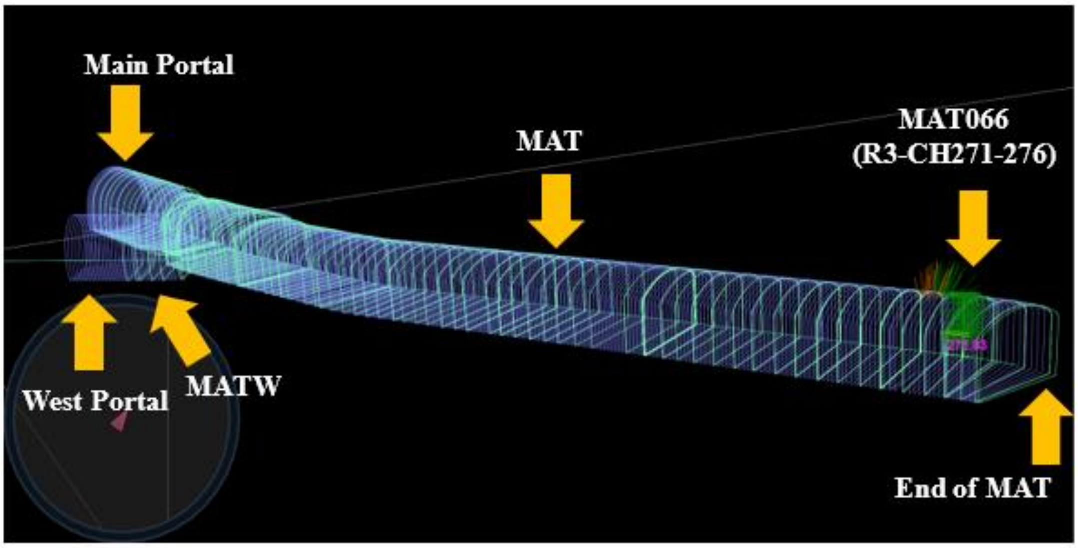
"The adoption of digital supervision workflow can streamline many of the repetitive paperwork associated with current practices. It allows real-time monitoring of inspection status so management can much more easily spot any potential problems before they are manifested." (CIC 2020). As the Review Report recommended under Recommendation 3, "site supervision personnel should focus more on results-oriented inspections for assuring that quality and design intent are being delivered rather than mechanistic checking and administrative procedures. It is worth exploring the need for preparing a relevant document spelling out the good practices and guidelines for rationalizing the relevant requirements for the industry's general reference." (CIC 2020). Somehow in this context, the recommendation triggers the exploration of what really need for a step up by an active supervision for a drill and blast projects.

To facilitate live monitoring by RSS with the aid of MWD, various sensors for collecting the drilling data are installed at the booms of jumbos **(Photo 5)**. The current application of the MWD sensor could only provide for an on-site monitoring inside the cabinet of the jumbo. In order to achieve a "supervision-anytime-anywhere" concept, RSS installed a router at the jumbo as for the data transmitting directly from the booms of jumbo to site office, thanks to the dedicated RSS innovation team. A site specific 5G network with the advantages of low latency, high-speed transmission, and high device capacity has been brought in to the whole tunnels and construction site by the project team. The drilling data collected at the jumbos is then transmitted via the 5G network to anywhere outside the tunnels such as office as well as spot on site for live monitoring of the blast holes drilling. A round report summarizing all the drilling data including as-built layout, geological and geo-mechanical data, etc. is generated and is stored in the hard disk at the jumbos and can be downloaded to the computer server at office, thanks to 5G network.

Photo 5: Jumbo Equipped with MWD Sensors

5 MWD and Chief Resident Engineer (CRE) Report

A CRE report after each round of blasting was prepared by RSS for review and endorsement by CRE under this the project. The CRE report recorded some further pre-blasting and post-blasting checks,



which is meant to supplement the statutory required Resident Explosives Supervisor (RES) report and post blasting report. There are three main sections including pre-blasting check, post blasting check and kinematic analysis of the unstable wedges. In this paper, the CRE report for blasting number MAT-066 is chosen to demonstrate the enhanced supervision developed by our project team through adopting MWD in pre-blasting check. The location of MWD data for MAT-066 is shown in **Figure 2**. All the MWD data obtained from the project can be combined together in BIM, which allows the access of all the project participants. It provides a convenient way for the engineers of RSS and the contractor to access and review the data for improved blasting control and outcomes.

Figure 2. Location of MWD for Blast No. MAT-066

5.1 Pre-Blasting Check – Enhancing the Supervision of Blast Hole Drilling

The total number of blast hole for MAT-066 was 252 nos., which contained 170 nos. production holes, 60 nos. perimeter holes and 22 nos. lifter holes. In the pre-blasting check, live checking for the profile on blasting surface, alignment and depth of total 252 nos. of as-built blast holes were performed by the works supervisors, which helps prevent the occurrence of significant deviation of as-built blast holes from the designed profile by immediate notification to the contractor for rectifying promptly. The deviation between the designed (blue coloured) and the as-built blast holes (red coloured) on the blasting face can be easily identified from MWD as shown in **Figure 3**. As a result, the profile checking of the as-built blast holes on the blasting surface resulted in 100% production holes, 93% perimeter holes and 100% lifter holes within the deviation range between 0mm and 400mm. For the profile check of the end point of the as-built blast holes, 93% production holes, 99% perimeter holes and 50% lifter holes were drilled within the deviation range between 0mm and 400mm. For the depth checking, 100% production holes, 99% perimeter holes and 100% lifter holes were drilled longer than the designed depth. The results are plotted in **Figure 4 – Figure 7** respectively. The graphical representation of as-built blast holes in MWD in 3-dimension is shown in Figure 5.

