

HOW WIDE CAN A ROCK CAVERN BE OPENED?

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ABSTRACT

The largest known cave, Sarawak Chamber, which is in the Gunung Mulu National Park, Malaysia, is a remarkable natural wonder and measures 700m by 400m and over 70m in height. A cave of this size can fit the entire city streets and skyscrapers. Theoretically, empirical rock and structural mechanics principles could be used to interpret these physical phenomena of large span rock-opening structures. On this basis, hypothesizing a jointed-rock cavern could be supported by reinforced rock arch using rock reinforcement techniques formed by application of confining pressure via the bolts or cables, utilising the inherent strength of the rock to support the rock load above the opening. This reinforced arch is considered as a continuous arched-structural beam all along the cavern. Generally, rock caverns and tunnels are designed mostly to be arch shaped, either circular or parabolic. However, the function of arch shape, geometry, span and ratio of the rise of arch for rock excavations have seldom been discussed, together with rock reinforcement applied on the opening periphery. An investigation initiative is proposed to examine the maximum span of the opening with respect to the critical load of the arch for the opening; properties of rock mass; and other variable coefficients related to geometry of the arch. This is done by using the rock reinforcement method together with the Dinnik's equation, which is a simplified rule with variable coefficients for the analysis of the elastic arch when the loss of stability occurs. A numerical model is conducted in this paper to get a preliminary concept and agreement on this combination applications between rock mechanics and structural design. A desktop investigation initiative is outlined at the next stage for further verification of the concept on how wide a rock cavern could be opened.

1 INTRODUCTION

For the past few decades, some local governments like Hong Kong, Singapore and Scandinavia region, suggested to build the city below ground in order to release more surface land area for building a better living environment. However, creation of underground space has its physical constraints either in soil or in rock. Construction of an underground space by cut-and-cover method in soil, the earth retaining structure cannot go deeper because there is a serious issue with supporting the soil's outward pressure and the limitations of construction equipment. For rock caverns, the effective opening span is controlled by rock mass structure and quality, rock strength and insitu stress fields even it is with or without rock pillar support.

Interesting is that natural caves with span over 80 m can be found around the world. The largest cave "Sarawak Chamber" (formerly the Mulu Caves are in the Gunung Mulu National Park in Borneo, Malaysia) is a remarkable natural wonder with size of about 700 (L) by 400 (span) meters and at least 70 meters high (Figure 1). With this size of cave, it is capable of fitting entire city streets and skyscrapers. In concept, it is believed in that insitu reinforced rock arch is able to form a similar large span of arched or fixed beam support (White and White, 1969 and Davies, 1951) for rock cavern.



Figure 1: One of spectacular views of Sarawak Chamber (Mulu National Park, 2020).

Well understood that arched cavern provides a more stable structure than a flat roof cavern. As of structural mechanics, arches and arched structures have a wide range of applications in bridges, dams and can also be applied to building

structures. For a structural unit, an arch is a member shaped with supported loads in which these loads are transmitted to support primarily by axial compressive thrusts in the arch. The member must be sustained by supports capable of developing lateral as well as normal reaction components.

With reference to rock masonry arch and structural arch stability theories then applied on rock excavations using reinforced rock arch design that is based on the behaviour of rock bolts to act as reinforcement of the rock arch around the opening appears to be applicable in concept. Kong (2018) study found that the rock reinforcement approach for hard rock openings provides thrust capacity equivalent to the internal support by means of improving the strength of the rock mass at the excavation boundary by application of confining pressure via the bolts. Therefore, the rock arch formed by the tunnel periphery (i.e. arched roof and walls) is considered to be a supporting arch capable of sustaining a thrust at the arch ends.

Rock caverns and tunnels are designed mostly to be arch shaped either circular or parabolic. However, the function of arch shape has seldom be studied and discussed, together with rock reinforcement strategy applying on the rock openings. Imagining the reinforced rock arch (for the rock cavern) as an arched structure that is under the compressed load (i.e. the rock load), the critical load (of this compression load) is the maximum load at which the structure is still stable. The critical load for the arched structure is related to geometry of the arch such as arch lift, span, shape (e.g. circular or parabolic) and the properties of rock mass quality and strength around the opening.

The following sections give an initial insight in understanding the function of the reinforced rock arch how feasible acting as an arched structure to build a large span hard rock opening; in order that a desktop study proposal for further investigation is outlined.

2 ARCH STRUCTURES

Arched structures are often used as supporting elements for bridges or other long-span structures. Majority of these cases of arch members are considered as a purely under compression in a static condition. Thousands of years ago, large span arched structures such as masonry arch bridge (for example of the Gutach Bridge built in 1900 with a main span of 64m, see Figure 2) had been used for several hundred or thousand years and these structures (or bridges) can still be found around the world. In twentieth century and beyond, structural arched bridge with span over five hundred metres can be engineered and built (under different site conditions and terrain constraints; e.g. the New River Gorge Bridge built in 1977 with main span of 518 m over the New River Gorge near Fayetteville, West Virginia in US).



