A preliminary study of the economic dimension of underground rock caverns for water storage at Singapore

Junlong Shang, Zhengxian Chua, Hoongping Peh, Zhiye Zhao*

Nanyang Centre for Underground Space, School of Civil and Environmental Engineering,
Nanyang Technological University, Singapore.
Email: jlshang@ntu.edu.sg

Abstract— Due to scarce land resources in Singapore, it is imperative to increase water storage capacities to meet the increasing demand of water to secure a sustainable development, which can be achieved in the underground by rock caverns. In this paper, a preliminary study on the effects of cavern span, height and radius on the cavern stability is presented to provide a guidance on the cavern construction in the context of Singapore. It is found that the radius of caverns should be around half of the span width (i.e., B/R=2) to reduce vertical displacement at the crown of cavern. The smaller the rock cover, the smaller displacement. The minimum rock thickness should be at least the same as the cavern span to eliminate excessive yielded element. Finally, rock support system is introduced to maintain the profile of caverns.

Keywords— Cavern dimension, Numerical modelling, Sustainable development, Underground rock cavern.

I. INTRODUCTION

Land constraint in Singapore has always been a major challenge in development and urban planning due to the limited land resources and high density of population [1]. Hence, maximizing spacing utilisation is always one of the main concerns in the urban planning in Singapore. Due to the increasing of water demand in Singapore (because of population and economic growth), the Public Utilities Board (PUB, a Singapore government agency) is looking for implementation of alternative water infrastructure to secure adequate water supply for the future generation[2].

This paper focuses on the economic shape and dimension of a pilot underground rock cavern, with a primary aim to provide guidance on actual design. Figure 1 shows a schematic diagram of the pilot cavern. The paper is divided into 2 parts. The first part involves an introduction of the numerical scheme used in the study, which is based on a finite element program named Phase 2 (RS2, [3]); and the second part presents results and suggestions. A conclusion is made for the size and shape of economic rock cavern for water storage in the Singapore context.

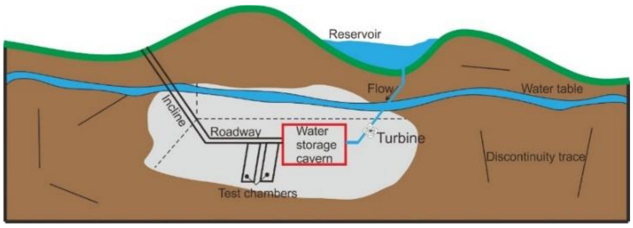

Figure 1 Schematic diagram showing a pilot underground rock cavern

II. METHODOLOGY

The RS2 is a 2D finite element program, developed by the Rocscience [3], which is often used in the numerical analysis of rock engineering problems. In the numerical study, caverns with two different shapes (i.e., square cavern and shoulder cavern) and various sizes were involved. The plain strain model in the RS2 was used in the study. Rock masses in the study was modelled as linear elastic and plastic material and generalized Hoek-Brown criterion was used. The displacement, stress and plastic zone around caverns were monitored and analysed. For a better accuracy (using the gravity stress field), the expansion factor of the model boundary was fixed at 3 to guarantee a sufficient size of the model. While the top boundary of the model represents the ground surface (i.e., ground elevation). The boundary condition was free at the top of the model; and it was partially and fully fixed at both sides and bottom, respectively.

For a conservative purpose, the worst rock condition of the Bukit Timah Granite at Singapore was emphasized. Table 1 shows the parameters used in the study.

TABLE 1. INPUT PARAMETERS OF NUMERICAL MODELLING

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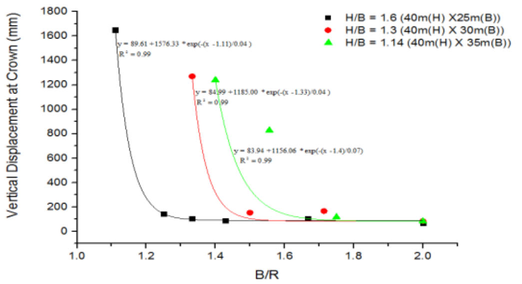
Field Stress Properties		Material Properties			
Field stress type	Gravity	Failure criterion	Generalized Hoek-Brown	Material Type	Plastic
Unit Weight of overburden	0.027MN/m^3	Intact Compressive Strength	75MPa	Dilation Parameter	0
Total stress ratio (horizontal/vertical in plane)	2	mb parameter (peak)	1.17319	m parameter (resid)	0.574326
Total stress ratio (horizontal/vertical out-of-plane)	2	s parameter (peak)	0.001273	s parameter (resid)	0.000138
		a parameter (peak)	0.511368	a parameter (resid)	0.543721

