Rock Load Transfer Mechanisms and Interactions at Cavern Junctions

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ABSTRACT

Rock at depth is subjected to stresses resulting from the weight of the overlying strata. When an underground opening is excavated, the stress field in this rock mass is locally disrupted and induces a new set of stresses surrounding the new opening. At tunnel and cavern associated junctions, the re-distributed stresses will alter the stress fields of adjacent openings. For example, loadings from a taller cavern will be transferred through the rock arch and concentrated as additional vertical stress above the crown of the shorter cavern. The load transferring mechanisms in this paper refer to the construction of the cavern complex, which involves developing new sewage treatment works in caverns to be constructed at Nui Po Shan, A Kung Kok, Sha Tin, to replace the existing Sha Tin Sewage Treatment Works (STSTW). Upon functioning of the new STSTW, the existing site will be released for other uses beneficial to the development of Hong Kong. The works at the new STSTW occupies about 14 hectares in the area comprising of Main Access Tunnel (MAT), Secondary Access Tunnel (SAT), fifteen Process Caverns, the Main Driveway (MD), Secondary Driveway (SD), four Branch Driveways, Ventilation Shaft, Ventilation Adit, two Effluent Pipelines, and lining and portal structure of MAT and SAT. These structures are excavated mainly by the drill-and-blast method in hard rock, with rock covering more than half of the excavation span/height above the crown. They are designed as drained and are primarily supported by the rock arch, reinforced by systematic permanent rock bolts with permanent sprayed concrete. In addition, drained cast-in-situ reinforced concrete lining is proposed for poor ground conditions.

For the proposed cavern complex, most of the Branch Driveways are taller than Process Caverns and MD/SD except for the middle cavern for sludge treatment (STC) purposes. STC's design span and height are 30 m and 35 m, respectively. Therefore, additional stresses are expected to transfer from Branch Driveways and STC to other Process Caverns and MD/SD. Numerical modeling using finite element methods has been established, where two-dimensional design models and three-dimensional verification models in accordance with the varying excavation profiles, overburden depth, and rock mass quality have been carried out. By observing the stress redistribution from the taller STC to other Process Caverns, the two-dimensional and three-dimensional models aim to study the stress concentration zones and the extent of the influence zone at tunnel and cavern associated junctions. The maximum deformation is located along with the crown of STC and intruding corners at the associated junctions, in which the Process Caverns with the largest excavation span and height are proposed.This paper provided a detailed description of the geology, cavern complex geometrical arrangements, rock mass properties for the modeling, methodology of modeling, and mechanism of load redistribution observed at the junctions.

Keywords: Cavern Junction, Rock Reinforcement, Rock Load Transfer

1 Introduction

1.1 Background

To enhance the land supply strategy in Hong Kong to support the rapidly growing social and economic development, an initiative was put forward by the Development Bureau (DevB) to launch strategic planning and technical studies as part of their 2009-10 Policy Agenda. The initiative aims at promoting the enhanced use of rock caverns as part of Hong Kong’s pursuit of sustainable development to build

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up sufficient land reserves to meet future social, environmental, and economic needs. As part of this initiative, the Drainage Services Department (DSD) proposed relocating the Sha Tin Sewage Treatment Works (STSTW) to caverns to release the existing site of approximately 28 hectares for other beneficial uses.

The works at the new STSTW occupies about 14 hectares in the area comprising Main Access Tunnel (MAT), Secondary Access Tunnel (SAT), five chains of Process Caverns, Main Driveway (MD), Secondary Driveway (SD), four Branch Driveways, Ventilation Shaft, Ventilation Adit, Effluent Tunnel, as well as the portal structure at Main Portal and Secondary Portal. In this paper, all these caverns/driveways holding the sewage treatment facilities are collectively referred to as Cavern Complex. STSTW is to be constructed at Nui Po Shan, A Kung Kok, Sha Tin, and the layout plan of the site area with an isometric view is presented in Figure 1.