Figure 2: Gutach Rail Bridge built in 1900 with a main span of 64m (Structurae, 2020).

Arch bridges or structures work by transferring the weight of the bridge and its loads to the supports primarily by axial compressive thrusts in the arch. In addition, the member must be sustained by supports capable of developing lateral and normal reactions components. Having a given loading, the arch shape must be chosen to avoid the introduction of bending moments.

This arched structure is a simple beam although the induced stresses constitute bending moments as well as axial thrusts. Of particular concerns, the criteria for a credible arch system are explicit: (i) the supports to be capable of sustaining lateral thrust, and (ii) the structural member to have an axial shape such that these thrusts are indeed developed under load.

Apart from the stone (or rock) masonry arch configurations, the modern engineered arched structure or bridge is considered as a monolithic or elastic structure. These structures are analysed using elastic theory (Kirchhoff, 1876; Timoshenko & Gere, 1961; Dinnik, 1946; Pippard, 1948; Pippard & Chitty, 1951) whereby the entire structure is assumed

to be a monolithic elastic unit where the true crown thrust is determined using equation that take into consideration of the deflection or elastic distortion of the material under load.

2.1 STRUCTURAL ARCH BEHAVIOURS

The basic arch beam equation is shown on Figure 3 below. The principal of arch is when the load is uniformly distributed to them, the forces resolve into axial compressive stresses and thrust at the fixed base or support points (if adopted) then the base cannot perceive and transmit the bending moments. The fundamental feature of arched structures is that horizontal reactions appear even if the structure is subjected to vertical loads only. These horizontal reactions $H_A = H_C$ are called a thrust (Figure 3). This phenomenon is known as arch action.

Given the equation, as the height or rise of the arch decreases, the outward thrust increases and as a result, maintaining the arch action and preventing the arch from collapsing, and thus internal ties or external bracing must be employed. The efficiency of an arch can be demonstrated by comparing it with a beam of the same span under the same loading conditions. However, some structural response behaviours of arch are considered important for supporting uniform distributed static load, they are: -

- Fixed arch: statically indeterminate structures to the third degree, the end points require solid restraints. These types of arches are the most rigid but are sensitive to relative settlement at the supports as well as any additional forces created by changes in temperature.
- Two-hinged arch: statically indeterminate to the first degree and although are not as rigid as fixed arches, they are somewhat insensitive to relative settlement at the supports.
- Three-hinged arch: statically determinate and are not affected by settlement or the additional forces created by temperature changes.
- Parabolic arch: because both the shape of the arch and the shape of the bending moment diagram are parabolic, when the arch is subjected to a uniform load, the bending moment at every section of the arch is theoretically zero. The arch will be under pure axial compression.

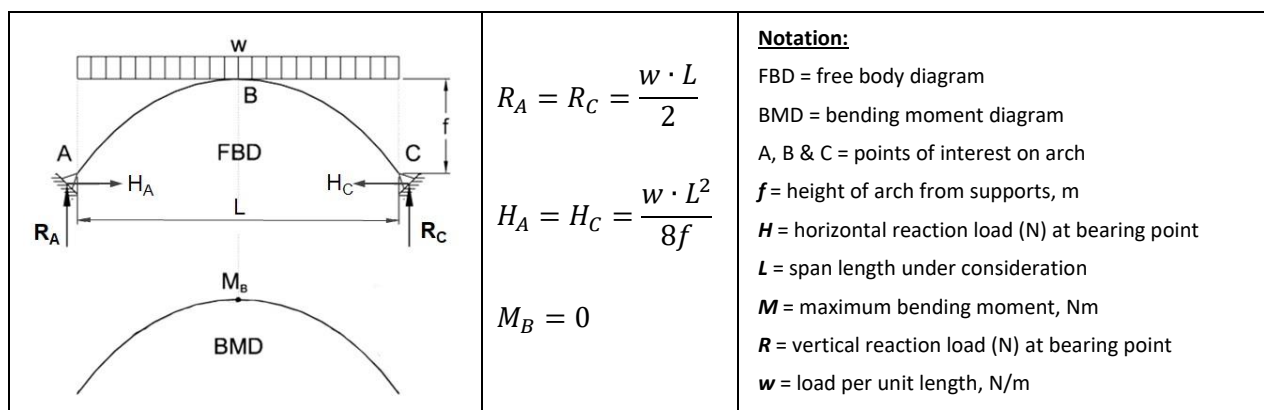


Figure 3: Simple arch beam equation.

2.2 ELASTIC ARCH AND STABILITY THEORY

Robert Hooke was the first to carry out scientific research on arches. His main finding was about the shape of an arch which could stand on its own. He provided his finding in an anagram (Hooke, 1675) which in English reads; "As hangs the flexible line, so but inverted will stand the rigid arch". In later years, Pippard et al. (1936; 1938; 1941; 1948; 1951; 1952; 1968) worked on arch bridge problems and conducted a series of experiments on model arches and concluded that the voussoir arch behaved elastically within certain limiting loads. He also demonstrated that the collapse of arch bridges was due to formation of hinges as the result of cracking. He then derived several equations using strain energy methods to calculate collapse loads based on the assumption that the arch ring was made of a homogeneous linear elastic material.