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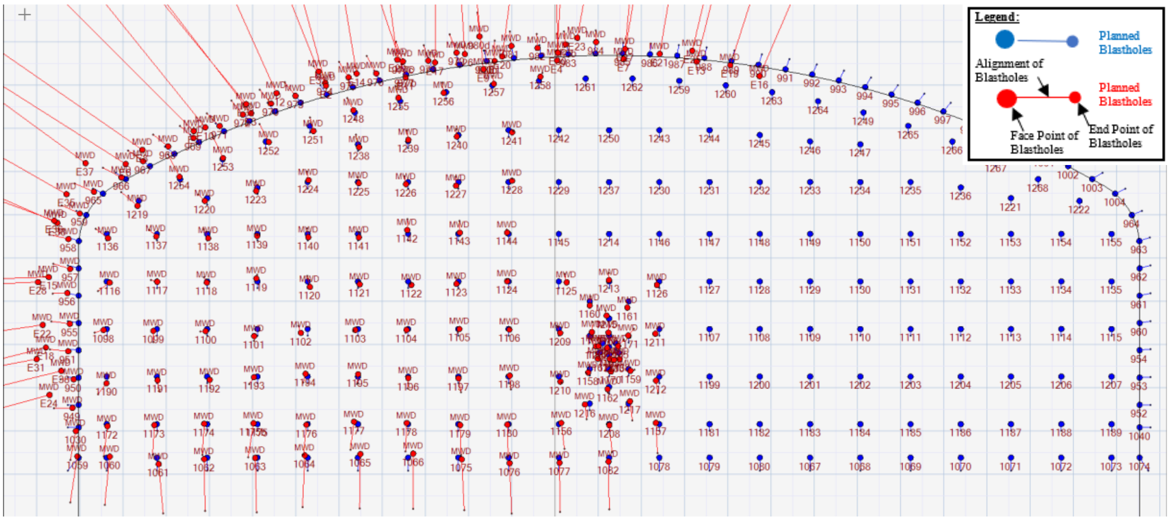

Figure 3: The deviation between the designed and as-built blast holes on the blasting face

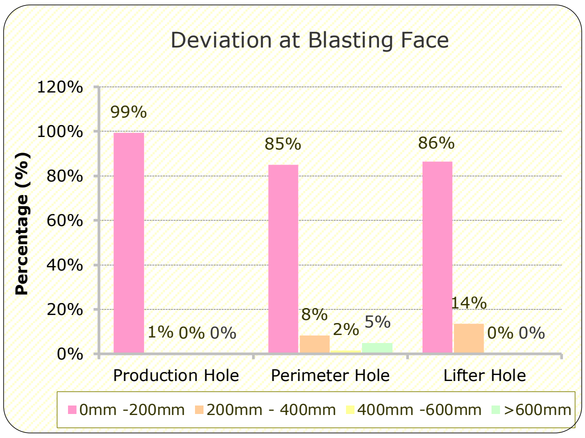

Figure 4: Profile Checking of the As-built Blast Hole on the Blasting Surface

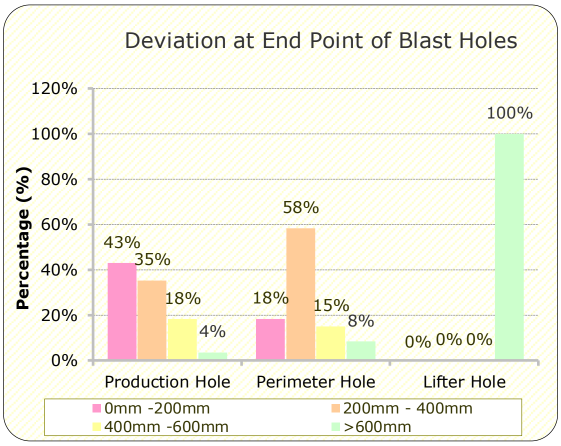

Figure 5: Profile Checking of the End Point of As-built Blast Holes

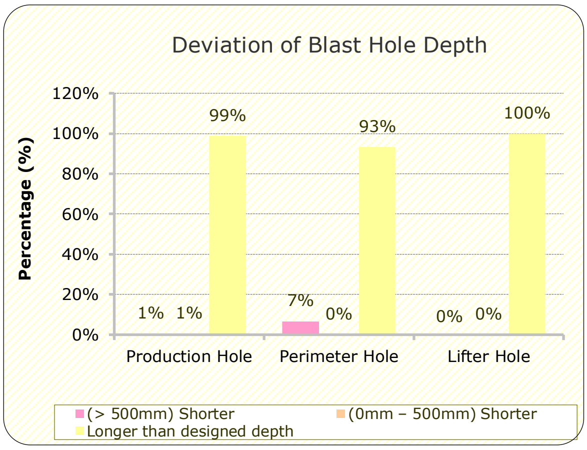

Figure 6: Depth Checking of As-built Blast Holes

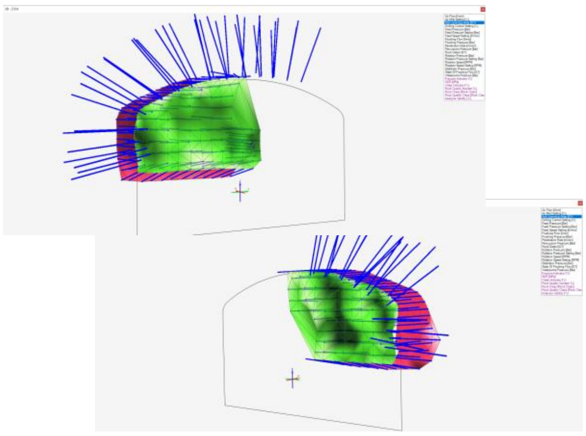

Figure 7: Graphical Output of As-built Blast in MWD

5.2 Pre-Blasting Check – Improve the Accuracy of Forecasting Rock Mass Condition ahead of Blasting Face

Our project team adopted MWD to improve the accuracy of forecasting the rock mass condition ahead of the blasting face. It can bridge the information gap between the early, somewhat uncertain geotechnical site investigation and the geological mapping done after excavation to optimise the tunnel temporary support design and enable a more prescriptive blast design. MWD provides a real time monitoring of geo-mechanical data in 3-dimension in real time in order to optimize the drilling and blasting cycle and achieve so-called “data driven productivity”. The key geo-mechanical data including penetration rate, percussion pressure, rotation pressure, flushing pressure, feed pressure is collected, which are shown in **Figure 8 – Figure 13**.

