Design and Construction for the First Semi-Cavern Building in Hong Kong – A Case Study in Tseung Kwan O – Lam Tin Tunnel

Clayton Y. K. Chan*, Billy W. L. Siu, Franklin K. L. To

AECOM Asia Company Limited, Hong Kong

*Corresponding author
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ABSTRACT

The Tseung Kwan O – Lam Tin Tunnel (TKO-LTT) has been commissioned since December 2022, which is a new truck road linking Tseung Kwan O and Kowloon urban area, with about 2.2 km long rock tunnels. This tunnel connects the Cross Bay Link in the east, and the Trunk Road T2 in the west, forming the integrated part of future Route 6, servicing the second tunnel for TKO residents to Kowloon with shortened travelling time. At the TKO Portal, two large-span caverns were designed and constructed to accommodate a semi-cavern tunnel ventilation buildings. This idea was proposed to reduce the surface footprint of ventilation building by placing its significant portion into the caverns. With this innovative semi-cavern building scheme, the slope cutting and stabilization works have been minimised, the disposal of excavated materials and tree felling have been reduced, it also improves the visual impact of the ventilation building and enhanced the construction programme. With portion of ventilation building inside the caverns, it could provide stable environment for E&M equipment with regard to weather protection, steady temperature and humidity.

The challenges in terms of geology, hydrogeology and geotechnical engineering have been overcome successfully throughout the project implementation. This innovative engineering solution also provided significant benefits to the project in terms of cost effectiveness, sustainability and energy efficient aspects in the construction and operation stages of the project. This semi-cavern building scheme is a perfect example that the industry is utilising underground space and promoting rock cavern development in Hong Kong. This paper presents a successful case study for the rock semi-cavern works in TKO-LTT from the planning, detailed design to construction stages.

Keywords: Rock Cavern, Tunnel Portal, Ventilation Building

1 Introduction

1.1 The Project

Before the commissioning of Tseung Kwan O – Lam Tin Tunnel (TKO-LTT), the existing Tseung Kwan O Tunnel (TKO Tunnel) constructed in 1990 was the main connection between TKO and East Kowloon. The TKO Tunnel was operating at its maximum capacity at peak hours and unable to cope with the future traffic demand arising from further developments in TKO. Therefore, the construction of TKO-LTT serving as an additional highway was required to relieve the existing traffic congestion in order to meet the future traffic demands arising from the planned population in TKO area.

In September 2013, AECOM Asia Company Limited was commissioned by the Civil Engineering Development Department (CEDD) of the HKSAR Government to provide the design and construction services for the TKO-LTT. It is a 4.2 km dual two-lane highway involving the construction of tunnels, viaducts, at grade roads, reclamation, building facilities, landscaping and environmental protection works.

The overview of TKO-LTT is presented in Figure 1. It has been successfully commissioned since December 2022. It is a new truck road linking Tseung Kwan O and Kowloon urban area, the main tunnel

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is an approx. 2.2 km long rock tunnels connecting the Cross Bay Link and the Trunk Road T2, forming the integrated part of future Route 6, servicing the second road tunnel for TKO residents to Kowloon with shortened travelling time.

Figure 1: *Tseung Kwan O – Lam Tin Tunnel (TKO-LTT) ((CEDD, 2015)*

1.2 General Site Descriptions and Ground Conditions

The main tunnel is within slightly to moderately decomposed rock, the western and central portions of TKO-LTT is underlain predominantly by Mount Butler Granite (Klb), whereas the eastern portion is underlain by tuff belonging to Mount Davis Formation (Krd). The superficial geology generally comprises deposits and fill materials. These include fill, colluvium, alluvium, residual soil and saprolite of highly to completely decomposed granite and tuff. The thickness of these stratums varies along the main tunnel alignment.

A number of weakness zones, fault zones and geological contacts were inferred within the project area. These include weathered seams, core loss, dyke intrusion and mineralization, greisenized zone and minor weak zones associated with the topographic depression lines. The Rennie's Mill Fault zone indicated on the published geological map was encountered during the construction works of Harbour Area Treatment Scheme (HATS) Tunnel Stage 1 in the 1990s. A geological granite-volcanic contact was also identified where zone of high permeability and alteration may be anticipated.