The mathematical basis of stability theory of arches was first implemented by Kirchhoff (1876). The earliest systematic analysis of equilibrium stability was performed by Bryan (1888). Southwell (1914) continued further studies of the general stability theory of equilibrium of elastic bodies. Significant contributions (from Russia and German) solving the problem of stability of arches added by Timoshenko (1961), Morgaevsky (1939, 1961), Dinnik (1946), Chudnovsky (1952). Experimental work on the subject was contributed by Gaber (1934), Dinnik (1946), Pavlenko (1966).

Stable equilibrium state means that if the structure, under compressed load is disturbed from an initial equilibrium state and after all disturbing factors are removed, then the structure returns to the initial equilibrium state. This is concerning

to the elastic structures. If a structure consists of plastic or elasto-plastic elements, then a complete returning to the initial state is impossible. However, equilibrium state is assumed to be stable, if a structure even tends to return to the initial equilibrium state. In case of rigid bodies, the stable position of a structure in a stable equilibrium form of a deformable state is assumed that the acting compressed load is less than the critical one.

The critical force ' q_{cr} ' is the maximum force at which the structure holds its initial equilibrium form (the structure is still stable), or minimum force, at which the structure no longer returns to the initial state (the structure is already unstable) if all disturbing factors are removed.

Unstable equilibrium state means that if a structure under compressed load is disturbed from an initial equilibrium state and after all disturbing factors are removed, then the structure does not return to the initial equilibrium state. In this case, the acting compressed load is larger than the critical one.

Change of configuration of a structure under the action of compressed load is called a loss of stability of the initial form of equilibrium or a buckling. If the compressed load is a static one, then this case is referred as the static loss of stability. If a structure switches to other state (as a result of loss of stability) and remains in this state in equilibrium, then this new equilibrium state is called the adjacent form of equilibrium.

The state of a structure that corresponds to a critical load is called the critical state. The switching of a structure into a new state occurs suddenly and as a rule leads to the collapse of a structure. The theory of static stability of structures is devoted to methods of calculation of critical loads.

For the analysis of stability of the uniform parabolic arches with different boundary conditions, arches are subjected to vertical loads only in all cases. The parabolic uniform symmetrical arch is subjected to vertical uniform distributed load q within span of an arch (Dinnik, 1946). This calculation derived by Dinnik is a homogeneous differential equation of third order with variable coefficients with respect to bending moment M which arises in the arch when the loss of stability occurs, and the parameter of critical load is $q^* = q \cdot R_0^3 / E \cdot I$. (where R_0 is the radius of curvature at the crown of the arch).

The Dinnik equation (Dinnik, 1946) shows that the critical load of arch is proportional to $E \cdot I / (span)^2$. For a parabolic arch subjected to vertical load uniformly distributed on a horizontal projection, it may be calculated by formula:

$$q_{cr} = K_v \frac{EI}{span^3} \quad (1)$$

$$H_{cr} = K_h \frac{EI}{Span^2} \quad (2)$$

where: q_{cr} is the critical vertical load of arch; H_{cr} is the critical horizontal reaction of arch; K_v and K_h is a coefficient (see Table 1); E is an elastic modulus of arch; I is the moment of inertia of arch; and $span$ (or L_s) is the arch span.

Table 1: Critical-load and horizontal reaction parameters for uniform elastic arches in pure compression

f / L_s	Three-Hinged Arch		Two-Hinged Arch		Fixed Arch	
	$(q_{cr} \cdot L_s^3) / (E \cdot I)$	$(H_{cr} \cdot L_s^2) / (E \cdot I)$	$(q_{cr} \cdot L_s^3) / (E \cdot I)$	$(H_{cr} \cdot L_s^2) / (E \cdot I)$	$(q_{cr} \cdot L_s^3) / (E \cdot I)$	$(H_{cr} \cdot L_s^2) / (E \cdot I)$
	K_v	K_h	K_v	K_h	K_v	K_h
0.1	22.5	28.1	28.5	36.3	60.9	76.2
0.2	39.6	24.8	45.4	28.8	103.1	64.5
0.3	47.3	20.6	46.5	20.6	120.1	50
0.4	49.2	14.1	43.9	14.1	117.5	36.7
0.5	43	9.6	38.4	9.6	105.3	26.3

3 REINFORCED ROCK ARCH

Reinforced rock arch is a treated ground to improve the strength of the rock mass at the rock opening boundary by application of confining pressure via the bolts. This supporting arch is capable of sustaining a thrust (i.e. rock load) at the arch ends as shown in Figure 4.

As revealed by Kong (2018), Lang (1961) developed one of the long-lived empirical design rules that were established on the basis of a range of laboratory, field and theoretical studies, used for pattern rock-bolting of permanent excavations during the construction of the Snowy Mountains Hydro-electric Scheme in Australia. These empirical design rules have

been reviewed by Brown (1999) and later re-modelled by Hoek (2007) using patterned bolts to stress up aggregate in a frame model.