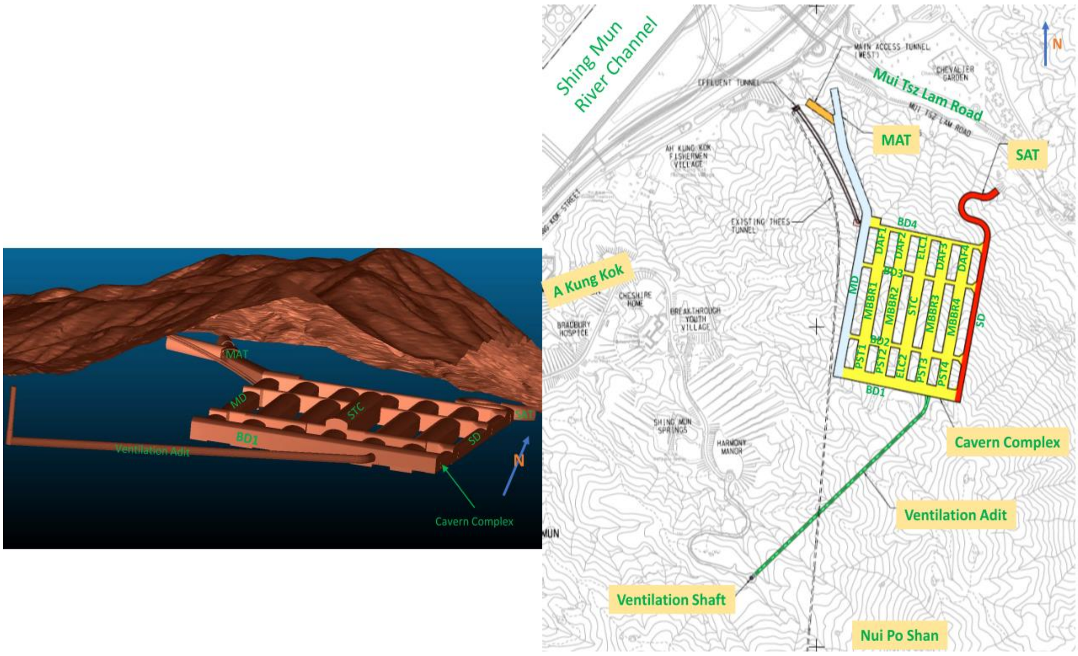


Figure 1: Layout Plan of STSTW (with Isometric View)

1.2 Geological Conditions

The proposed Cavern Complex is situated beneath the natural hillslope, where the existing ground level ranges from +87 mPD at the end of the proposed SAT to +312 mPD at the southeastern edge of the Cavern Complex. The general topography increases towards the southeast, and the steepest gradient is noted on the northeast facing hillslope above the eastern part of the Cavern Complex. The majority of the Cavern Complex is located beneath north to northeast-facing hillslope, where an east-facing hillslope is encountered above the southeastern part of the Cavern Complex.

The solid geology of the site area is predominantly equigranular medium-grained Granite with some porphyritic fine-grained Granite of the Shui Chuen O Granite of the Early Cretaceous age. The proposed Cavern Complex is well below the engineering rock head, which is inferred from borehole data based on the criterion of at least 5 m penetration by boreholes into the moderately strong or better rock of weather Grade III or better with at least 85% core recovery to the length of 1.5 m core run. The engineering rock head within the site generally follows the topography and ranges from +28 mPD at the Secondary Portal to +285 mPD at the southeastern corner of the Cavern Complex.

The rock cover (the vertical distance between the underground structures and engineering rock head) of the Cavern Complex ranges from 45 m to 169 m approximately. A generalized geological section A-A is presented in Figure 2 to illustrate the rock cover above the cavern's roof is well above one excavation span, depending on its physical location. On top of the rock head, it is overlaid by a layer of saprolite which comprises highly (Grade IV) to completely (Grade V) decomposed rock with a thickness of up to 20 m. Colluvium is mainly found above the saprolite on the lower slopes close to Mui Tsz Lam Road and locally on the slopes over the Cavern Complex and other structures. The typical thickness of colluvium is 0.5 m to 3 m.