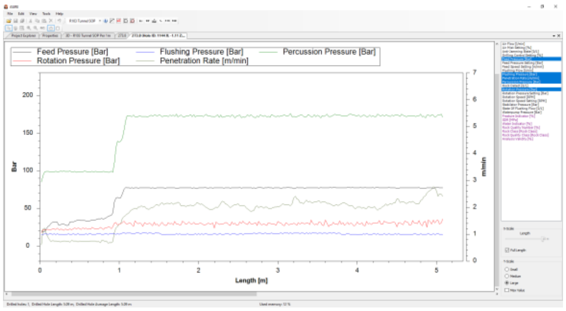

Figure 8: Variation of Key Geo-Mechanical Data along Drill Hole Depth

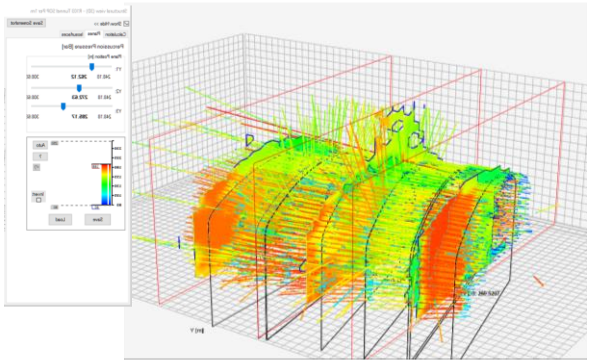

Figure 9: Layered View of Percussion Pressure in 3D Structural View

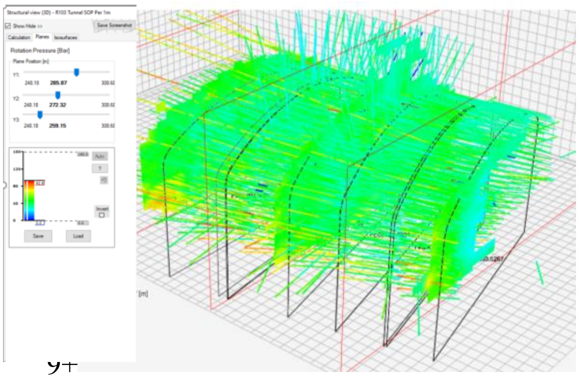

Figure 10: Layered View of Rotation Pressure in 3D Structural View

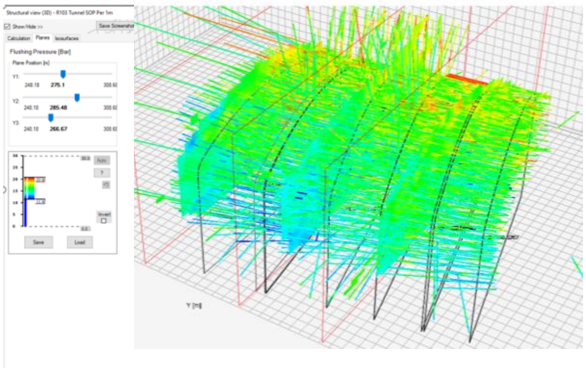

Figure 11: Layered View of Flushing Pressure in 3D Structural View

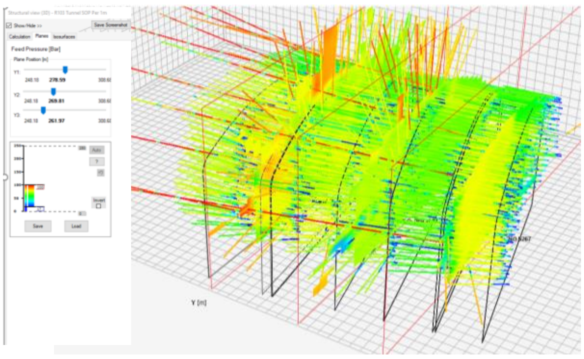

Figure 12: Layered View of Feed Pressure in 3D Structural View

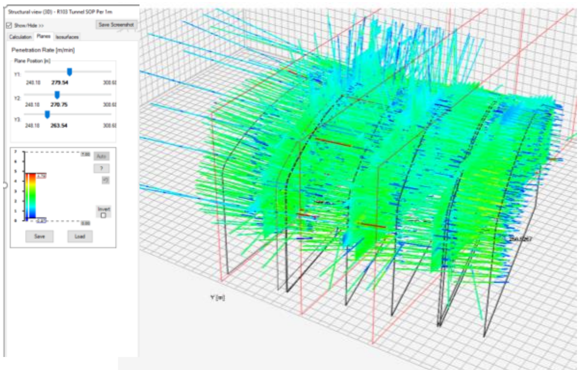

Figure 13: Layered View of Penetration Rate in 3D Structural View

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The geo-mechanical data was analysed by MWD's extended function, which is called GeoSure, to normalize and filter the operational and machine influence to obtain the various geological indicators for the rock mass condition ahead of the blasting face. The geological indicators include Fracture Indicator, Rock Drilling Resistance, Water Indicator, Rock Quality Number.

5.3 Fracture Index (FI)

The FI is a ratio indicating the length of an encountered fracture with respect to the data sampling interval, which is a pre-set value of 2cm. The lower the value represents the smaller the size of the fracture at the respective sampling interval, which 0% implies no fracture while 100% implies the voids is bigger than the sampling interval. From the FI obtained in MAT-066, as shown in **Figure 14 - Figure 17**, the FI generally lies between 10% - 20% with only a small localized area with FI up to around 30%. Therefore, RSS anticipated that the size of fracture ahead the blasting face is small.