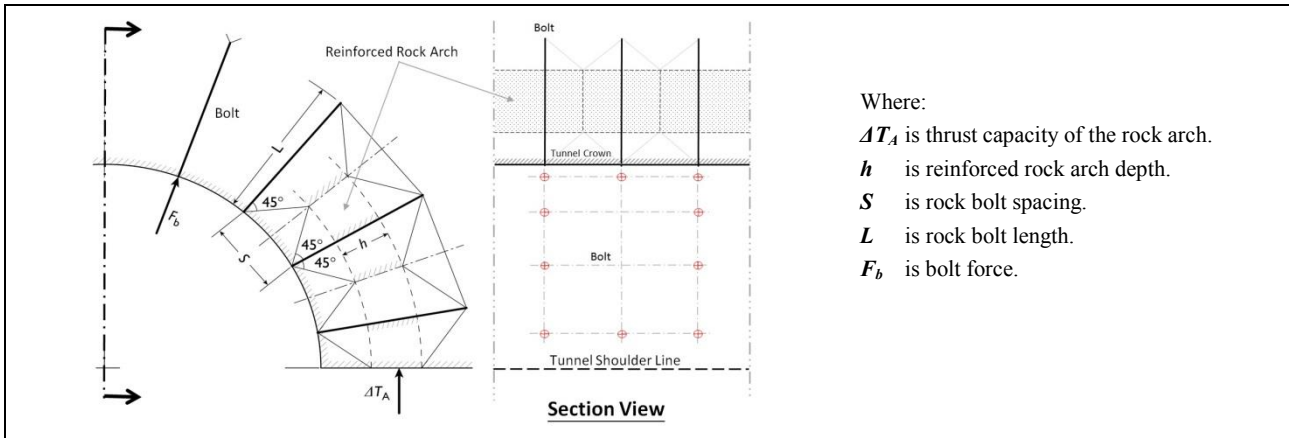


Figure 4: Geometry of tunnel bolting and rock arch thickness (excerpted from Kong, 2018)

Hoek’s (2007) model (based on Figure 5(a) of Lang 1961) demonstrated that a zone of compression is induced in the region shown in red [Figure 5(b)]. This will provide effective reinforcement to the rock mass when the rock bolt spacing S is less than 3 times the average rock piece diameter, and the rock bolt length L will be approximately of $2S$ to $3S$ (particularly for closely spaced joints rock mass). The “zone of compression” of rock mass has been treated to become isotropic in strength due to the effects of tensioned pattern bolts. An axial pre-stress is developed due to Poisson’s effect of normal stress on account of the bolt’s pre-tension. This pre-stress can stabilize the rock beam effectively as in the case of pre-stressed continuous concrete beam, which agrees with the Bischoff and Smart (1997) suggested model of reinforced rock arch. If a highly compressible feature such as a fault or a clay seam, or a highly fractured rock mass [i.e. Q (Barton et al., 1974) < 0.1 or Geological Strength Index (GSI) (Hoek, 1994; Hoek et al., 1995; Hoek and Brown, 1997; Hoek et al., 1998) < 30 as suggested by Martin et al. (2003) crosses the compression ring, it is possible that the required compression could not effectively be developed, and that the reinforcement will be inadequate.

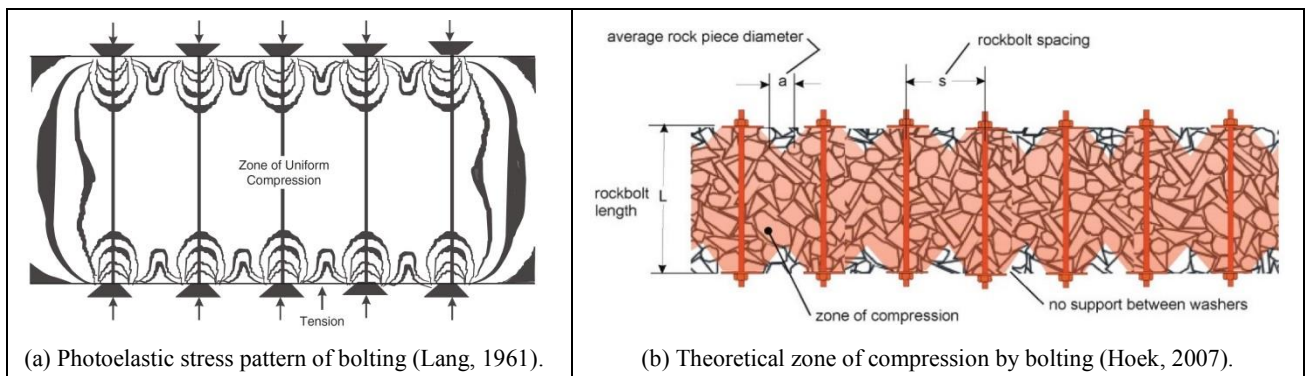


Figure 5: Illustration of “zone of compression” formed by stressed pattern bolt in media

