Design Optimization of Permanent Systematic Rock Bolts and Shotcrete Lining for Large-Span Caverns in Hard Rock

Franklin. K.L. To*, Bridges, G.D.C., Andrew K.W. Seto

AECOM Asia Company Ltd., Hong Kong

*Corresponding author
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Abstract

The hilly terrain in Hong Kong is underlain by hard and massive igneous rocks. This brings favorable conditions to develop underground space including rock caverns as an alternative source of land supply. In recent years, the government departments have been playing a leading role to study the feasibility of rock cavern development in Hong Kong. These studies include the relocation of existing sewage treatment works, service reservoirs, refuse transfer stations, archive centre and laboratory to rock caverns. After completion of the relocation, the previously occupied surface land can be released for other developments beneficial to the communities. For an underground excavation in competent rock, the use of empirical design approaches is usually fast and straightforward to assess the rock mass conditions and determine the rock support systems. However, there are a number of limitations that empirical approaches cannot adequately address regarding the design of rock caverns, in particular the appropriateness for large-span excavation and influence of multiple parallel excavations. However, these limitations could be addressed appropriately by carrying out numerical modelling, which is a very powerful tool to handle ground and support material properties with greater complexity. It allows the designer to develop a more flexible and compatible range of possible supports. This paper discusses some key technical components of rock engineering related to the design and modelling of large-span rock caverns in order to achieve a cost-effective permanent support system. A comparison is carried out between the rock support requirements for a range of cavern excavation spans and parallel excavations predicted by empirical approach and numerical modelling.

Keywords: Shotcrete lining, Design optimisation, Cavern, Rock bolts

1 Introduction

1.1 Recent Rock Cavern Development in Hong Kong

Whilst being globally famous as a densely built environment with a population of over 7.4 million, less than 25% of the land area in Hong Kong has been developed out of the total area of about 1,100 km^2. This is because much of Hong Kong comprises hilly terrain, rural areas and protected areas including country parks and special areas, restricted areas, conservation-related zonings and water gathering grounds. Development of these areas are prohibited under statutory protection.

Under such circumstance, the flat land available for development has become scarce in Hong Kong. Traditional approaches of land development including flat land, open-cut site formation of moderately hilly terrain and large-scale reclamation have been playing an important role in Hong Kong's continuous land supply. However, these approaches have caused the built-up areas to be largely concentrated within the foothills of natural terrain extending towards the shoreline or the reclaimed land.

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About 85% of the hilly terrain in Hong Kong is underlain by hard and massive igneous rocks such as granite and volcanic tuff. This brings favorable conditions to develop underground space including rock tunnels and caverns as an alternative source of land supply. In recent years, the government departments have been playing a leading role to study the feasibility of rock cavern development in Hong Kong. A territory-wide Cavern Master Plan (CMP) as shown in Figure 1 has been prepared to guide and facilitate the planning and implementation of long-term cavern development. The CMP delineates 48 numbers of Strategic Cavern Areas (SCVAs) that are suitable for cavern development in terms of geological considerations and the current planning perspectives.

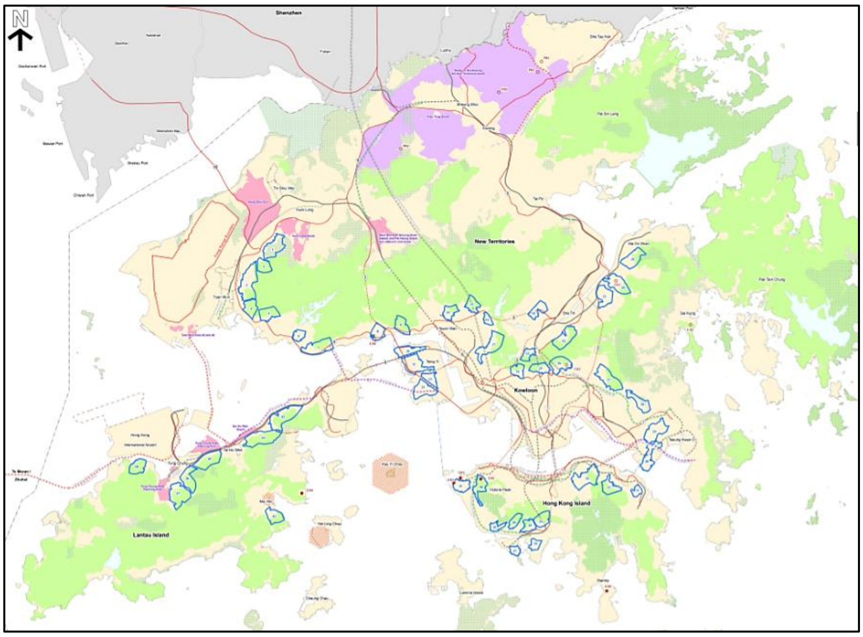

Figure 1: The Cavern Master Plan (CEDD and PlanD, 2017)