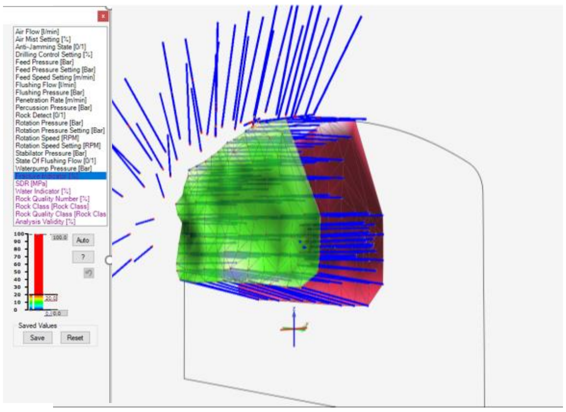

Figure 14: FI of MAT-066 in 3D

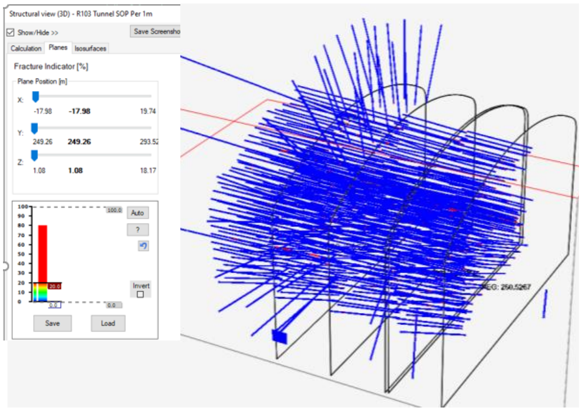

Figure 15: FI over a Tunnel Portion at MAT-066 in 3D

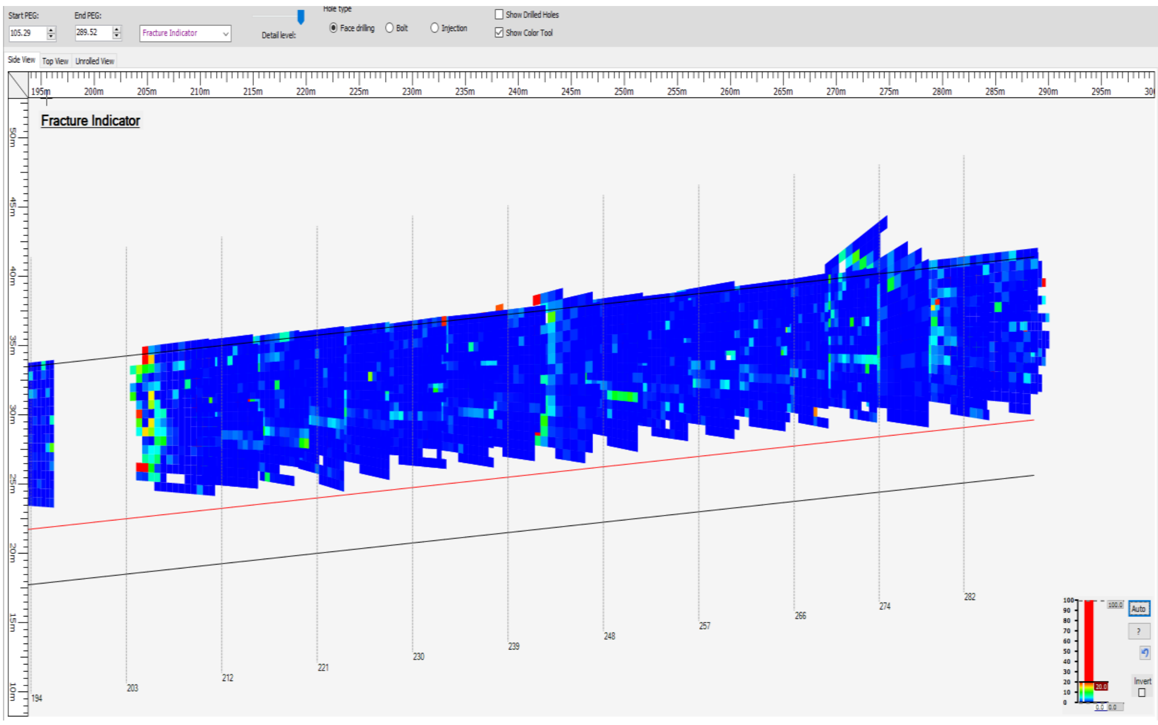

Figure 16: Overall Side View of FI across the Whole Tunnel

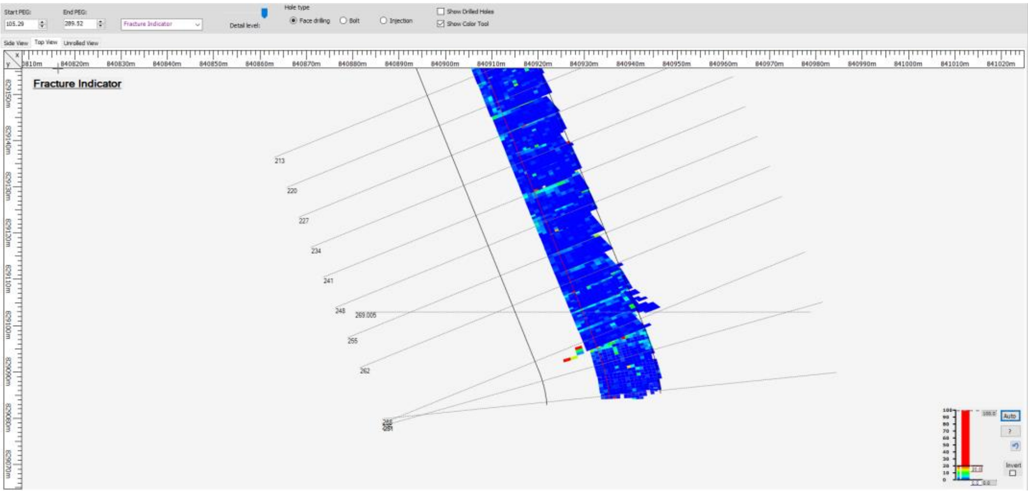

Figure 17. Overall Top View of FI across the Whole Tunnel

5.4 Rock Drilling Resistance (RDR)

The RDR indicates the rock's resistance to the drilling system, which is in direct proportion to the uniaxial compressive strength (UCS) of the rock with a site-specific coefficient. In order to correlate RDR obtained and the uniaxial compressive strength UCS of the rock mass, 3 nos. of rock core samples, as shown in **Photo 6 – Photo 8**, were retrieved across the tunnel and were sent to the laboratory for testing the UCS. The laboratory test results were then compared with the RDR recorded. The RDR results obtained from MWD at the retrieved rock core samples is shown in **Figure 18**. The results show that the UCS and DRD are in an approximate ratio of 1:1 and the detail of results are summarized in **Table 1**.

Table 1. Comparison of UCS and RDR

Sample No.	UCS (MPa)	RDR (Mpa)
1	136.4	~150
2	79.7	~80
3	124.3	~120

After the site-specific coefficient has been established, the RDR obtained can be used to anticipate the UCS of rock mass ahead of the blasting face. The results of RDR obtained for MAT-066 are shown in **Figure 19 – Figure 22**. The UCS of the rock mass was obtained between 50Mpa and 200Mpa. No localized weak zone was detected.