1.3 Rock Semi-Caverns Works at TKO Portal

At the eastern Tseung Kwan O Portal of the main tunnel, two large-span caverns were designed and constructed to accommodate part of the East Ventilation Building (EVB). This idea was proposed to reduce the surface footprint of ventilation building by placing part of the building underground. The photomontage in Figure 2 was prepared during the design stage to illustrate the general arrangement of the semi-cavern ventilation building at TKO Portal, it provides stable environment for E&M equipment with regard to weather protection, steady temperature and humidity.

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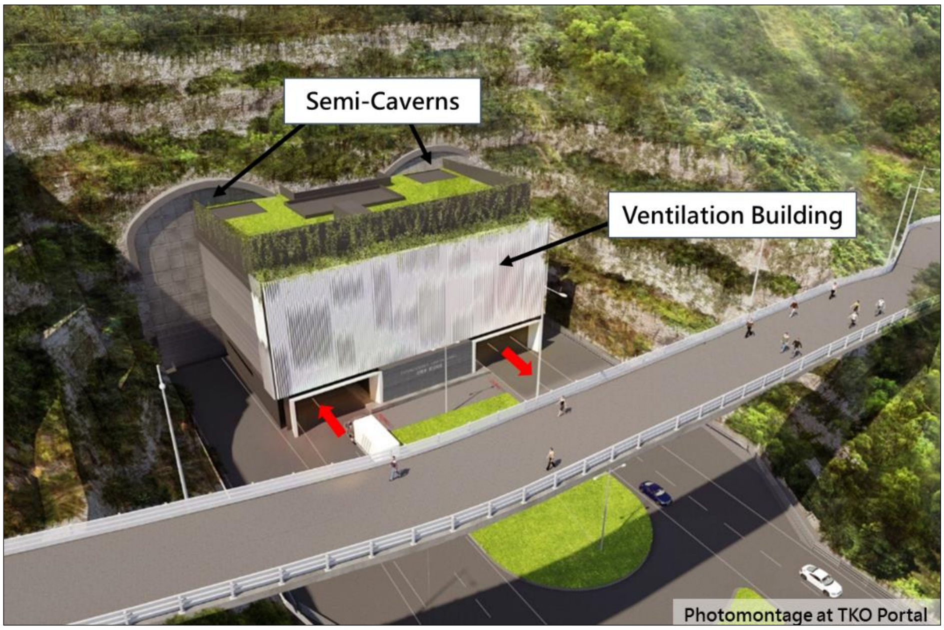

Figure 2: *Photomontage at TKO Portal*

2 Planning and Design

2.1 Geological Setting at TKO Portal

The TKO Portal is located at the western shoreline of Junk Bay in TKO. It is adjacent to the Junk Bay Chinese Permanent Cemetery. One of the particular highlights for the semi-cavern scheme is that, these two caverns were not proposed and constructed within the current Strategic Cavern Areas (SCVAs) under the Cavern Master Plan (CMP). Therefore, more challenges in terms of geology, hydrogeology and geotechnical engineering were expected and encountered during the course of design and construction stages of the project.

The area is underlain by tuff belonging to Mount Davis Formation (Krd). The rockhead level varies between approximately +60mPD and +85mPD, with the highest level at the northwest and the lowest at the southwest. Two isolated outcrops of the Krd formation, surrounded by granite, are located between Yau Tong and TKO. Much of the rock has been thermally metamorphosed by the granite. The Krd Tuff is typically described as fine to coarse ash Tuff locally intruded by brecciated quartz veins. Chloritized and silicified Tuff and coarse ash lithic Tuff are encountered in places as well. Iron and manganese staining are commonly observed on the joint surfaces. Calcite, chlorite, kaolin and epidote coatings at the joint surfaces are also recorded locally in some boreholes. Chlorite, quartz and silicified pyrite infillings are identified locally in some of the boreholes.

In addition, localized dyke rocks such as aplite, basalt, and quartz syenite were identified from the published geological map and localized borehole records. Extremely weak to weak zones containing Grade III/IV, IV and V materials were found in Tuff. Various weathering grades of localized dyke such as Aplite and Basalt were occasionally observed. The superficial geology generally comprises Quaternary Deposits and fill materials, with varying thickness in the onshore and offshore areas.