Recent on-going projects include the relocation of existing sewage treatment works, service reservoirs, refuse transfer stations, archive centre and laboratory to rock caverns. After completion of the relocation, the previously occupied surface land can be released for other developments beneficial to the communities.

2 Empirical Approaches for Cavern Excavations

2.1 General

The term "empirical" refers to the methodology to first gain information (directly or indirectly) then correlate relationships by testing, observation or experience. The simplest form is applying a best-fit line of y=mx+c for a sample group of data. Empirical approaches such as the Terzaghi's Arching Theory (1946) and the Q-system developed by Barton et al. (1974) are the most common methods used for underground excavation in competent rock. They are fast and straightforward to assess the rock mass conditions and determine the rock support systems without spending high cost and time on carrying out sophisticated numerical modelling.

2.2 The Rock Arching Theory

The rock arching theory developed by Terzaghi (1946) was the first successful rock mass classification for tunnel engineering. The theoretical rock arch above crown is self-supporting and only the weight of loosened rock after excavation is acting on the tunnel supports as illustrated in Figure 2. The support pressure was estimated based on the known strength of failed wooden blocks and back-analysis of a 5.5m wide tunnel supported by steel-arches. Nine categories of pressure were developed for different rock mass conditions.

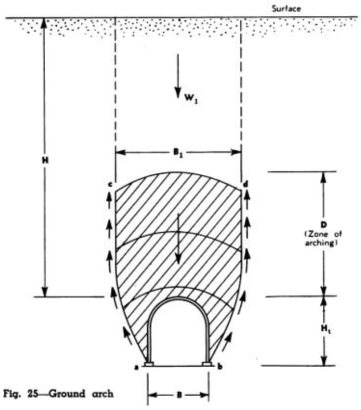

Figure 2: The rock arching theory (Terzaghi, 1946)

2.3 The NGI Q-System

The empirical Q-system for rock mass classification and its relationships to tunnel supports were first developed by Barton et al. (1974) and updated by Grimstad & Barton (1993) at the Norwegian Geotechnical Institute (NGI), Norway. It has been continuously updated since then with more than 2,000 case histories from underground openings, and takes into account the advancement in construction technology. The Q-value is formulated by the multiplier of six different rock mass parameters as presented in Equation 1:

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

(i) Rock Quality Designation RQD
(ii) Joint Set Number J_n
(iii) Joint Roughness Number J_r
(iv) Joint Alteration Number J_a
(v) Joint Water Reduction Factor J_w
(vi) Stress Reduction Factor SRF

The first component (RQD / J_n) describes the relative size of rock blocks, or how fractured the rockmass is. The second component (J_r / J_a) describes the shear strength of inter-block discontinuities. The third component (J_w / SRF) describes the in-situ stress conditions and the active stress due to groundwater inflow in the rock joints surrounding the excavation boundary. These individual empirical parameters were developed from monitoring data and back-analysis of case histories from a large number of underground excavations, both stable and unstable.

The Q-value ranges from a minimum of 0.001 to a maximum of 1000, and is typically represented on a logarithmic scale. It gives a description of the stability of an underground opening in jointed rock masses. High Q-values indicate good stability and low values means poor stability. It has been widely adopted to assess the rock mass quality, estimate rock support pressure and determine the supports for hard rock underground excavation in Hong Kong.

In addition to the rock mass quality (Q-value), there are also two important factors governing the rock support design in underground openings. These include the safety requirement expressed by Excavation Support Ratio (ESR) and the size of excavation (span and height). In general, a wider excavation profile requires more rock support for stabilization than a smaller excavation profile. For the factor of safety, the ESR can be applied, for example a highway tunnel with heavy traffic would be assigned a lower ESR than an underground sewage tunnel with limited maintenance requirements (lower value being more conservative). The variable Equivalent Dimension is then given by span or height (in m) divided by ESR.