Photo 6: Rock Core Sample No.1

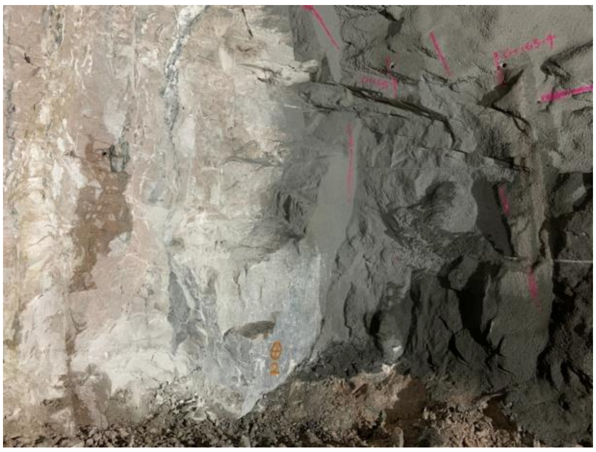

Photo 7: Rock Core Sample No.2

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Photo 8: Rock Core Sample No.3

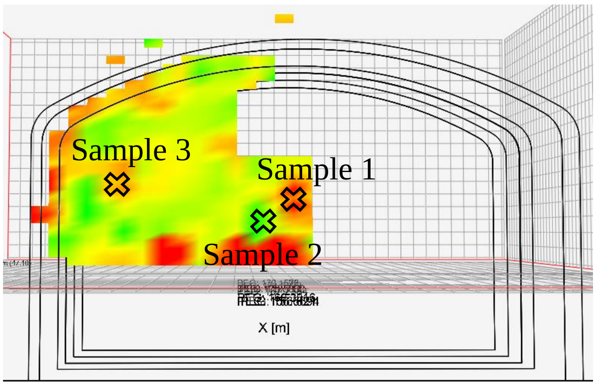

Figure 18: RDR results from MWD for Rock Core Samples Retrieved

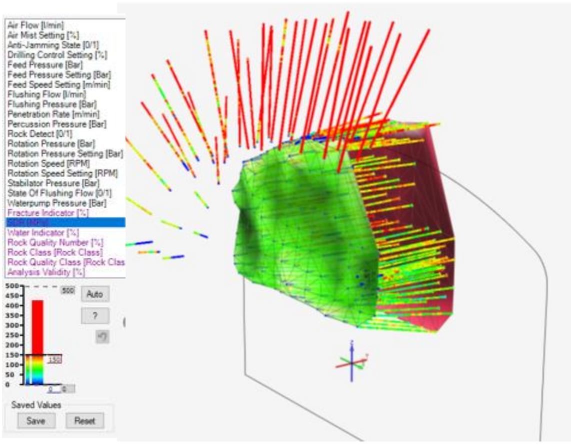

Figure 19: RDR of MAT-066 in 3D

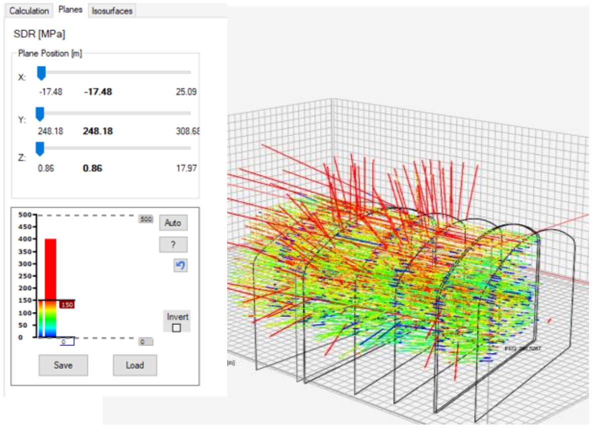

Figure 20: RDR over a Tunnel Portion at MAT-066 in 3D

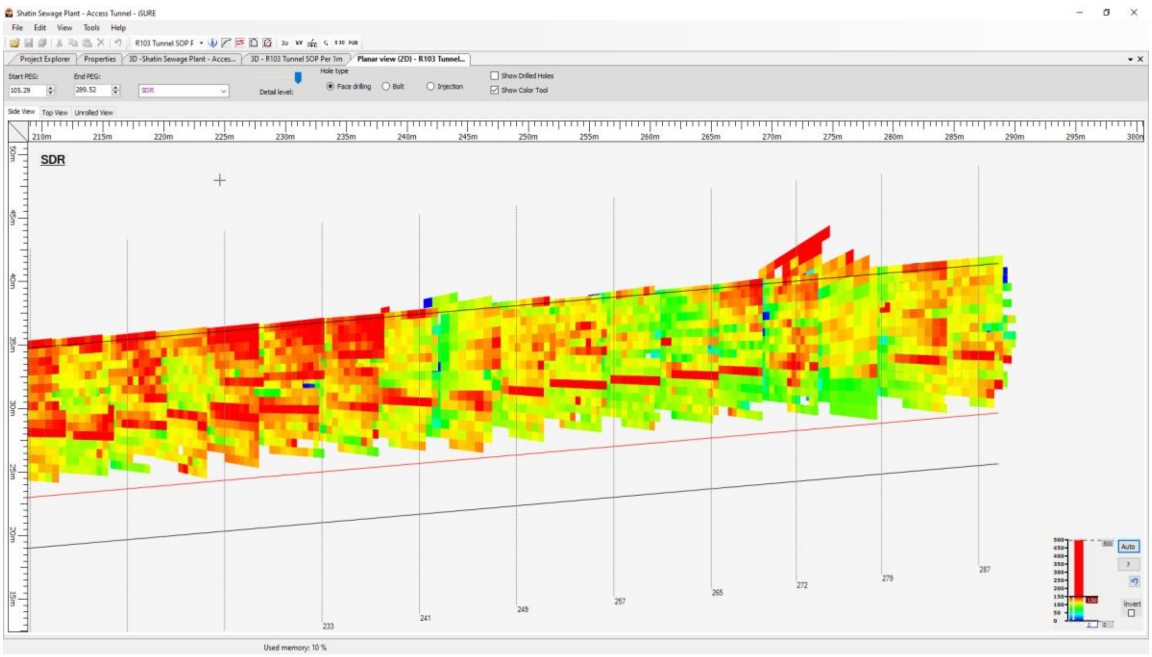

Figure 21: Overall Side View of RDR across the Whole Tunnel

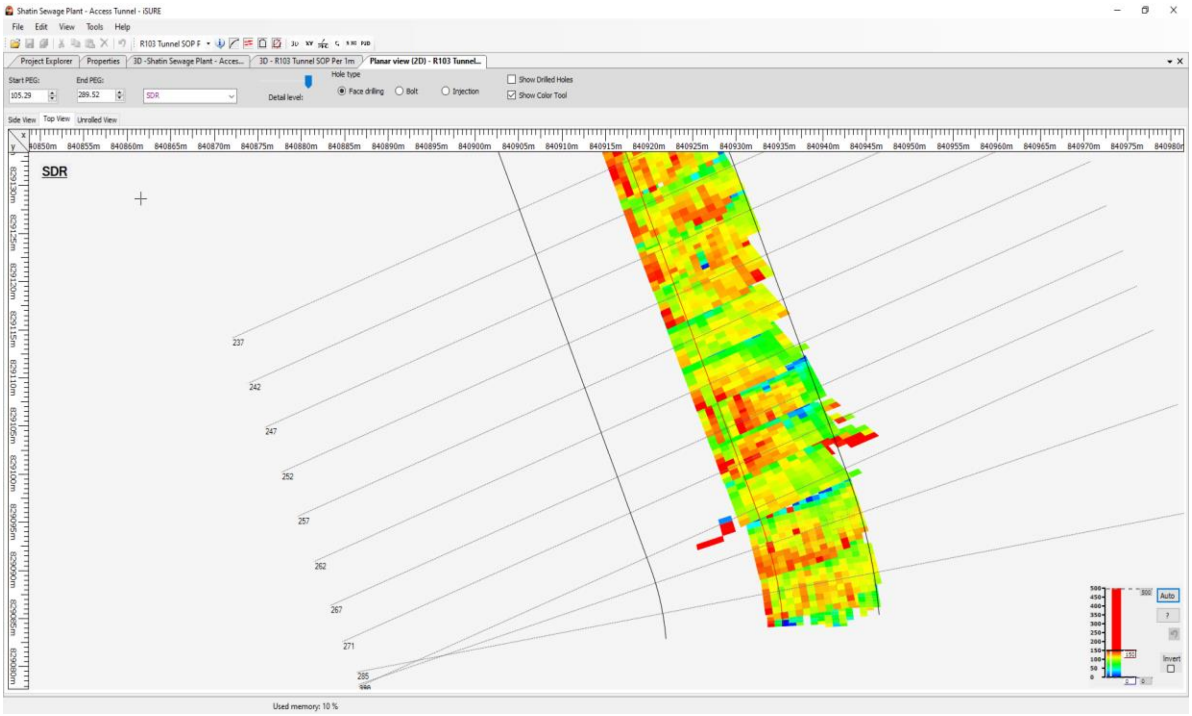

Figure 22. Overall Top View of RDR across the Whole Tunnel

5.5 Water Indicator:

The water indicator is given at the positions where fracture is present and significant and characteristic changes in flushing flow and flushing pressure are detected. For water indicator equal to 0%, the presence of water is unlikely at the fracture. Water indicator equals to 100% meaning that there is presence of water is very likely at the fracture. The results of water indicator obtained for MAT-066 are shown in **Figure 23 – Figure 26**. The water indicator is generally below 5% indicating that the occurrence of groundwater inflow at fractures is negligible.