Based on Bischoff and Smart’s (1997) model, the thrust capacity of the rock arch is simply determined by the ratio of unconfined compressive strength to tensile strength, with the provided bolt pressure. The thrust capacity of the rock arch (ΔT_A , half span of opening, in MN) is expressed as:

$$\Delta T_A = \frac{\sigma_c}{\sigma_t} \cdot \frac{F_b}{S^2} \cdot (L - S) \tag{3}$$

where: σ_c is the unconfined compressive strength (UCS) of rock mass

σ_t is the tensile strength of rock mass

(other notations refer to Figure 4)

According to a Mohr-Coulomb criterion, (σ_c / σ_t) can be rewritten as $q = \tan^2(\pi/4 + \phi/2)$; where ϕ is the rock mass friction angle. AT_A can be equivalent to the Q support pressure (Barton et al., 1974) and could be considered as of the critical load of reinforced rock arch. Given the equation, the bolt length and spacing is directly controlled by the UCS and tensile strength of rock mass around the opening. In terms of rock strength, a stronger rock mass may require shorter bolt lengths and contrarily a weaker rock mass may need longer bolt lengths in place.

Kong (2018) commented that comparing the Eq. (3) to Q-bolt-length equation [i.e. $L_{Q\text{-system}} = 2 + (0.15B / \text{ESR})$, Barton et al., 1974], it is hard to get agreements or close relationship to determine the design bolt length using both approaches. For most cases when adopting closer bolt spacing, the estimated bolt length using Eq. (3) is shorter than the Q-bolt length. Contrarily in a wider bolt spacing arrangement, the estimated bolt length using Eq. (3) is longer than Q-bolt length. With confidence of more than 40 years' practical experience using Q-system and the above findings of bolt length relationship, it is recommended the design bolt length should be determined using both approaches whichever longer bolt length is estimated.

3.1 ROCK LOAD OF UNDERGROUND OPENING

Determination of rock support load of underground openings from a classical assumption made by Terzaghi (1946) to a well-recognized Q-system (Barton et al., 1974) has been briefly discussed by Kong & Garshol (2015). For a short note, Barton et al. (1974) advocated that the support pressure [i.e. roof support pressure (MPa) = $2 J_n^{1/2} Q^{-1/3} / (30 J_r)$; J_n and J_r refer to Q-system's notations] is independent of the opening width in rock tunnels. Verman (1993) also suggests that the support pressure is practically independent of the tunnel width, provided support stiffness is not lowered. This may be attributed to the dilatant behaviour of rock masses and joint roughness which prevent loosening of the rock mass. Goel et al. (1996) also studied this aspect of the effect of tunnel size on support pressure and found that there is a negligible effect of tunnel size on support pressure in non-squeezing ground conditions, but the tunnel size could have considerable influence on the support pressure in squeezing ground conditions.

Those researchers also concluded that Terzaghi's rock load class (and modified by Deere et al., 1970) has found limitations as summarised below:

- (i) Terzaghi's method provides reasonable support pressure for small tunnels (tunnel span of $B < 6$ m).
- (ii) It provides over-safe estimates for large tunnels and caverns (with span/diameter of 6 to 14 m) and
- (iii) The estimated support pressure values fall in a very large range for squeezing and swelling ground conditions for a meaningful application.

One of the directive case examples of a 62 m span Norwegian Olympic Ice Hockey Cavern (Barton et al., 1994) showed that Q-system defined support pressures may be more suitable to assess rock load acting on the tunnel/cavern roof, even for larger spanning underground openings. Taking these into account (by exclusion of some underground mining excavation methods), most of the civil tunnels or caverns are constructed in arched roof shape that can be circular or parabolic in form. By consideration of the reinforced rock arch theory utilising the inherent strength of the rock mass in combination with the structural arch stability analysis using the critical load of arch equation (Eq. 1) and Q support pressure. Accordingly, this hybrid support system is proposed based on desktop study using computer program to examine the validity of the background concept and theory.

4 PRELIMINARY LARGE SPAN CAVERN STABILITY ASSESSMENT

To start with the cavern stability assessment, a set of assumptions should be pre-accepted based on the current engineering practices and design standards. Numerical modelling [such as Discrete Element Method (DEM) or Finite Element Method (FEM) equipped with joint networks function] is also be used to facilitate the prediction of boundary deformation of openings. In this assessment, FEM numerical plane-strain model of PHASE² (Rocscience, 2011) is utilised to stimulate the engineering behaviours of the opening. In the models, elastic-plastic analyses are performed with rock support interaction, and Hoek-Brown failure criterion (Hoek & Brown 1997) is adopted in rock material. Joints network are also included in the model. Kong et al. (2016) reported that PHASE² demonstrates the validity to carry out the analysis taking into account any engineering problems and ground conditions such as variable principal stress fields in hard or soft rocks with or without joints network.