The formula proposed by Barton et al (1977) can be used to determine the initial systematic rock bolt length as presented in Equation 2. This is appropriate for systematic support, but may not be sufficient bolt length for potential rock wedges, which need to be assessed separately.

$$L = 2 + \frac{0.15\,B}{ESR} \qquad (2)$$

where L = bolt length (in m)

B = cavern span for roof support (could use cavern height H for wall support) (in m)

ESR = excavation support ratio (safety requirement)

The Q-value and Equivalent Dimension are then used to determine the rock support design using the rock support chart by NGI (2015) as shown in Figure 3. For a given combination of Q-value and Equivalent Dimension, the support requirements such as the required shotcrete thickness and systematic rock bolt spacing for a given rock support class can be obtained. However, there are a number of limitations that empirical approaches cannot adequately address regarding the design of rock caverns, in particular the appropriateness for large-span excavation and influence of multiple parallel excavations.

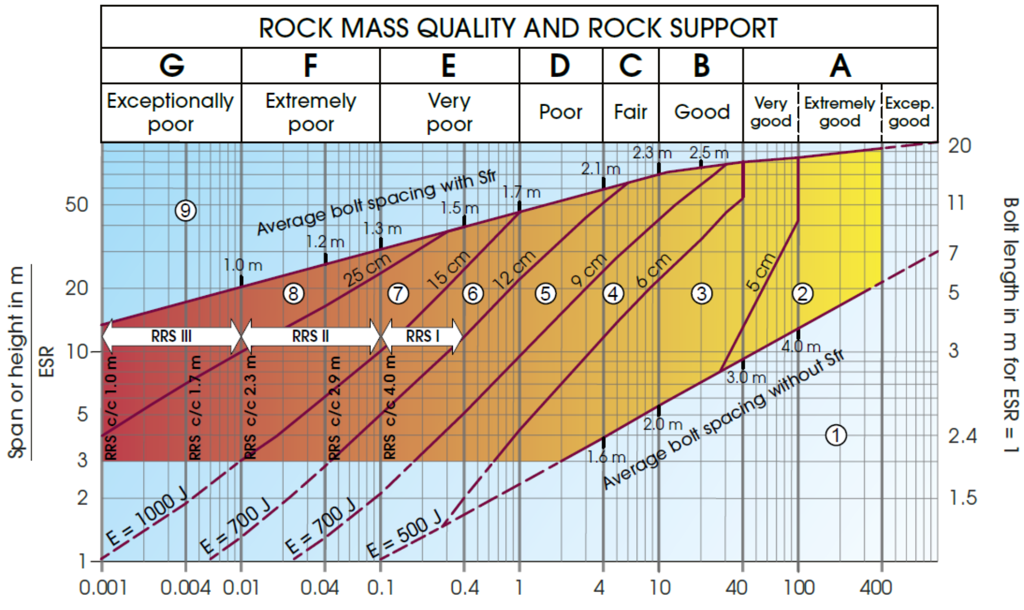

Figure 3: The Q-system rock support chart (NGI, 2015)

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2.4 The Generalized Hoek-Brown Failure Criterion

The strength of a jointed rock mass depends on both the mechanical properties of intact rock as well as the degree of freedom for the rock block to slide and rotate under different stress states. The yield mechanism is non-linear and the failure mechanisms are often brittle.

The Hoek-Brown Failure Criterion was first derived by Hoek and Brown (1980) from testing results of rock specimens to estimate the deformation and strength characteristic of a jointed rock mass based on the interlocking effect and discontinuity conditions. Later in 2002, the modified Generalized Hoek-Brown (GHB) Failure Criterion was further developed as presented in Equations 3 to 6 to overcome the bias of data towards hard rock.

$$\sigma'_1 = \sigma'_3 + \sigma'_{ci} \left(m_b \frac{\sigma'_3}{\sigma'_{ci}} + s\right)^a \quad (3)$$

$$m_b = m_i \exp\left(\frac{GSI - 100}{28 - 14D}\right) \quad (4)$$

$$s = \exp\left(\frac{GSI - 100}{9 - 3D}\right) \quad (5)$$

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{-GSI/15} - e^{-20/3}\right) \quad (6)$$

where σ'_1 = Major Effective Principal Stress
σ'_3 = Minor Effective Principal Stress
σ_{ci} =Uniaxial Compressive Strength
m_i = Hoek-Brown Intact Constant
m_b = Hoek-Brown Constant
s = Rock Mass Materials Constant
a = Rock Mass Materials Constant
D = Blast Disturbance Factor