Local and minor occurrences of basalt dykes, pegmatite, quartz monzonite, and quartz synenite may be encountered within the Cavern Complex, but their effects on the excavation are considered insignificant. A few minor faults are expected crossing the Cavern Complex. Groundwater can be assumed to be close to the ground surface; however, it is not significant to the analysis results as the proposed Cavern Complex is designed to be drained except for the local portions near Main Portal and Secondary Portal.

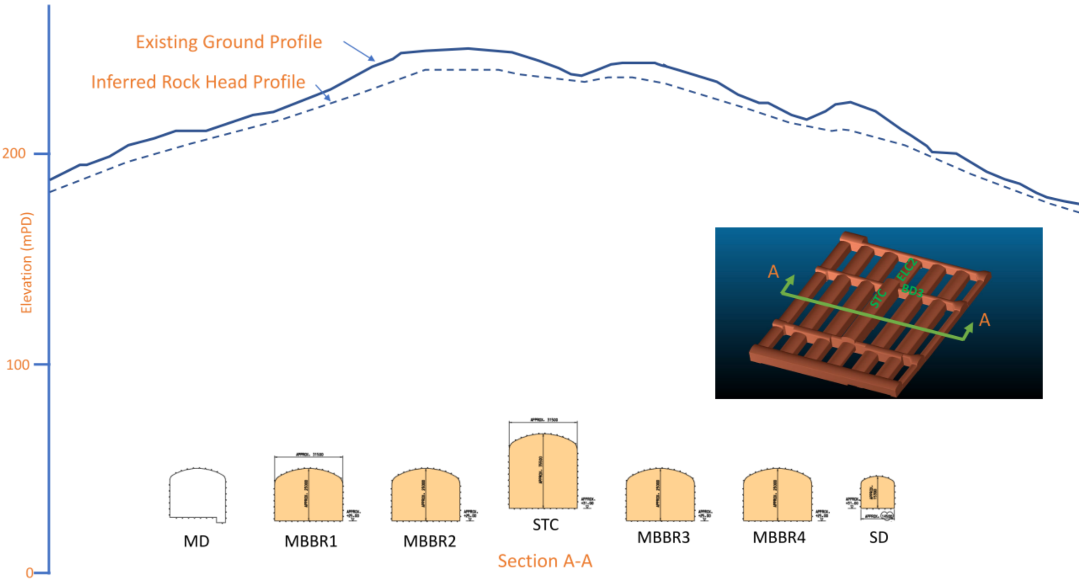


Figure 2: Geological Section A-A

2 Geotechnical Parameters

2.1 Rockmass Properties

Using the available relevant field and laboratory test data, the adopted design parameters of rock mass used explicitly in this study as a framework for the analysis are taken in the middle range, as shown in Table 1.

A detailed assessment of the rock mass quality "Q index" has been carried out based on the borehole records from the project-specific deep boreholes drilled in vicinity of the site area during feasibility study and detailed design stages as well as the archived ground investigation results which are available, and their associated core photographs, and the interpretation of the stereonets and assessment of the lineaments.

For the Q-logging of the borehole records, the J_n values within Granitic bedrock typically range from 6 to 15 but may increase further where features such as core loss or weakness are indicated.

The J_w parameter has generally been taken as 1, but a value of 0.66 has been assigned where the rock mass shows adverse geological features such as core loss or weakness, which may likely increase groundwater inflow into the tunnel

A minimum SRF value of 10, 7.5, 5, or 1 has been assigned for zones of competent rock depending on the depth below the engineering rock head level. However, the value would be increased to 2.5, 5, or 10, where the core loss or weakness zones were recorded in boreholes.

The ranges of the Q index around the Cavern Complex were assessed as shown in Table 1.In Table 1, the Generalized Hoek-Brown parameters are derived from the Geological Strength Index (GSI), which is correlated to the Q index and the intact rock strength. The parameters in this table are not considered for design purposes as large variations will occur on-site, which can only be apparent after the excavation has been carried out and the rock face has been mapped.