III. RESULTS

A. Effect of Crown Radius

The influence of crown radius on cavern stability was presented in this section. The effect of crown radius was studied in term of B/R since the crown radius is related to the span width. Three caverns with different sizes were focused, which is 40 (H)×25 m, 40 (H)×30 m(B) and 40 (H)×35 m(B). The height of the caverns was fixed to allow the effect of B/R on the vertical displacement (at crown) to be investigated. The depth of rock cover was fixed as well (90 m for the square cavern and 80 m for the shoulder cavern, respectively). The vertical crown displacement monitored is plotted against B/R, as shown in Figure 2.



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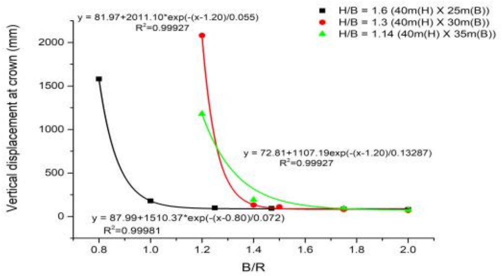


(b)

Figure 2. Vertical displacement at crown vs. B/R. (a) Square cavern, rock cover = 90 m and (b) shoulder cavern, rock cover = 80 m

As shown in Figure 2, the vertical displacement at crown increased exponentially when the B/R ratio was decreased to a certain value. Generally, the greater the span width, the smaller the B/R ratio (around 1.7). However, there will be a range of B/R ratio where the displacement remains at lowest and varies from case to case. It is also found that the smallest vertical displacement at crown (for both square and shoulder caverns) occurred when B/R =2 (Figure 2).

To investigate the effect of rock cover, more simulations were performed through varying the depth of rock cover (for a shoulder cavern of 40 (H) x 25 m (B)). In the simulations, B/R ratios of 1, 1.5 and 2, respectively, were used. Figure 3 shows relationship between the vertical crown displacement and the depth of the rock cover.

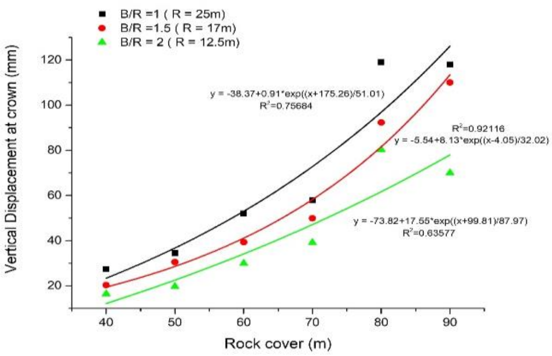
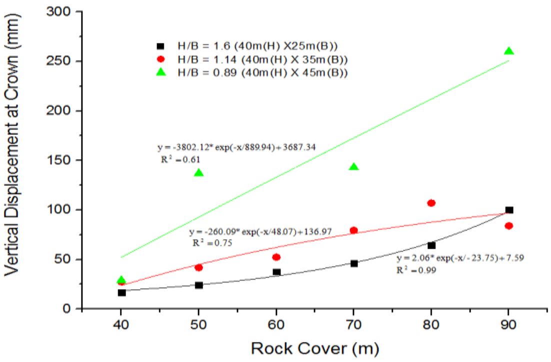


Figure 3. Vertical displacement at crown vs rock cover (shoulder cavern).

It can be seen that a minimum value of vertical displacement (at crown) was measured for each rock cover when B/R=2 (green line, Figure 3). Thus this ratio is suggested in the cavern design, which applies to rock covers with different depths.