The Geological Strength Index (GSI) was introduced by Hoek (1994) and Hoek, Kaiser and Bawden (1995). It is used to estimate the rock mass strength by considering the reduction of the intact rock strength due to adverse rock structure and block surface conditions. It can be correlated to the NGI Q-system using Equation 7.

$$GSI = 9 \ln Q' + 44 \quad (7)$$

where $Q' = \frac{RQD}{J_n} \times \frac{J_r}{J_a}$

3 Rock Reinforcement Approaches for Cavern Excavations

3.1 Conventional Cast-in-situ Permanent Concrete Lining

Many highway and railway projects in Hong Kong were constructed in the form of rock tunnels and caverns. The temporary support includes rock dowels/bolts with a thin layer of shotcrete, and the permanent support mostly includes permanent cast-in-situ concrete lining as shown in Figure 4. The local design practice for temporary and permanent tunnel supports are different. Temporary supports are used to control the rock mass deformations and ensure a safe working environment, and they should be installed immediately after the excavation if required. Permanent supports are used to maintain stable rock mass conditions throughout the design life to meet the serviceability and durability requirements. According to Geoguide 4 (2018), temporary supports should not be taken to contribute any of the structural capacity of the permanent support unless satisfying the serviceability and durability requirements throughout the 100-120 years design life.

Figure 4: Conventional Cast-in-situ Permanent Concrete Lining

The use of permanent cast-in-situ concrete lining for large-span rock caverns has been successful in Hong Kong, such as the 24.2 m span cavern for MTR Island Line Tai Koo Station completed in 1985 and the 24.3 m span cavern for MTR South Island Line Admiralty Station completed in 2016. For permanent cast-in-situ concrete lining, the conventional "rock support" design approach is adopted in which concrete and reinforcement are used as structural materials to sustain all possible loadings. The design load involves an array of load combinations, including the overburden, groundwater and different internal facilities. They should be checked against the structural capacity of the lining such as axial, shear and bending moment accordingly.

3.2 Theoretical Rock Arch

The in-situ stress conditions existing in a rock mass at a specific depth below ground can have one or more origins. The major components usually comprise the gravitational stresses and tectonic stresses. According to GEO (2018), there is no evidence of high tectonic stresses in Hong Kong rocks. Local strong igneous rock has a typical uniaxial compressive strength (UCS) that ranges from 75 MPa to 200 MPa, which is much greater than structural concrete. Compared with the redistributed stresses after excavation, high stresses will not be a problem for local cavern construction at modest depths given the high strength of most of the rocks encountered.

An arched structural form has been widely used in civil engineering projects such as bridges and arched dams. This also applies to rock cavern engineering. After excavation, the overburden weight of loosened rock above the cavern crown is redistributed to the sidewalls. Hard rock is strong in compression but very weak in tension. With an arched roof, the best stress distribution is obtained to reduce the zone of tensile stresses in the cavern crown. This utilizes the "arching-effect" within the rock mass and therefore improves the ground stability, allows a more cost-effective support system and reduces the overbreak for excavation.

As such, the "rock reinforcement" design approach has been developed to offer a practical method to consider the hard rock as a structural material to self-support itself by utilizing the hoop stress within the arch of the rock above the roof of the cavern. Permanent rock bolts are installed as rock reinforcement to guarantee the formation of this arch, and permanent shotcrete supports rock wedges between bolts. The inherent strength of the rock mass is utilized by applying confining pressure from the rock bolts. The thrust capacity is therefore increased and the theoretical rock arch formed around the cavern is capable to resist the hoop force and can stabilise the opening by supporting the ground above the excavation. The design load involves the field stresses in rock mass. They should be checked against the individual failure modes.

The use of permanent rock bolts and shotcrete for large-span rock caverns has been successful in Hong Kong, such as the 15 m span cavern for DSD Stanley Sewage Treatment works completed in 1995 and the 27 m span cavern for EPD Island West Transfer Station completed in 1997. The on-going DSD project to relocate the Sha Tin Sewage Treatment Works to caverns in Figure 6 involves the construction of a cavern complex with 7 parallel rock caverns up to 32m width x 33m height in order to handle a large sewage treatment capacity. Upon completion, the relocated STSTW will be the biggest cavern sewage treatment works in Asia.