In this assessment, 3 joint sets (parallel deterministic network) joint network model with 50m long and 0.85 factored persistence and 1m spacing of each joint set are assigned for the assessment. Regarding Lang (1961) and Hoek (2007) when using the rock reinforcement approach for hard rock opening, Kong (2018) suggested that no rock joints network will be included within the reinforced rock arch compression zone in the PHASE² model. It is because the "zone of compression" of rock mass has been treated to become isotropic in strength with the effects of tensioned pattern bolts forming a continuous rock arch. The general set up of PHASE² model is illustrated in Figure 6.

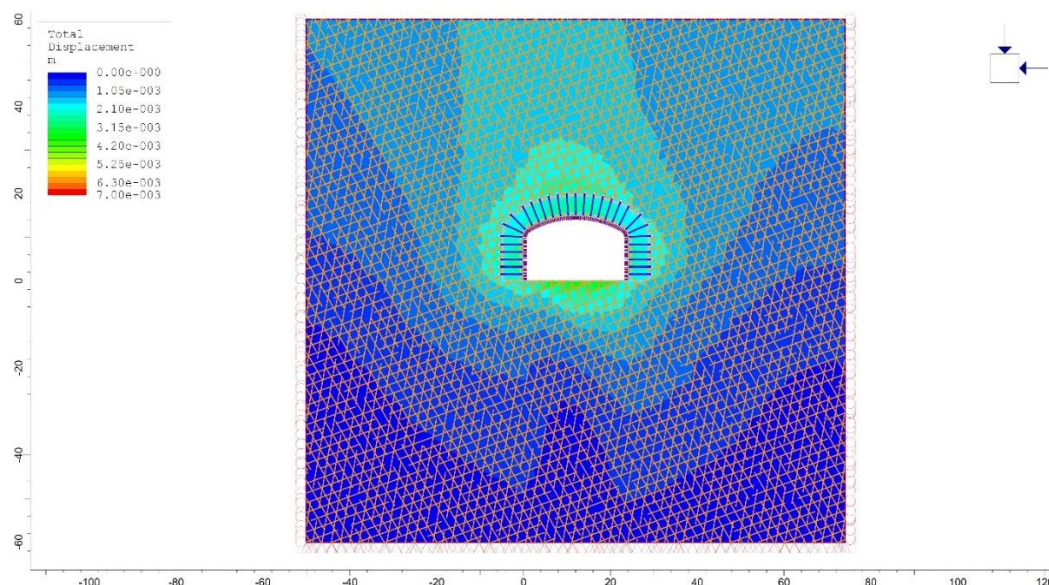


Figure 6: Typical set up of PHASE² model (with joints network) for this assignment

As discussed above, determination of support pressure of the opening will be estimated based on Q-system (Barton et al., 1974) support load equations that are able to provide a high confident level of estimation for the required supporting load. Also, the limit state design by factoring the required support load to 1.5 is considered in the assessment according to Eurocode 0 (BSI, 2010). This support pressure will then be used to estimate the maximum span of the opening using Dinnik's equation that assuming the support pressure is a critical load for the reinforced rock arch. It is considered that three hinged arch's critical load coefficient is more sensitive than two-hinged or fixed arches. Hence, three hinged arch's critical load coefficient (see Table 1) is adopted to determine the potential maximum opening span of rock cavern.

This comes with a set of assumed rock design parameters such as Q and/or GSI value, UCS_{intact} of rock, shear strength of rock joints, design load of rock bolts or cables, etc. In situ stress ' k ' ratio (i.e. $\sigma_h / \sigma_v = 59.9/z + 0.664$ (Kwong & Wong, 2013; where z = depth (in m) below ground surface) is adopted for the model.

It is understood that the perimeter deformation of an underground excavation is one of key aspects to be check for the cavern stability. The governed vertical deformation limit of the rock arch beam of span/250 will be adopted with reference to Eurocode 2 (BSI, 2014) or AS 3600 (Australian Standard, 2018) for this assessment.

For the model, an elasto-plastic rock material is assumed. Other parameters inputted to the model are listed in Table 2. For this example, the estimated support load based on assumed $J_n = 12$ and $J_r = 1$ for the roof (using Q-system) is 313 kPa. The cavern span could be opened by 132 m [using Eq. 1 with critical load of 313 kPa x 1.5 (i.e. a partial factor based on BSI, 2010)] for the ratio of rise/span of 0.2. Thus, rock bolt length = 17.23m is calculated based on Q-system's recommended bolt length.

Table 2: Input parameters for PHASE² model

Unit weight of rock	26 kN/m ³	Joint roughness coefficient (JRC)	6
Poisson's ratio	0.25	Joint wall compressive strength	20 MPa
UCS_{intact} of rock	40 MPa	Residual friction angle of joint	35 degree
Intact rock modulus	22275 MPa	Joint normal stiffness	4183 MPa
Rock mass modulus	3557 MPa	Joint shear stiffness	1673 MPa
Bolt capacity (Ø28mm high yield bar)	185 kN	Rock mass quality	GSI = 40 (approx. Q = 0.4)

4.1 FINDINGS OF THE CASE MODEL

The result of the model reveals that the cavern with such a large span opening is stable with a maximum roof and mid-wall deformation of 320 mm and 100 mm is predicted respectively. This magnitude of deformation is less than the current design standards of span/250 (i.e. $132/250 = 528$ mm for roof and $50/250 = 200$ mm for wall). Also, no yielded bolts are determined in the model. The model output image is shown on Figure 7.