2.2 Ground Investigation and Geological Model

Multi-staged consultancy agreement is commonly adopted for medium to mega-scale government infrastructure projects in Hong Kong. For the TKO-LTT project, these multi-stages since 2009 included the feasibility study stage, investigation & preliminary design stage, and finally the design &

construction stage. Ground investigation works in each of these stages were carried out for different purposes and requirements. During the early planning stage, the ground investigation works aimed to assess the planning and selection of different tunnel alignment options. It also tried to identify any potentially problematic ground and minimized the geotechnical risks conditions along the tunnel alignment. After the confirmation of tunnel alignment by consolidating multi-disciplined aspects, further ground investigation works were carried out to focus at specific locations and depths, to obtain geotechnical information for subsequent detailed design.

At the TKO portal, two caverns for the construction of a semi-cavern ventilation building were planned in highly fractured volcanic tuff with complicated geological conditions. This was an ambitious design that required a thorough study to ensure its constructability in the planning and design stage.

Extensive ground investigation works including vertical boreholes, inclined boreholes and horizontal directional coring (HDC) were carried out and interpreted into a three-dimensional geological model as illustrated in Figure 3. The ground investigation results assisted the interpretation of the locations for the two inferred geological features and revealed that the both features dip sub-vertically. Different dipping scenarios from angle of 70 to 85 degree for both features were incorporated into the three-dimensional geological model for assessing the geological impact on the subsequent cavern construction.

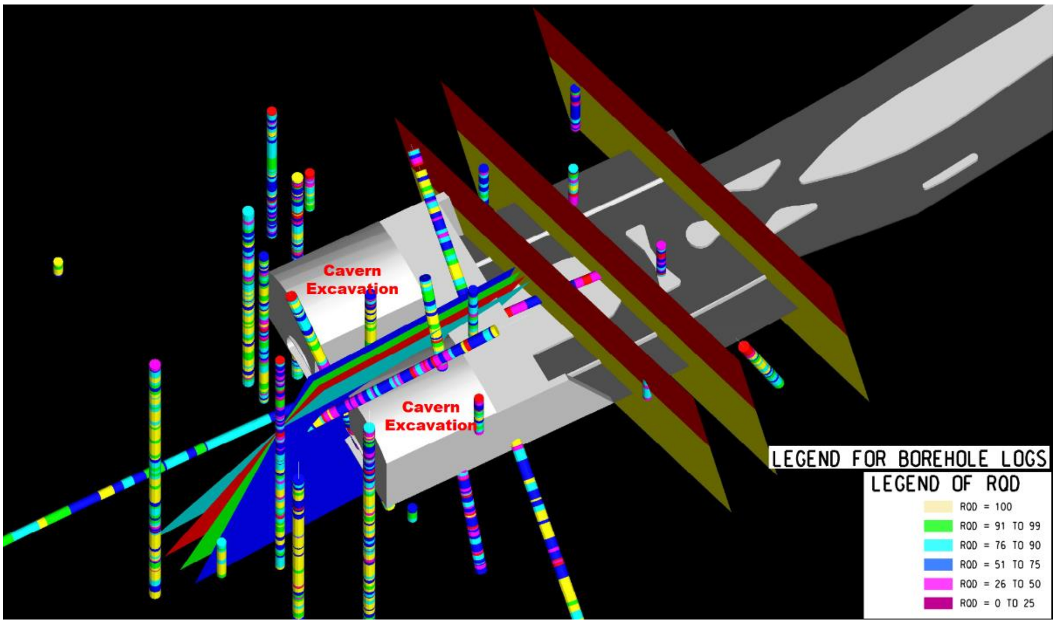

Figure 3: *Three-Dimensional Geological Model for the Caverns at TKO Portal*

2.3 Engineering Parameters

Throughout the assessment using the relevant field and laboratory test data from the ground investigation information, the engineering properties for the volcanic tuff at TKO portal area were summarized in Table 1.

Table 1: *Summary of Engineering Properties*

Rock	Unit Weight, (kN/m^3)	Poisson's Ratio ν	Intact Modulus, E_i (MPa)	Permeability k (m/s)	Uniaxial Compressive Strength, UCS (MPa)
MDT/V	27	0.25	45000	2.00E-07	150
SDT/V	27	0.25	50000	4.00E-07	170

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Over 8,100 rock discontinuity readings were obtained from boreholes using Borehole Acoustic Televiewer surveys from the project-specific ground investigation works. The data of dip and dip direction from the televiewer survey was contoured by rock types and stereographic plot results of the joint sets of tuff are summarized in Table 2.