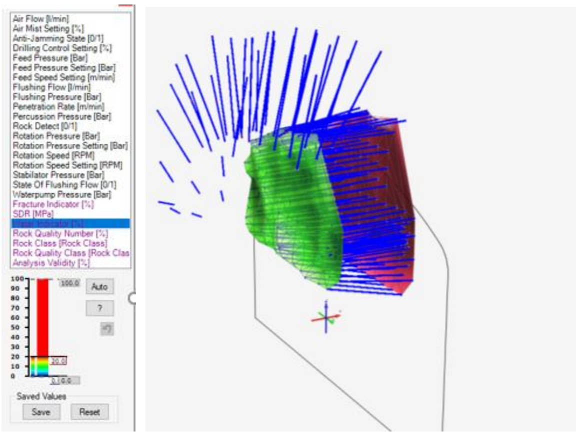

Figure 23. Water Indicator of MAT-066 in 3D

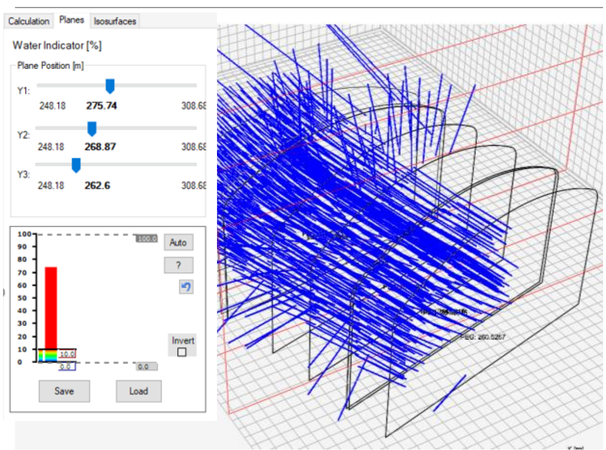

Figure 24. Water Indicator over a Tunnel Portion at MAT-066 in 3D

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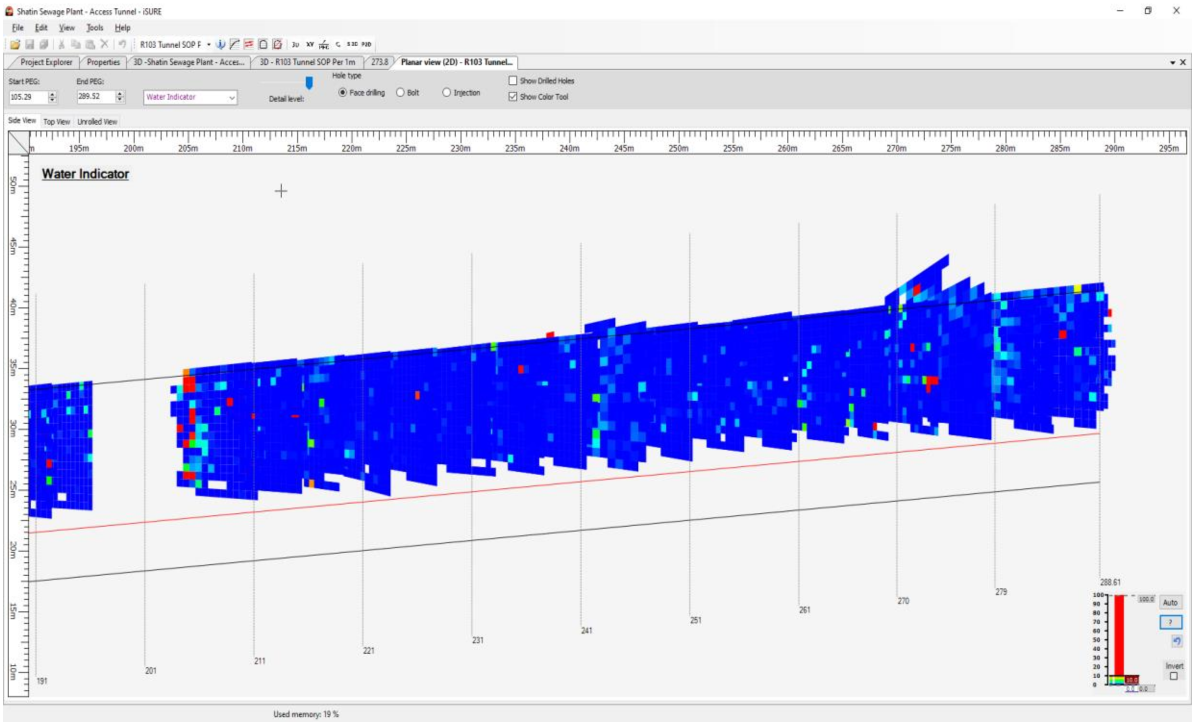

Figure 25. Overall Side View of Water Indicator across the Whole Tunnel

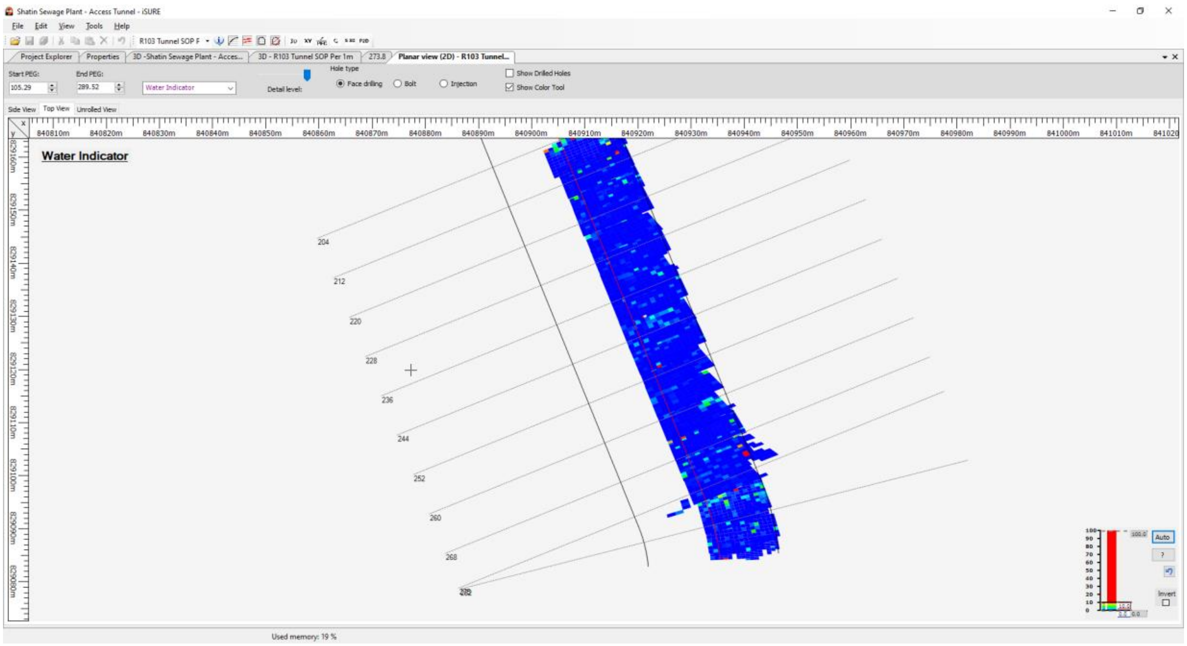

Figure 26. Overall Top View of Water Indicator across the Whole Tunnel

5.6 Rock Quality Number (RQN)

The RQN is defined as the total sum of intact rock over or equal to 10cm rock samples, which follow the same calculation principle of Rock Quality Designation (GEO 2017). The results of RQN obtained for MAT-066 are shown in **Figure 27 – Figure 30**. The RQN between 90% and 100% is generally obtained and the result is consistent with the FI obtained.