Table 1: Rock Mass Properties

Parameter	Bulk Unit Weight (kN/m^3)	UCS (MPa)	Tensile Strength (MPa)	Young's Modulus E (GPa)	Poisson's ratio υ	Shear Modulus (GPa)			
MDG	25.5	75	5	15	0.3	10			
Rock Mass	Q	m_i	E_i (MPa)	MR	GSI	E_m (MPa)	m_b	s	A
	5.9>Q>1.9	32	27524	367	54	10370	6.08	0.00571	0.504

2.2 Rock Joint Parameters

Optical and acoustic televiewer tests were carried out in the vertical, inclined, horizontal boreholes, and horizontal directional coring. Major joint sets in different sub-areas have been identified from stereographic analysis in Table 2 for the Cavern Complex.

Table 2: Rock Joint Parameters

Area	Major Joint Set 1	Major Joint Set 2	Major Joint Set 3	Major Joint Set 4	Major Joint Set 5
Cavern Complex	245°/81°	053°/82°	343°/85°	320°/18°	221°/81°

Based on all the rock joint shear test results conducted, the typical values of peak friction angle, residual friction angle, and cohesion for estimating rock joints shear strength are 40°, 30°, 0 kPa, respectively, with an estimated JRC of 5 and JCS of 25% of UCS.

2.3 In-situ Stress Assumptions

Based on the over-coring and hydraulic fracturing tests, the ratio of the maximum principal horizontal stress to the vertical stress and the ratio of the minor principal stress to the vertical stress is taken as 2.1 and 1.0, respectively, in the following analysis. These site-specific data generally give a higher ratio of the maximum principal horizontal stress to the vertical stress than other projects, which implies a more favorable condition for large rock cavern development. Therefore, again, these ratios are explicitly adopted in this study for the purpose of analysis only.

3 Development of Rock Arches

3.1 Rock Reinforcement

Drill-and-blast is proposed for the Cavern Complex, where the engineering rock cover is more than one excavation span/height above the crown of the cavern. They are primarily supported by the rock arch reinforced by systematic rock bolts with permanent sprayed concrete. The support classes shall be determined based on the mapped Q values by the engineering geologist after excavation.

The envisaged construction sequence for the permanent systematic rock bolts and permanent sprayed concrete is shown as follows:

1. Drill probe holes in front of the tunnel face and carry out pre-excavation grouting in case of excessive groundwater inflow;
2. Excavate the caverns/tunnels by drill-and-blast method;
3. Carry out geological mapping to determine the support classes according to the mapped Q-values;
4. Survey to identify any overbreak/underbreak and the associated remedial works;

5. Install temporary sprayed concrete, smoothing sprayed concrete layer (as required), and permanent rock bolts;
6. Install the drainage strips and permanent sprayed concrete, and
7. Repeat the above procedures to advance the construction of a permanent rock support system.

Top-heading and bottom-benching methods are anticipated considering the cavern profiles, logistic construction flow, blasting operations, pull length, mucking out, and excavation cycle-time etc.

3.2 Rock Load Transfer Mechanisms

Rock at depth is subjected to stresses resulting from the weight of the overlying strata. When an underground opening is excavated, the stress field in this rock mass is locally disrupted and induces a new set of stresses surrounding the new opening.

At tunnel and cavern associated junctions, the re-distributed stresses will alter the stress fields of adjacent openings. For example, loadings from a taller cavern will be transferred through the rock arch and concentrated as additional vertical stress above the crown of the shorter cavern. An illustrative sketch of the stress transfer mechanism is shown in Figure 3.

For the proposed Cavern Complex, most of the Branch Driveways are taller than the Process Caverns and MD/SD except for the middle cavern STC for the Sludge Treatment purposes. Therefore, additional stresses are expected to transfer from Branch Driveways and STC to the Process Caverns and MD/SD at those localized junctions. Different sewage treatment facilities are housed in different caverns/tunnels, and they are collectively given the term Process Caverns. For illustration purposes, in this paper, the study focuses only on the junctions of STC, the Process Cavern called ELC2, and the Branch Driveway called BD3.