Table 2: *Summary of Major Joint Sets*

Joint Set	Dip Direction	Dip Angle
Set 1	101°	23°
Set 2	213°	72°
Set 3	305°	70°
Set 4	052°	77°

2.4 Development of the Innovative Semi-Cavern Scheme

The East Ventilation Building (EVB) was required at the TKO Portal to maintain the ventilation (air exchange and smoke extraction system) for the main tunnel for satisfying the environmental and fire engineering requirements. In order to create the site formation area for EVB, extensive soil and rock slope cutting with an excavation volume of approximately 440,000m^3 was previously proposed in the preliminary design stage.

To shorten the construction period, the exposed EVB footprint was significantly reduced by adopting an innovative underground rock cavern to partially house the EVB part embedded into the hillside as illustrated in Figure 4. The exposed part of EVB is still required to maintain effective ventilation, facilitate maintenance and equipment delivery and minimise fire safety provisions for some major plants/rooms. This arrangement significantly reduced approx. 180,000m^3 of excavated materials and hence 470,000 tons of inert construction waste has been reduced.

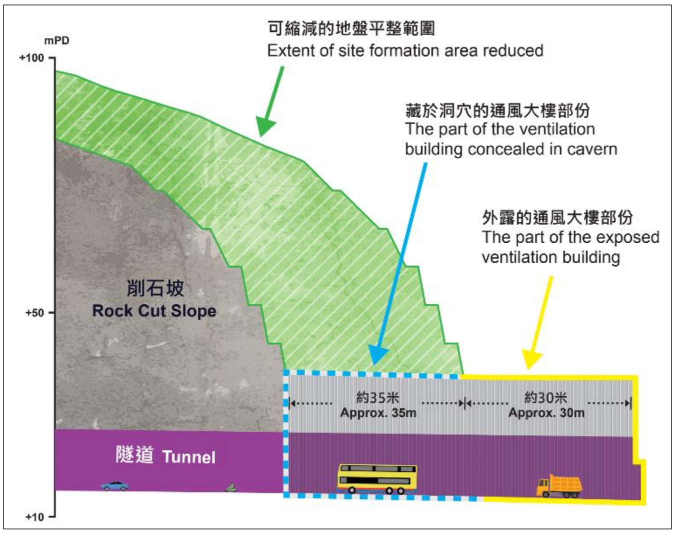

Figure 4: *Reduced Site Formation Works at TKO Portal(CEDD, 2020)*

The semi-cavern approach results in a building seamlessly integrated with the natural and built setting as shown in Figure 5, enhancing the sustainable design approach this project has adopted throughout the various stages of the works. With this innovative semi-cavern building scheme, the slope cutting and stabilization works have been minimised, the disposal of excavated materials and tree felling have been reduced, it also improve the visual impact of the ventilation building and enhanced the construction programme.

The preservation of vegetation and habitat was also enhanced by greatly reducing the tree felling area by approximately 46%. Environmental and visual enhancement was achieved by reducing the exposed EVB structure, while maintaining the same building height such that the impact of views from nearby residential buildings were minimised.