Figure 5: Rock bolt installation in hard rock

Figure 6: Relocation of Sha Tin Sewage Treatment Works (STSTW) to Caverns

4 Numerical Modelling for Cavern Excavations

4.1 General

Apart from empirical approaches, the design of permanent systematic rock bolts and shotcrete supports for large-span caverns can be carried out using the numerical modelling such as the finite element method (FEM) and the discrete element method (DEM). They are powerful tools to handle complicate engineering problems such as complex geology, imposed loadings, excavation sequence and 3-dimentional geometric problems.

As discussed in Section 2.3, there are a number of limitations that empirical approaches cannot adequately address regarding the design of rock caverns, in particular the appropriateness for large-span excavation and influence of multiple parallel excavations. However, these limitations could be addressed appropriately by carrying out numerical modelling. A total of six finite element models were established using the software Phase^2 Version 8 developed by the Rocscience (BD Ref: G0179). The adopted geotechnical parameters are listed in Table 1. The support requirements for systematic rock bolts and shotcrete were determined separately using the Q-system rock support chart and numerical models. Discussion and comparison were made.

The rock mass was modelled as continuum with considerations of rock mass modulus E_m and GHB failure criterion instead of discontinuum. A detailed comparison study could be further carried out.

Table 1. Summary Table of Geotechnical Parameters

Geotechnical Parameters	Adopted Values			Descriptions
Unit Weight	γ	=	27 kN/m^3	-
Uniaxial Compressive Strength	σ_{ci}	=	100 MPa	-
Young's Modulus	E_i	=	30000 MPa	-
Poisson's Ratio	v	=	0.3	-
Rock Cover	D	=	100m	Moderate Depth
Rock Quality Designation	RQD	=	80	Good
Joint Set Number	J_n	=	12	Three joint sets plus random joints
Joint Roughness Number	J_r	=	1.5	Rough, irregular, planar
Joint Alteration Number	J_a	=	1	Unaltered joint walls, surface staining only
Joint Water Reduction Factor	J_w	=	1	Dry excavations or minor inflow
Stress Reduction Factor	SRF	=	1	Medium stress, favorable stress condition
Q-value (assume Q=Q')	Q	=	10	Fair/Good Rock
Material constants	m_i	=	32	Granite
In-situ Stress Ratio	k	=	1.5	-
Excavation Span Ratio	ESR	=	1	Type of excavation = E

4.2 Large-Span Excavation

The cavern profile should satisfy the spatial requirements for facilities accommodation. As summarized in Geoguide 4 (2018), the typical span of completed caverns in Hong Kong ranges from 15 m to 27 m. Clients usually prefer larger caverns for their projects, but this may not be cost-effective because a larger opening would require more permanent support and greater rock pillar width between adjacent excavations.

A hypothetical comparison was carried out among three different caverns with span of 15m, 25m and 35m and same height of 15m. The required supports in Table 2 were determined using the NGI rock support chart.

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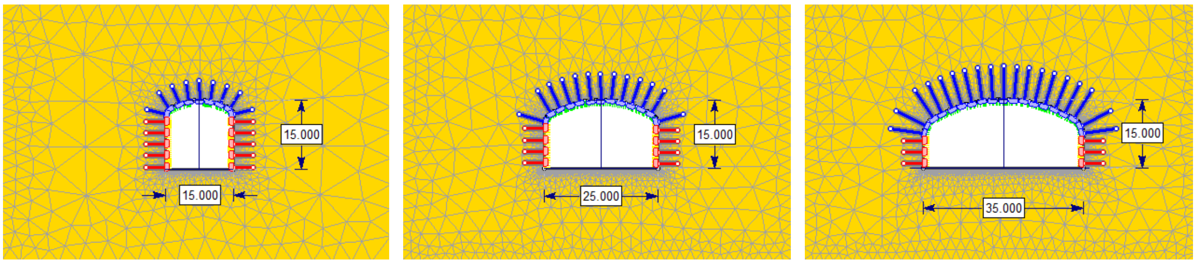
Table 2. Rock support requirements using the Q-system rock support chart by NGI (2015)

Cavern Size	Systematic rock bolts				Shotcrete lining	
	Crown		Wall		Crown	Wall
	Length	Spacing	Length	Spacing	Thickness	Thickness
15 m (W) x 15 m (H)	4.3 m	2.3 m c/c	4.3 m	2.5 m c/c	60 mm	60 mm
25 m (W) x 15 m (H)	5.8 m	2.3 m c/c	4.3 m	2.5 m c/c	70 mm	60 mm
35 m (W) x 15 m (H)	7.3 m	2.3 m c/c	4.3 m	2.5 m c/c	80 mm	60 mm

Based on empirical approaches, the rock bolt length and shotcrete thickness increased for caverns with larger span. Although there was no change in bolt spacing as the rock mass quality (Q=10) was baselined, the total number of systematic rock bolts indeed increased significantly following the perimeter of larger opening. There was no change in wall support requirements as the same cavern height of 15 m was provided.