The load transferring mechanisms in this paper will refer to the construction of the Cavern Complex at the junctions of the Sludge Treatment STC, ELC2, and BD3 with their locations, as shown in Figure 2. The internal span and height of STC are 30 m and 35 m, respectively. For ELC2, its internal span and height are 30 m and 13 m, respectively, whereas BD3's internal span and height are 10 m and 23 m, respectively. Numerical modeling using finite element methods has been established, where two-dimensional design models and three-dimensional verification models in accordance with the varying excavation profiles, overburden depth, and rock mass quality have been carried out. By observing the stress redistribution from STC to BD3/ELC2, the two-dimensional and three-dimensional models aim to study the stress concentration zones and the extent of the influence zone at tunnel and cavern associated junctions. Within the context of this paper, continuum mechanics is assumed for the analysis where the rock mass behavior is considered homogeneous and isotropic without adverse weakness and blocky rock mass influence.

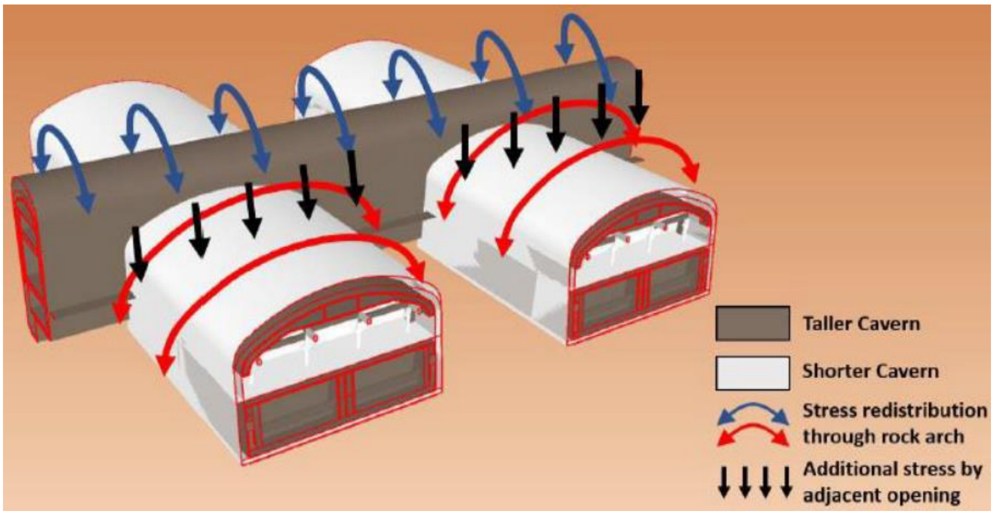


Figure 3: Rock Load Transfer Mechanisms at Junctions

4 Finite Element Modelling

4.1 Verification Model for Full Cavern Complex

A three-dimensional analysis can provide clear indications of stress concentrations due to the stress interactions of three-dimensional geometry. Therefore, an elastic analysis was first carried out by a three-dimensional finite element program 'RS3 Version, 2.023'developed by Rocscience Inc., to assess whether the zone of influence at the intersections is limited to about one diameter of the smaller openings. As a result, the maximum deformation of a few millimeters is located along with the crown of STC and intruding corners at the associated junctions, in which the Process Cavern with the largest excavation span and height is proposed. Figure 4a shows the major principal stress contour, σ_1, where stresses redistributions are found at the transition from crown to wall/pillar, but no sign of excessive stress concentration is observed. Also, the vertical stress contour plot shows no sign of excessive vertical stress observed at the junctions intersecting Branch Driveways. It is because the proposed Cavern Complex involves seven parallel large-span openings with closely-spaced rock pillars, and the in-situ stress field has been greatly disrupted. A longitudinal section showing the vertical stress contour intersecting the Branch Driveways along STC is shown in Figure 4b.

Initially, the in-situ stress within the rock mass follows the ground profile of the overlying stratum. After excavating the Cavern Complex, the stress is re-distributed through the rock arch to the wall/pillar along STC. The zone of stress redistribution decreases at approximately 45° until reaching the excavation boundary at the end of the excavation. After further excavating the Branch Driveways, the stress at junctions is further re-distributed. As a result, the extent of the influence zone is slightly less than one excavation span of the Branch Driveways. Based on this observation, it is practical to simplify the problem into two-dimensions by considering the additional vertical stresses at critical sections to verify the maximum forces on permanent rock bolts at all junctions.