B. Effect of Cavern Span

Literature has shown that cavern span is one of the most critical factors in determining the optimum shape of caverns [4]. The influence of cavern span to vertical crown displacement is presented in this section. In the study, the vertical crown displacement is used to evaluate the effect of cavern span on the overall stability of cavern. In the numerical modelling, the cavern height was fixed at 40 m (for both cases i.e., square and shoulder caverns) and the crown radius was half of the cavern span, which was suggested in Section III-A. Figure 4 shows relationship between vertical displacement (at crown) and depth of rock cover.



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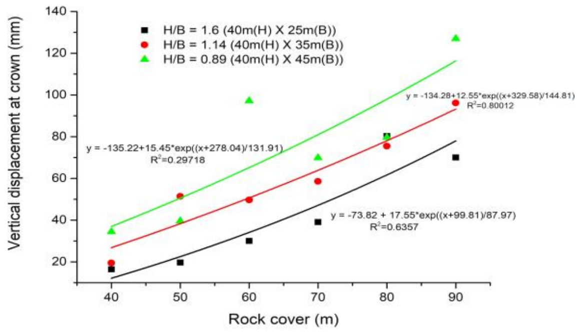


(b)

Figure 4. Vertical displacement at crown vs rock cover (B/R=2). a Square cavern and b shoulder cavern.

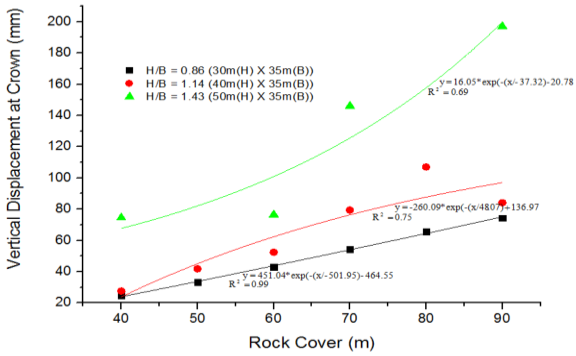
As shown in Figure 4, the vertical crown displacement increased dramatically when the cavern span was increased from 25 m to 45 m. An increase in the vertical crown displacement was also noted when the rock cover depth was increased. The relationship between the depth of the rock cover and the vertical crown displacement is approximately linear proportional.

These observations agree well with the general rule - increasing of rock depth will leads to an increase in the vertical stress acting at the crown. Because the rock above the rock cavern can be treated as loading acting on it. As the vertical stress increases, the strain at the top of the roof will increase according to the Young' Modulus Theory (the Young' Modulus, *E*, equals to normal stress divide by normal strain). Therefore, the larger the strain, the greater the vertical displacement at crown. It is concluded that increasing rock depth will increase the vertical displacement at the crown of rock caverns.

To minimise the vertical crown displacement (for the stability point of view), the cavern span therefore should be strictly controlled (in this study, the most suitable cavern span is approximately 25 m) and depth of rock cover should not be too deep (in this study, preferably 40 m which is 1.6 times of the cavern span).

C. Effect of Cavern Height

It is also important to understand the influence of cavern height on the overall cavern stability. To investigate the influence of cavern height, both cavern span (35 m) and cavern span to crown radius ratio (B/R) were fixed (20, for both square and shoulder caverns). Again, vertical displacement at crown for different depth of rock cover was measured in the simulation, which was plotted against rock cover (Figure 5).



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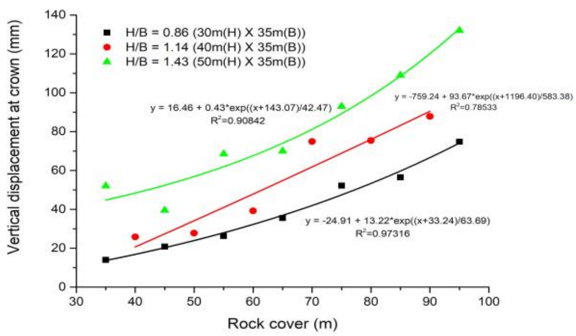

(b)

Figure 5. Vertical displacement at crown vs rock cover (crown radius =B/2). a Square cavern and b shoulder cavern.