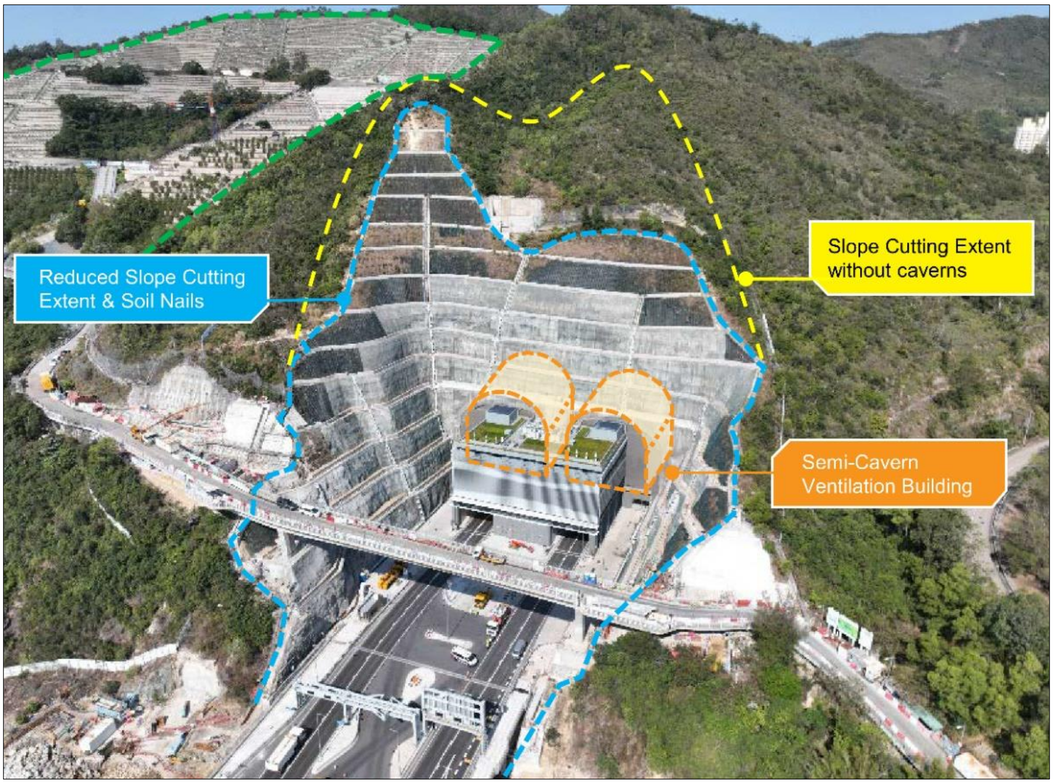

Figure 5: *Seamless Integration of EVB with the Natural Environment*

2.5 Cavern Profile and Geometry

The cavern internal profile was developed to meet the functional requirements of both the ventilation building and the main tunnel, such as the ventilation facilities, E&M equipment and utility services within the ventilation building, maintenance requirements, carriageway, structural gauge, sightline, ventilation area, traffic control and surveillance system (TCSS) and emergency walkway. The external profile was further determined based on the rock mass quality and support installation requirements.

An arched shape was designed as the geometric setting for the crown of semi-cavern. After excavation, the stresses surrounding the excavation profile will be re-distributed. The arched structural form utilises the rock arching as well as development of hoop stress along the concrete lining. The earth pressure at cavern crown is then effectively transferred through the arch to the cavern sidewalls. This arrangement increases the overall structural robustness which greatly reduces the cavern support requirements.

Based on the above-mentioned design requirements, the cavern profile and geometry were further developed. The excavation span and height for the caverns were about 26m and 31m respectively. The cavern height includes 7m depth of arch roof and 24m of straight wall. Cross section and longitudinal section showing the general arrangement of the semi-cavern EVB are indicated in Figure 6 and Figure 7 respectively.