4.2 Two-dimensional Plastic Model

The finite element program, PHASE2 Version 8.0, developed by Rocscience Inc., was used to check the permanent rock bolt supports due to the additional vertical stresses with the Generalised Hoek-Brown failure criteria. In addition, the convergence-confinement method was used to model the relaxation of ground loading during the blast face advances following the methodology by Kersten Lecture (2008) and Vlachopoulous and Diederichs (2009). The blast face advancement is modeled by decreasing face support pressure from full to zero in multiple stages without installing any rock reinforcement or support. The deformation is measured for all stages.

The equivalent support pressure versus distance from the blast face of the tunnel is then calculated. This deformation versus face support pressure relationship will determine the amount of ground relaxation behavior of the rock mass when unsupported and imply the amount of loading sustained by the rock bolts and the temporary or permanent supports to the tunnel/cavern when installed accordingly. In the model, sprayed concrete and rock bolts were activated sequentially in pace with the relaxation of ground loading during blast face advances. Stage factors are available in PHASE2 Version 8.0 for simulating the relaxation of ground loading as a function of the excavation stage. In the numerical model stage, the ground loading is relaxed by changing the ground stiffness at the initial stage from 1E to 0.5E for first blast face advancement, 0.3E for second blast face advancement and installation of permanent supports, and full excavation for further blast face advance. A 1 m blast disturbed zone was set up around the excavation to simulate the damage and strength loss in rock mass caused by blasting. A disturbance factor D=0.2 was applied to the blasting damage zone.

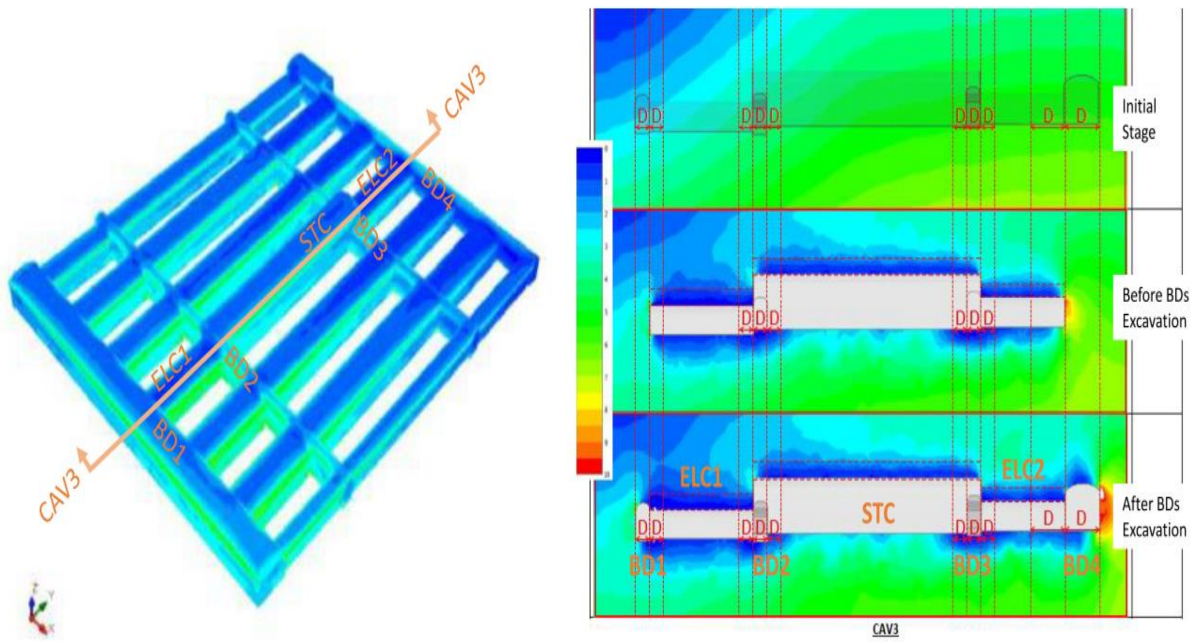


Figure 4: a) Major Principal Stress at Full Cavern Complex Model, b) Change of Vertical Stress along STC

An example of a design checking model along STC is presented in Figure 5. It assesses the ground interactions due to multiple openings at junctions. In addition, it determines the additional vertical stresses to be transferred from Branch Driveways through the rock arch and concentrated at the crown of Process Caverns and MAT/SAT. The additional stress is determined based on the difference in vertical stress before and after excavation.