Three finite element models were established for each of the cavern with different span as illustrated in Figure 7. The geological parameters in Table 1 and the rock supports in Table 2 were adopted. In compliance with the assumption in rock support chart by NGI (2015), fully-grouted high yield steel reinforcement with 20mm bar diameter and 157 kN ultimate tensile capacity was assigned for the permanent systematic rock bolt. For the permanent shotcrete lining, Grade 40 structural concrete (f_{cu}=40MPa) was used.



15 m (W) x 15 m (H) 25 m (W) x 15 m (H) 35 m (W) x 15 m (H)

Figure 7: Finite element models for caverns with different span

The maximum mobilized bolt force in each numerical model and the utilization percentage of ultimate bolt tensile capacity were studied. In accordance with Geoguide 4 (2018), a minimum factor of safety 2.0 should be established on the ultimate tensile strength of permanent grouted rock bolt. This means a maximum of 50% utilization is allowed. For permanent shotcrete lining, the provided factor of safety in each numerical model based on the M-N interaction diagram was also studied. The results are summarized in Table 3.

Table 3. Results from finite element models for caverns with different span

Cavern Size	Systematic rock bolts				Shotcrete lining	
	Crown		Wall		Crown	Wall
	Max. bolt force	Utilization (157 kN)	Max. bolt force	Utilization (157 kN)	FOS	FOS
15 m (W) x 15 m (H)	12 kN	7.6 %	15 kN	9.6 %	2.8	3.4
25 m (W) x 15 m (H)	14 kN	8.9 %	21 kN	13.4 %	3	2.6
35 m (W) x 15 m (H)	18 kN	11.5 %	26 kN	16.6 %	3.4	2.4

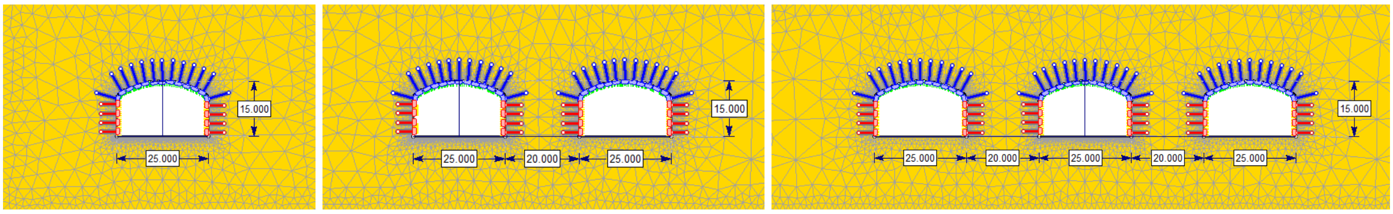
Based on the numerical analysis, the maximum systematic bolt force increased with increasing cavern span. Higher bolt force at walls than at crown was observed. However, a very low utilization percentage of ultimate bolt tensile capacity was noted. This means the empirical rock support chart is a bit too conservative for cavern support design in hard rock (this paper does not cover poor rock mass conditions). Therefore, further design optimization to increase the bolt spacing and reduce the bolt length determined from empirical approach is technically feasible, subject to the approval from relevant checking authorities. For permanent shotcrete lining, increasing cavern span adversely affected the factor of safety in the wall. This result is different from the empirical approach.

4.3 Multiple Parallel Excavations

It is important to integrate the cavern development with surface facilities for capitalizing the strategic benefits and synergy effect. For example, connecting the underground supporting and recreational facilities with surface buildings and railway stations. This can be achieved by providing an access tunnel to connect the portal access with the cavern complex. A cavern complex usually comprises multiple parallel caverns with rock pillars between each opening which are interconnected by adits. As per Geoguide 4 (2018), the typical pillar widths between caverns should be at least half and full cavern span or height, whichever is the greater.