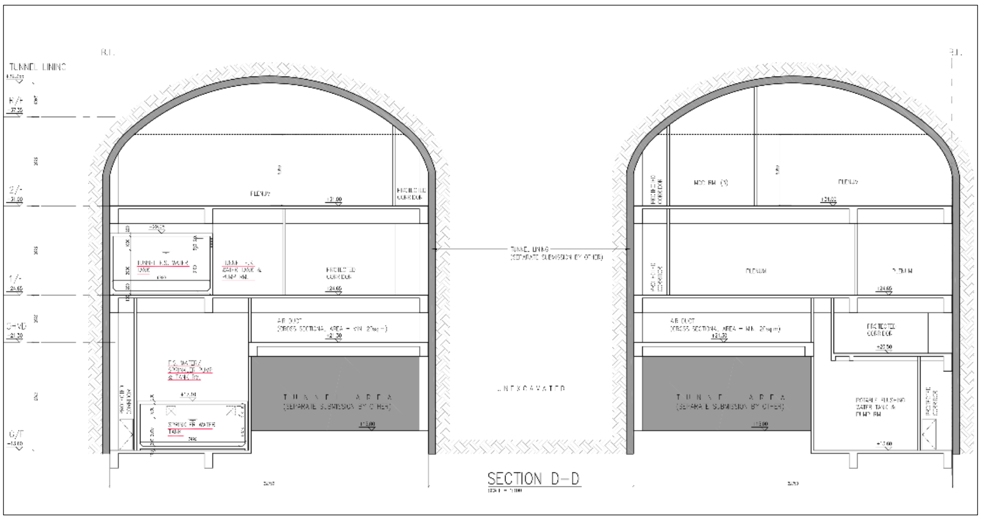

Figure 6: *Cross Section of Semi-caverns and EVB Facilities*

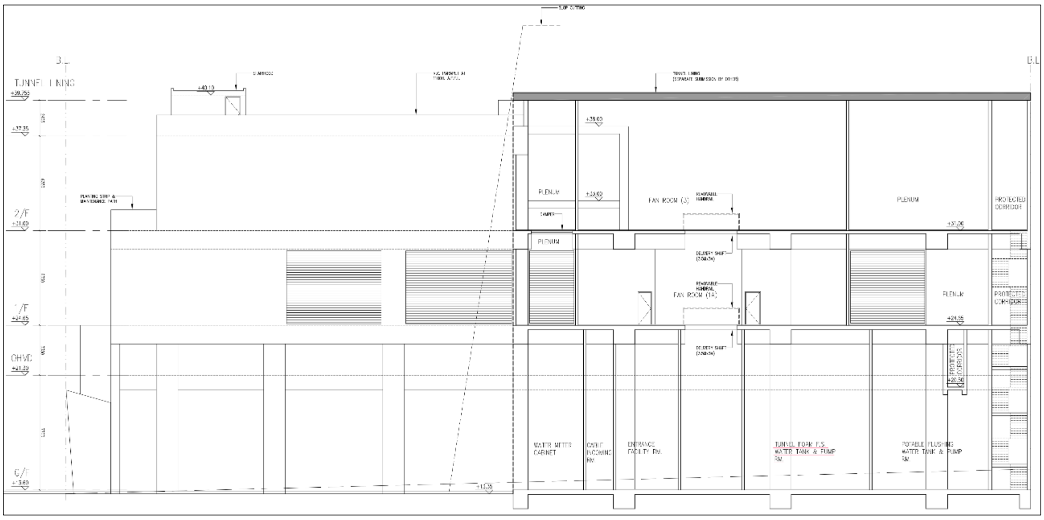

Figure 7: *Longitudinal Section of Semi-caverns and EVB Facilities*

2.6 Design and Analysis of Rock Supports

The caverns were designed to be self-supported. No ground loadings shall be transferred on to the EVB structures.

Computational software was used for the design and analysis of rock supports. Kinematic analysis was carried out using the software UNWEDGE with the rock joint sets interpreted from the ground investigation data as shown in Figure 8. Finite Element Model (FEM) software Phase^2 (now re-named as RS2) was adopted to study the earth load act on the lining and rock pillar stability using the Generalized Hoek-Brown (GHB) failure criterion as presented in Figure 9.

The permanent support of the caverns was designed to withstand the induced rock supporting pressure from the surrounding ground after excavation. For the portion of caverns where the rock cover is less than one span of cavern, permanent support was designed to withstand the pressure from full overburden above the cavern.