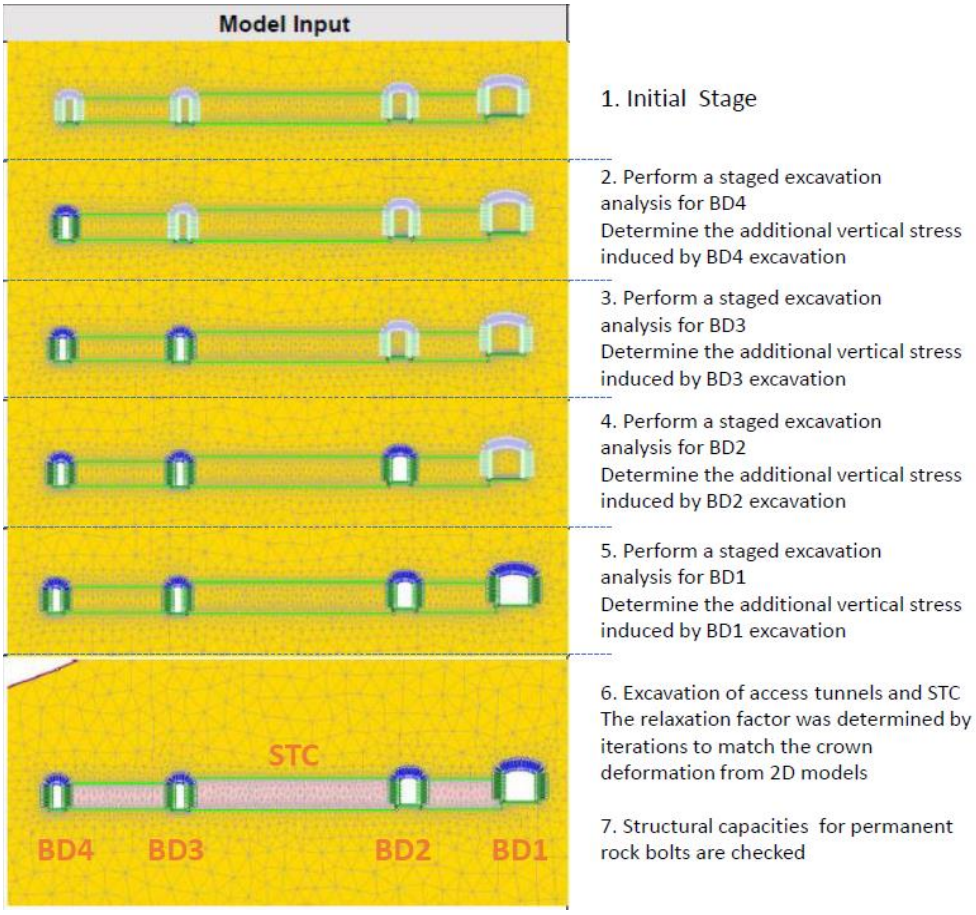
Uniform distributed loadings are incorporated in the models to simulate the effect of additional loadings at junctions, as illustrated in Figure 6. The magnitude of the uniform distributed loadings was assigned a range of 100 kPa to 300 kPa, at a location above the roof of the short caverns.

The induced stresses of the permanent rock bolts are well within the structural capacities, as demonstrated by the plot of axial forces in Figure 6.