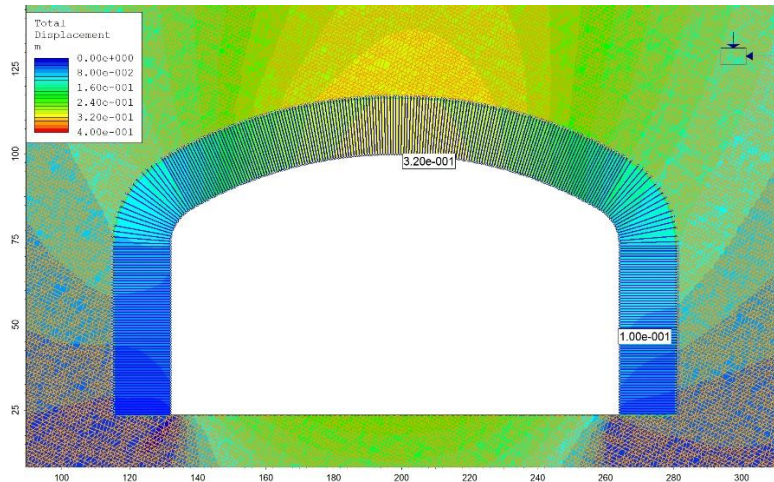


Figure 7: Result of perimeter deformation to the 132 m span opening in jointed rock

Moreover, in terms of isotropic media, hence, no joints network is included in the model, the modelled roof deformation of the opening is 142 mm and mid-wall is 67.5 mm as shown on Figure 8. This deformation is much less than the anisotropic model (see Figure 7 of the above). Based on these two models, a key message promotes that it is important to include joints network for jointed rock opening especially for rock mass quality such as $GSI > 30$ (Martin et al., 2003) or $Q > 0.1$ in order to obtain a more reasonable result and ground (or rock mass) responses.

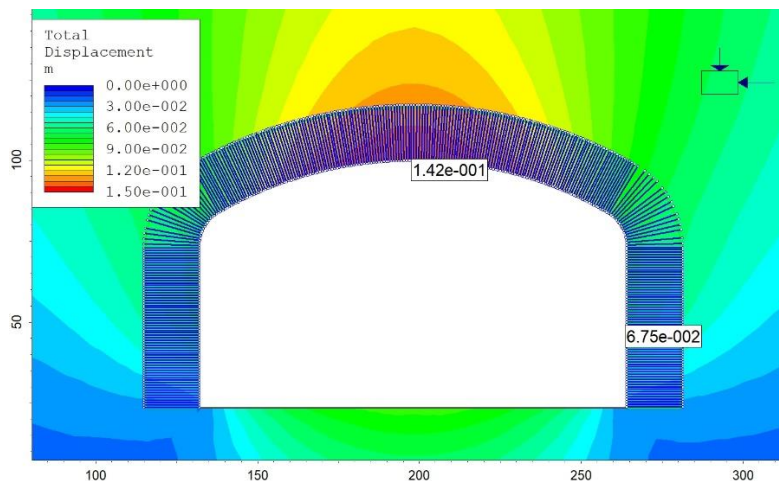


Figure 8: Result of deformation to the 132m-span opening in isotropic media

Based on this preliminary case study in a rock mass of $UCS_{(intact)} = 40$ MPa; $Q = 0.4$ and a ratio of rise/span 0.2 for the roof arch shape assumptions, the reinforced rock (arch) support using patterned rock bolts can be considered as a continuous rock arch beam to support the rock opening. This reinforced rock arch could be determined by adopting structural arch beam theory and its structural stability requirements.

Although this model appears to be agreed with the above prescribed assumptions, however, there are large amount of uncertainties still existence and lots of arguments need to confirm in order to get a solid conclusion that this hybrid system by considering both rock mechanics and structural mechanics is valid. These uncertainties comprise the limit of the rock strength, depth of opening (with consideration of insitu stress k ratio), thus detailed examination is required to be carried in the next stage study.

5 CONCLUSIONS

It is no doubt that rock reinforcement method has been used in many underground rock excavations works successfully. This method can be able to utilises the inherent strength of the rock to support the rock load above the opening. Hence, minimizes the use of structural concrete lining for the opening can be proposed to provide sustainable and cost-effective solutions (Kong, 2018), as the rock reinforcement method reduces in construction time and resources that no formwork or rebar fixing are required for permanent lining. With confidence of more than 40 years' practical experience using Q-

system, the support rock load using Q support load may be feasible to be using in this concept for determining a maximum span of opening.