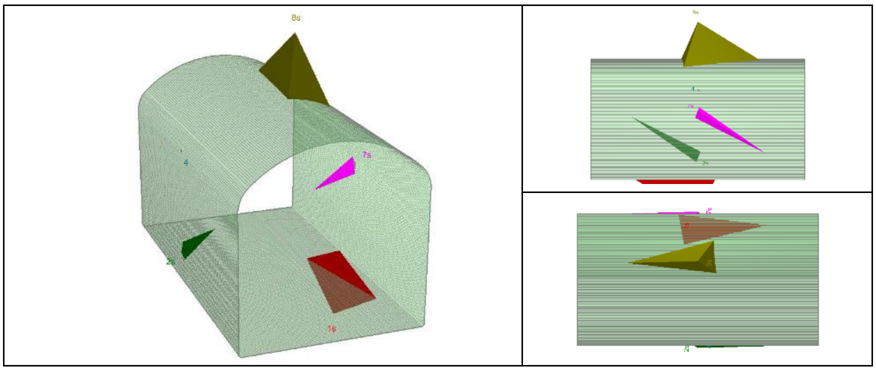

Figure 8: *Kinematic Analysis for Support Design and Analysis*

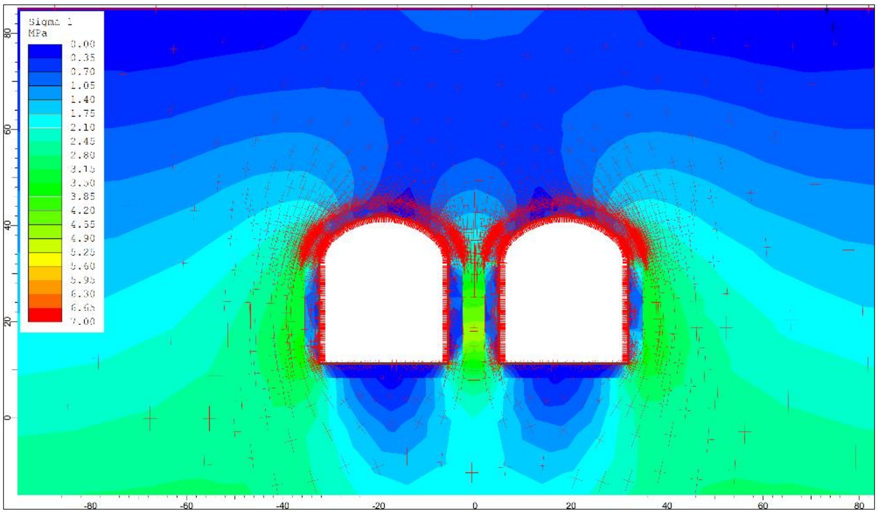

Figure 9: *Finite Element Model for Support Design and Analysis*

3 Construction

The excavation works commenced in August 2018. The two caverns are located in moderately and slightly decomposed volcanic tuff with three to four numbers of identified rock joints sets. Although the UCS values of volcanic tuff obtained from the laboratory tests were in general larger than 100 MPa, the volcanic tuff are highly fractured in nature. The cavern excavation was carried out by mechanical method using hydraulic breakers, top-down synchronizing with the site formation works as shown in Figure 10.

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Figure 10: *Top-heading Excavation by Mechanical Method*

The design of temporary cavern supports was carried out based on the empirical approach and further verified by numerical modelling. At shallow rock cover, the excavated ground was temporarily supported by a combination of steel canopy tube, lattice girder (as shown in Figure 11) and shotcrete; where after reaching ground with sufficient rock cover, the temporary supports comprised the installation of rock bolts, fibre-reinforced shotcrete and steel bars as rock pillar reinforcement.

Figure 11: *Installation of Lattice Girder Segment*

The progressive nature of mechanical excavation allowed a close monitoring of ground movement throughout the excavation, enabling timely strengthening works to ensure the stability of the caverns under such challenging ground conditions.

Following the completion of top-heading excavation, the subsequent cavern bench excavation and portal slope site formation works were carried out as shown in Figure 12. The excavation sequence was well-planned to overcome the major challenges including interfacing issues, machinery movement, logistic arrangement, and the handling of excavated materials in order to complete the works within the tight schedule.

Figure 12: *Cavern Bench Excavation and Portal Slope Site Formation Works*

The excavation works was completed in March 2020. The permanent works for the caverns and semi-cavern EVB commenced after the completion of rock excavation works. The permanent lining works included fibre-reinforced sprayed concrete at the crown and cast-in-situ reinforced concrete for side walls and end wall. Figure 13 shows the installation of waterproofing system and casting of reinforced concrete lining at side walls. The construction of the semi-cavern East Ventilation Building was eventually completed in July 2022 (refers to Figure 14).

Figure 13: *Waterproofing and Reinforced Concrete Lining at Side Walls*

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Figure 14: *The completion of Semi-Cavern and EVB works*

4 Conclusion

The TKO-LTT project has achieved the commissioning target by 2022, and the operation of the tunnel has been successful in alleviating traffic congestion in the TKO area, existing TKO tunnel and eastern Kowloon major roads approaching the Eastern Harbour Crossing.

The two large-span caverns for ventilation building integration were successfully constructed. The surface footprint of ventilation building was significantly reduced, and achieved a great construction time and cost saving in extensive slope cutting and stabilization works, avoid huge among of tree felling, minimize visual impacts and reduce the rock excavation period to minimize the nuisance to public during the construction stage.

This innovative engineering solution provided significant benefits to the project in terms of cost effectiveness, sustainability, environmentally friendly and energy efficient aspects in the construction, operation & maintenance stages of the project.

The semi-cavern EVB at TKO-LTT will serve as a good model to promote the use of underground space and rock cavern development in Hong Kong.

5 Declarations

5.1 Acknowledgement

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