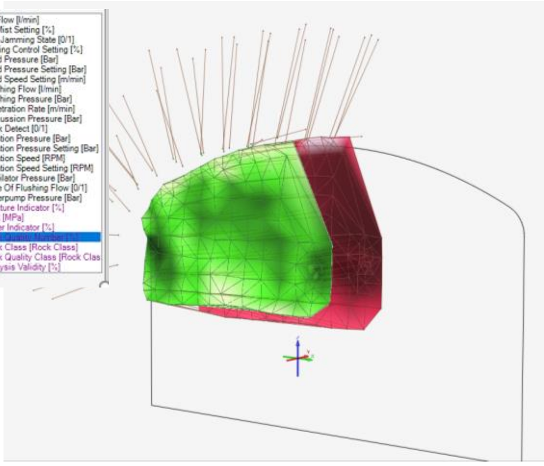

Figure 27. RQN of MAT-066 in 3D

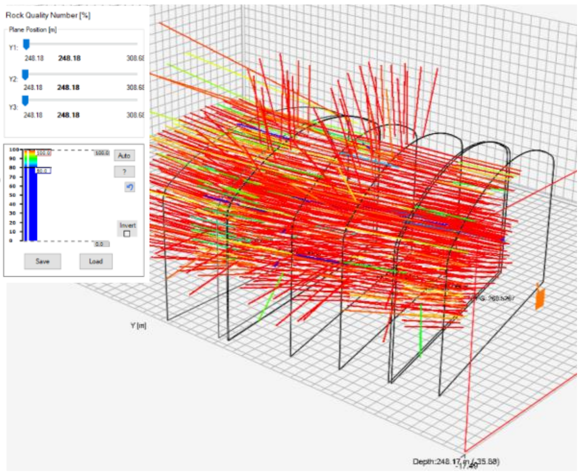

Figure 28. RQN over a Tunnel Portion at MAT-066 in 3D

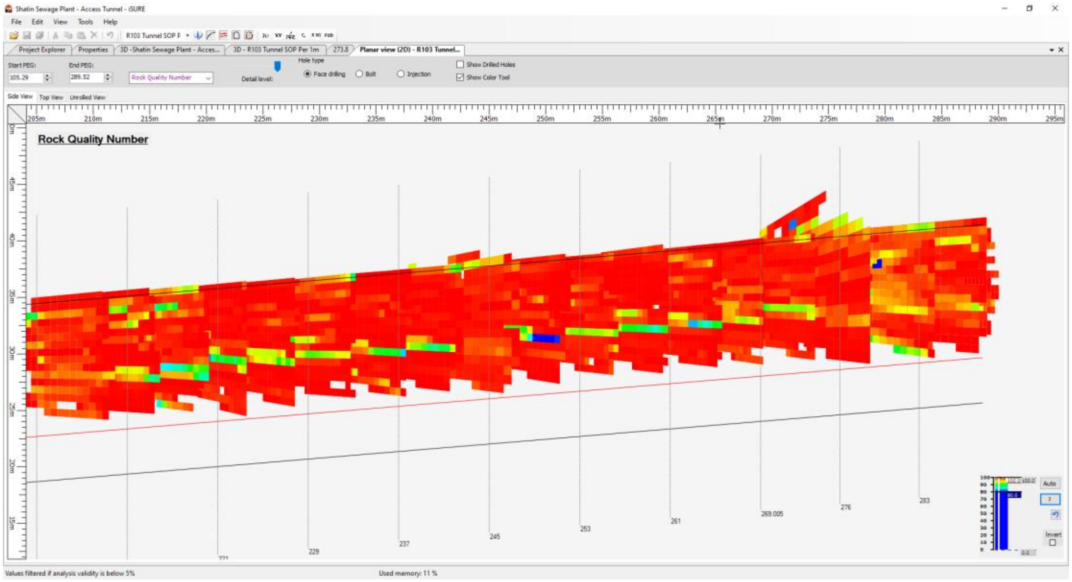

Figure 29. Overall Side View of RQN across the Whole Tunnel

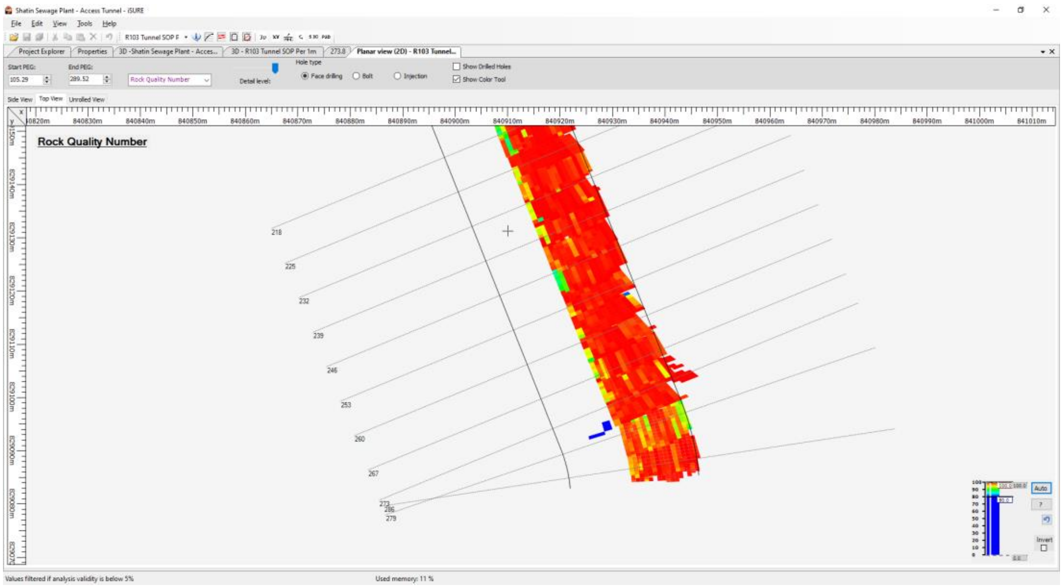

Figure 30. Overall Top View of RQN across the Whole Tunnel

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6 Conclusion

According to Cavern Master Plan published by Hong Kong SAR government, the systematic use of rock caverns will be the long-termed options to increase the land supply. While Relocation of Sha Tin Sewerage Treatment Works to Cavern is a pilot public works project for cavern development in Hong Kong, our project team endeavours to adopt various innovative technologies in our project so as to lead the development of an industry culture that embraces change, innovation and new technologies to drive forward productivity, efficiency and enhanced project delivery outcomes. One of which we adopted was MWD and a case study for application of MWD on one of the blasting (MAT-066) has been discussed in this paper.

In MAT-066, our RSS carried out 100% three-dimensional live-checking of the as-built blast holes in real-time and provided a useful guidance to the contractor to implement immediate corrective actions to prevent the drilling of the blast holes from going any further in wrong alignment once the alignment is deviated from the designed profile. The quality supervision of the blast hole drilling by RSS has become more active and effective than ever before and the workmanship of the contractor was turned out to be improved substantially. The MWD provides a digitalized and quantitative way to the profile checking of the as-built blast holes such that greater than 90% and 99% of the as-built blast holes were found to be very slightly deviated from the designed profile and were longer than the designed drilling depth respectively in MAT-066. The good workmanship of the blast hole drilling laid a good basis for delivering good blasting outcomes.

The conventional approach for the underground infrastructure projects based on advanced site investigation and geological mapping during excavation could be benefit from the supplementing the instantaneous information on the rock mass condition ahead the blasting face. The RSS in this project adopted MWD to measure and collect various geo-mechanical data and produce several useful geological indicators including Fracture Index, Rock Drilling Resistance, Water Indicator and Rock Quality Number to facilitate a more prescriptive tunnel support design and blast design. Now that the Shatin Cavern Project team is adopting various technologies, the digital workflow and MWD is generating more data than ever before, leaving the team with tonnes of data and getting more ways to benefit from it and hopefully for the future cavern development in Hong Kong.

7 Publisher's Note

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