Further to Kong (2018) study when using rock reinforcement approach, it is evident that the application of confining pressure via pattern bolts suffices to improve the strength of the rock mass; especially for rock strength greater than 40 MPa (that it is based on most of the structural concrete strength of 40 MPa to be used for tunnel lining) and Q could be greater than 0.1 or GSI > 30 at the underground opening. These assumptions could be considered in the next stage of study because it is considered valid as the support points of the rock arch are subject to vertical and horizontal reaction loads induced by the roof support load of opening. At these load support points, rock failures (e.g. bearing or shear failures) could be occurred leading to the overall stability of the arch cannot be sustained.

The preliminary concept of the reinforced rock arch using structural arch beam's behaviours for underground rock excavation appears to be valid, especially for estimating the maximum span of opening under certain rock mass and ground conditions. In order to reinforce this concept and its validity, a range of rock mass and ground conditions are required to be further investigation by obtaining a broad picture and relationship of this hybrid system by consideration of rock and structural mechanics. Thus, a further investigation initiative is outlined in the following section.

6 OUTLINED FURTHER INVESTIGATION

Thirst for continuing demand of usable land to build a better living environment is one of key challenges for many cities and countries such as Hong Kong, Singapore, Finland, etc. The use of the underground space such as development of rock caverns will be one of the solutions to increase land supply. The initiative of this study attempts to deduce a rule or method of identifying a rock cavern with the potential maximum opening span under certain of rock and ground conditions for the development during the feasibility and detailed design stage.

Using the assumptions as discussed in the above, the further investigation will be based on the desktop study using FEM computer modelling (i.e. PHASE²) to assess the relationship between:

- (i) reinforced rock arch by rock bolting/cablig and structural arch's equation (i.e. Dinnik equation's critical load of arch);
- (ii) the function of arch shape, geometry, span and ratio of the rise of arch (i.e. the ratio of rise/span of 0.1, 0.2, 0.3 and 0.4 to be examined with respect to Table 1) for rock excavations;
- (iii) two rock mass strengths of moderately strong (e.g. 40 MPa) and strong rock (e.g. 70 MPa) with respect to maximum span of opening;
- (iv) two rock mass qualities of $Q = 0.2$ (GSI = 35) and $Q = 1$ (GSI = 45) with three joint sets (parallel deterministic joints network), and 1m and 1.5m spacing respectively to be include in the model;
- (v) 60 m and 250 m rock cover with variable insitu stress using an equation [for example: $k = 110.0/z + 1.29$ (Kwong & Wong, 2013), where z = depth (in m) below ground surface]; and
- (vi) Additional models for stratified rock mass conditions with horizontal and 45-degree inclined rock structures might be included in the study.

Based on the above conditions, at least 32 models will be assessed; also, detection of boundary conditions/deformation of the opening, and stresses change at cavern crown and shoulder will be examined. Also, a range of failures or instability evaluation criteria could be adopted to assess the stability of underground openings, such as displacement criteria including 'Roof Sag Ratio', 'Wall Convergence Ratio' and 'Floor Heave Ratio' (Zhang & Mitri 2008); and the depth (or extent) of yielding zones (Perras & Diederichs, 2010, 2016; Vlachopoulos & Vazaios, 2018 and Abdellah, 2017) into the rock mass surrounding tunnel opening. These criteria will be used to check the FEM models in this study.

Q-system (Barton et al., 1974) defines that Q-values between 0.1 and 1 is classified as a very poor rock quality. For $Q = 0.1$, the rock mass is highly fractured in nature and more joint sets with closely spacing need to be considered. However, it appears to be difficult by including more closely spaced joint sets in PHASE². As reported by Kong et al. (2016), the PHASE² programme will take a considerably longer time to finish, or some undetermined "no response" situations may be encountered. Therefore, this study will focus on Q-value between 0.2 and 1.

The assessment results could be able to come up with conclusions and findings, such that the key domain of this investigation is to modify the critical load prediction (based on Table 1 above) of structural arch for rock reinforcement with respect to different shape of arch rise. The proposed new equation (i.e. the critical load of reinforced rock arch) could be a function of opening span, rock mass modulus, reinforced rock arch size as well as some other factors related to insitu stress ratio and material strength reduction.

Also, the result of this study possibly could give a reference guideline for land use planning for underground cavern development, and/or mining excavation development in a feasibility and concept stage.

Attention is drawn that although the concept of the study and investigation models are a computer simulation, however, in reality of all cases of underground construction, one of important strategies is to ensure the performance and ground responses especially of large span openings; on-site deformation monitoring should be necessary for further validation in which Eurocode 7 Part 1 (BSI, 2013) the observational method could be performed to offer a substantial set of advantages in terms of avoiding the “calculation trap” or “uncertainty”, but this is a crucial alternative solution during construction. If this maximum span opening estimation method is finally be assessed to be valid and potentially to be adopted for construction, the detailed design and assessment process shall come with the observational method. By doing this, it could give a complete cycle to evaluate the results between the analyses and the monitored performance.

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