For concurrent excavations in multiple caverns, the interaction between adjacent opening such as excessive stress relaxation and excessive deformation in rock mass should be minimized. The stress redistribution and damage zone surrounding each opening will superimpose at the rock pillar location, and the global rock mass stability will be affected.

Three finite element models were established to study the influence of multiple parallel excavations to the design of permanent systematic rock bolts and shotcrete lining. A hypothetical comparison was carried out among three different scenarios of cavern arrangement: single, double and triple parallel excavations. Each cavern was 25 m (W) x 15 m (H) with 20 m rock pillar (80% of cavern span) between as illustrated in Figure 8.



Single Cavern Double Caverns Triple Caverns

Figure 8: Finite element models for caverns with multiple parallel excavations

Similarly, the maximum mobilized bolt force, the utilization percentage of ultimate bolt tensile capacity and the factor of safety on shotcrete lining were summarized in Table 4.

Table 4. Results from finite element models for caverns with multiple parallel excavations

Cavern Size	Systematic rock bolts				Shotcrete lining	
	Crown		Wall		Crown	Wall
	Max. bolt force	Utilization (157 kN)	Max. bolt force	Utilization (157 kN)	FOS	FOS
Single Cavern	14 kN	8.9 %	21 kN	13.4 %	3	2.6
Double Caverns	16 kN	10.2 %	29 kN	18.5 %	2.4	2.2
Triple Caverns (Excavate caverns at two sides first)	16 kN	10.2 %	30 kN	19.1 %	2.4	2
Triple Caverns (Excavate middle caverns first)	18 kN	11.5 %	35 kN	22.3 %	2.2	1.8

Based on the numerical analysis, the maximum systematic bolt force increased substantially due to multiple parallel excavations. Higher increment of bolt force at walls than at crown was observed, with almost doubled utilization percentage of ultimate bolt tensile capacity. The reason is due to the superimposed vertical stress concentration at the rock pillar location as shown in Figure 9.

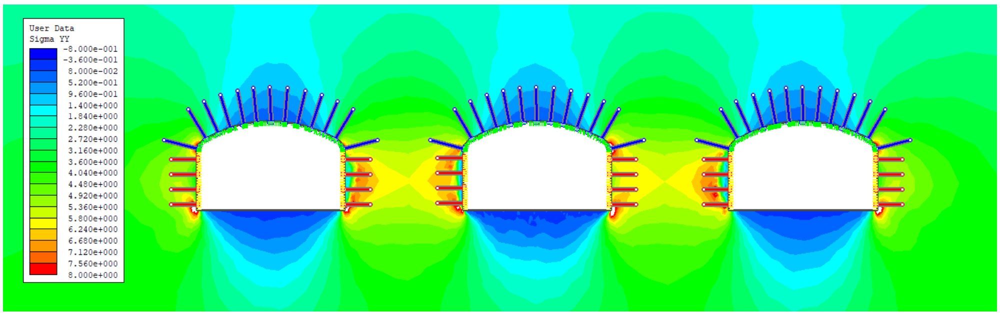


Figure 9: Superimposed vertical stress (s_{YY}) concentration at rock pillars in FEM

In addition, it was observed that varying the excavation sequence will impose a slight impact on the final systematic rock bolt force and shotcrete lining support. The influence on adjacent excavation was more apparent when the middle cavern was excavated first followed by the caverns at two sides. Nevertheless, the empirical rock support chart is still conservative for cavern support design in hard rock and further design optimization is technically feasible.

5 Conclusions and Recommendations

In consideration of technically feasibility, cost-effectiveness and sustainability, it is envisaged that the use of systematic rock bolts and shotcrete lining will become the dominant permanent support system for large-span caverns in Hong Kong, rather than conventional cast-in-situ concrete lining. However, there are a number of limitations that empirical approaches cannot adequately address regarding the design of rock caverns.

In this technical paper, a total six numbers of finite element models were established to investigate and validate the appropriateness of using empirical design for large-span excavation and influence of multiple parallel excavations. The results from numerical analysis have shown that the permanent support requirements are more stringent with increasing cavern span and multiple parallel excavations. a very low utilization percentage of ultimate bolt tensile capacity was observed. Therefore, it is successfully demonstrated that the use of empirical rock support chart by NGI (2015) is conservative for cavern support design in hard rock (this paper does not cover poor rock mass conditions). Further design optimization to increase the bolt spacing and reduce the bolt length determined from empirical approach is technically feasible, subject to the approval from relevant checking authorities.

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