It can be seen from Figure 5 that increasing cavern height led to an increase of vertical crown displacement. Vertical crown displacement increased when the depth of rock cover was increased. The relationship between the depth of the rock cover and the vertical crown displacement is approximately linear proportional (similar to the effect of cavern span, Figure 4). In conclusion, the cavern height should be controlled (preferably 30 m based on this study) and the depth of the rock cover should be carefully assessed (preferably 40 m based on this research).

D. Effect of Rock Support

In this section, the effect of rock support on cavern stability is presented. Caverns with a height of 30 m and a span of 20 m were used to analyse the effect of rock support. The properties of the rock bolts and lining are assumed the same as those of the Jurong Rock Cavern (Singapore) and are shown in Tables 2 and 3[5].

TABLE 2 GFRP ROCK BOLT PROPERTIES (GLASS FIBRE REINFROCED POLYMER BOLTS)

Bolt type		Swellex/Split Sets	
Tensile capacity	0.35MN	In plane spacing	1.5m
Tributary area	$380mm^2$	Out of plane spacing	1.5m
Bolt modulus	50000MPa	Bond shear stiffness	100 (MN/m/m)
Bolt length	5m(roof), 6.5m(wall)	Residual tensile capacity	0
Bond strength	0.188MN/m	Allow joints to shear Bolt	Yes

TABLE 3 SHOTCRETE PROPERTIES

Lining Type	Formulation	Thickness	Young's modulus	Poisson's ratio
Standard Beam	Timoshenko	0.08m	20000MPa	0.15

In the study, the length of rock bolts (at roofs and sidewalls) was estimated in terms of cavern span and height by using an empirical equation proposed by Barton et al. [6]. The spacing of rock bolts was estimated by the Rock Mass Rating system [7]. The rock bolt lengths used in the study were 5 m for roof and 6.5 m for sidewalls, while the spacing between them was 1.5 m. The vertical displacements measured at the cavern crown after installing the rock support are compared with the unsupported cases, which is shown in Figure 6

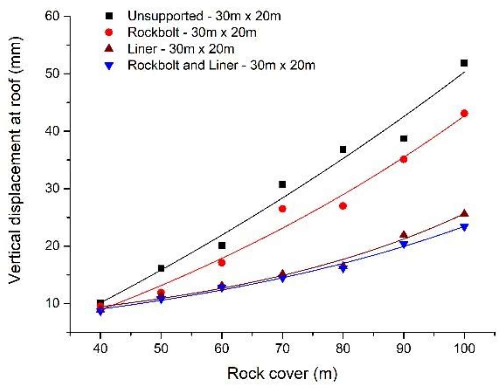

Figure 6. Vertical displacement at crown vs rock cover – Rock support analysis (shoulder cavern).

It can be seen from Figure 6 that the vertical displacement at cavern crown was reduced dramatically when rock bolting was applied, especially for cases with higher depth of rock cover. The reduction of vertical displacement (at crown) was up to 50% when both rock bolt and lining were used. As anticipated, the combination use of rock bolt and lining shows a better supporting result. In addition, there is no need to do rock support since the rock support system is not effective for cases with shallow overburdens (Figure 6). Importantly, the vertical displacement of the supported caverns (at crown) with lining were more-or-less the same as those of supported ones using the combined rock bolt and lining. Hence, for a practical and cost point of view, it is feasible to install lining only for the cavern support, especially at shallow depth.

IV. CONCLUSION

In this paper, the effects of cavern span, height and radius on cavern stability were investigated. It is suggested that the radius of caverns should be around half of the span width to minimize the vertical displacement at crown and horizontal displacement at sidewall. The height and span of caverns should also be assessed carefully. The displacement at crown decreased when the rock cover was reduced. A rule of thumb is suggested: the minimum rock thickness should be at least the cavern span to prevent excessive yielded element above the cavern.

Additionally, a rock support scheme is needed to reduce the vertical displacement at cavern crown, especially in the deep underground. The variance of vertical crown displacement between unsupported and supported rock caverns depends largely on the depth of rock cover.

V. REFERENCES

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