5 Conclusions

Numerical modeling using finite element methods has been established, where two-dimensional design models and three-dimensional verification models in accordance with the varying excavation profiles, overburden depth, and rock mass quality have been carried out. It is observed that the maximum deformation is located along with the crown of STC and intruding corners at the associated junctions, in which the Process Cavern with the largest excavation span and height is proposed. Furthermore, the vertical stress contour plot shows no sign of excessive stress concentration observed at the junctions intersecting Branch Driveways. The extent of the influence zone is slightly less than one excavation span of the Branch Driveways. Based on this observation, it is practical to simplify the problem into two-dimensions by considering the additional vertical stresses at critical sections to verify the maximum forces on permanent rock bolts at all junctions. The induced stresses of the permanent rock bolts are well within the structural capacities, as demonstrated by the plot of axial forces.

The analysis within the context of this paper is based on continuum mechanics, where the rock mass behavior is considered homogeneous and isotropic without adverse weakness and blocky rock mass influence. This could be another topic interesting for further investigations and studies.



1. Initial Stage

2. Perform a staged excavation analysis for BD4
Determine the additional vertical stress induced by BD4 excavation

3. Perform a staged excavation analysis for BD3
Determine the additional vertical stress induced by BD3 excavation

4. Perform a staged excavation analysis for BD2
Determine the additional vertical stress induced by BD2 excavation

5. Perform a staged excavation analysis for BD1
Determine the additional vertical stress induced by BD1 excavation

6. Excavation of access tunnels and STC
The relaxation factor was determined by iterations to match the crown deformation from 2D models

7. Structural capacities for permanent rock bolts are checked

Figure 5: Methodology to Determine Additional Vertical Stresses Acting from a Taller to Shorter Cavern

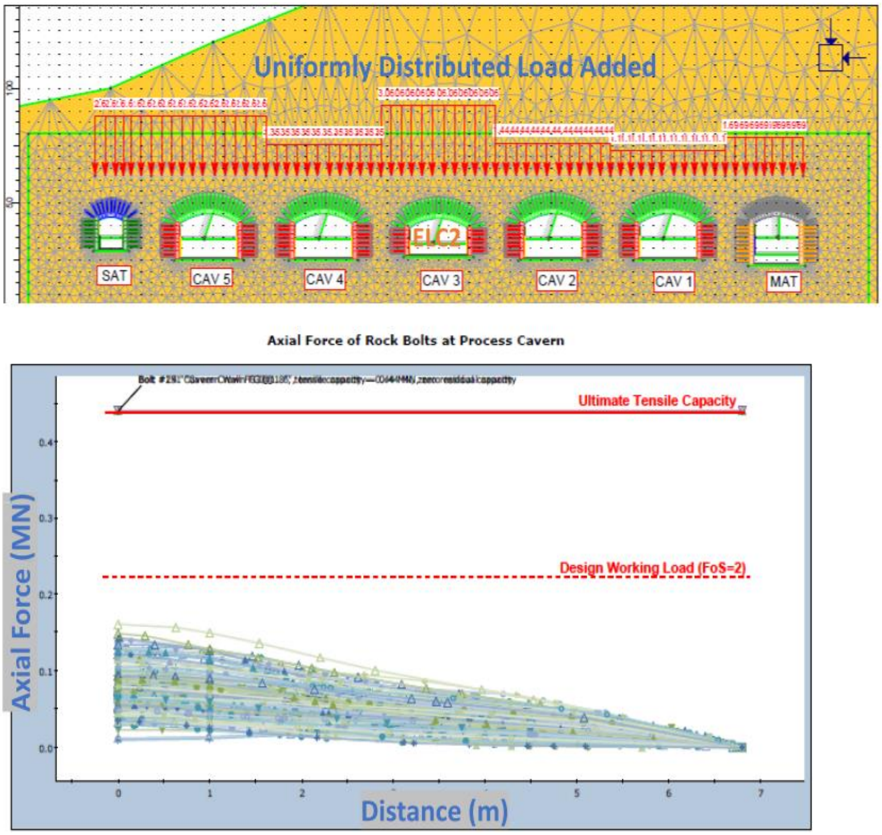


Figure 6: Additional Loadings at Junctions from STC to ELC2

6 Declarations

6.1 Acknowledgements

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6.2 Publisher's Note

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