Analysing Tri-arch Cavern Supporting Mechanism with 3D Numerical Modelling

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ABSTRACT

Multi-arch caverns and tunnels are commonly adapted in underground metro station projects to meet the required cross-sectional span. The supporting mechanisms of such caverns/tunnels is very different from single-arch or circular tunnels/caverns, which have been studied by some researchers and engineers with numerical, analytical and experimental approaches. However, many of these works were only based on the cross-sectional analysis, and not able to provide a comprehensive support mechanism including all the related structures. In this paper, using the example of tri-arch underground station in Melbourne Metro project, the supporting mechanism is studied in detail, including the interactions between surrounding rockmass and key supporting structures (i.e. lining, crown, downstand beam & column). 3D numerical modelling with FLAC3D has been utilised for the study, hence the supporting mechanism at both transverse and longitudinal direction are analysed and proposed. Parametric studies have also been carried out to identify the role of key supporting elements. The key findings of this paper include identifying the central cavern crown as the critical structure, proposing a load transferring mechanism between different structures and suggesting the major supporting mechanism to be providing tensile restrain to the surrounding rock mass. The findings from this paper provide supplements to the supporting mechanism of such caverns/tunnels, which can be used as design theoretical basis for future projects.

Keywords: Multi-arch cavern, rockmass, underground station, 3D numerical modelling, FLAC3D.

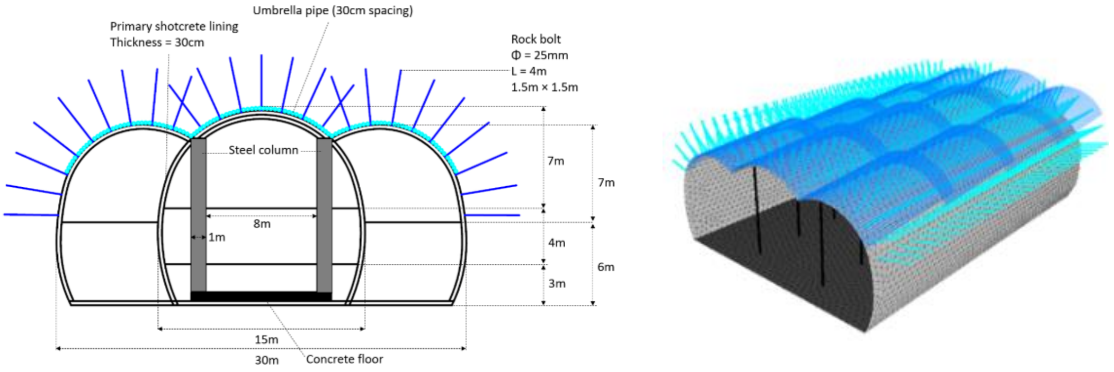
1. INTRODUCTION

Melbourne Metro Tunnel project aims to upgrade the existing railway network with a pair of new nine-kilometre twin tunnels, which pass underneath the Melbourne CBD region. The project promised to enable 39,000 more passengers to use the railway system during each the peak period, and it would be the first step for Melbourne's 'metro style' rail network. For the State Library Station, a design of large-span tri-arch caverns is utilised for the underground station platform and the twin railway tunnels. With an average overburden of 25 m of soft rock, the general excavation method is of conventional NATM excavation, with primary ground supports including shotcrete, rockbolt and umbrella fore-pipe when encountering weak ground (Figure 1). The design of a tri-arch cavern makes it possible for the underground station to reach an overall cross-span of 30 m, as well as providing with adequate ground support. This type of 'multiple-arch' cavern have been studied by some researchers and engineers with numerical, analytical and experimental approaches (e.g. Lai et al. 2011, Yoo and Choi 2017, Cao et al. 2018, Zhu et al. 2019). Most of these works are mainly focusing on the estimation of rock load on the structure (Figure 2). In this paper, using the example of State Library Station, the supporting mechanism of a tri-arch is studied in detail by 3D numerical modelling method with FLAC3D.

2. METHODOLOGY

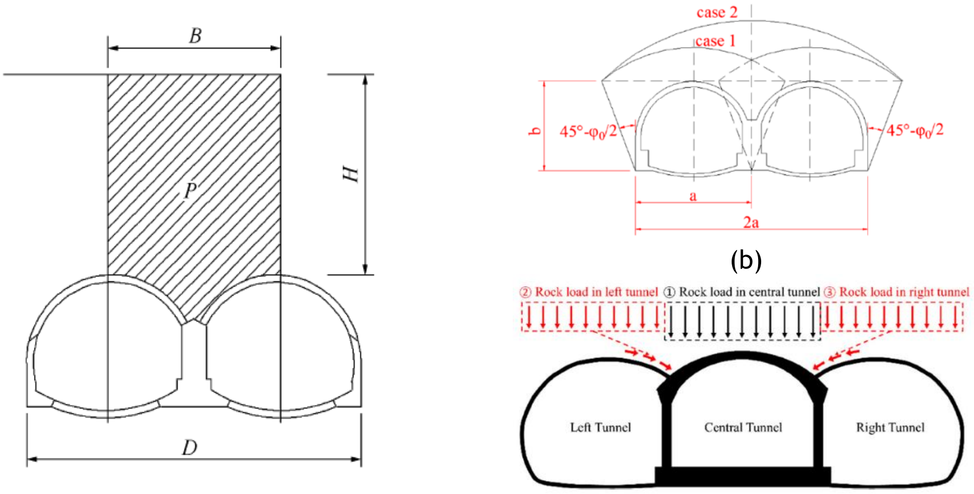
Most of the rock mass encountered at Melbourne Metro Project is known as Melbourne Formation (MF). Melbourne Formation consists of sandstone and siltstone, it is the basement rock through Melbourne region. Melbourne Formations are further classified in to four categories based on their weathering condition, namely MF1, MF2, MF3 and MF4. The conventional Mohr-Coulomb constitutive model has been utilised for all the Melbourne Formations, and these parameters are summarised in Table 1. The in-situ horizonal stresses are modelled as a factor to the vertical stresses (Table 2).

Modelling of ground supports is achieved by using FLAC3D build-in 2D Finite Element structure elements: the combining effect of shotcrete and lattice girder are modelled as shell elements; the steel columns are modelled by beam elements and rockbolts are modelled as cable elements. It is assumed that the connections between rock mass and linings, linings and columns are rigid, which means that all the components for velocity are fully transmitted between the target and source. The mechanical parameters of the supports are summarised in Table 3.



(a) (b)

Figure 1. Ground supports of tri-arch cavern for State Library Station, cross-sectional (left) and perspective view (right).



(a) (c)

Figure 2. Theoretical ground load on multi-arch tunnels: (a) Matsuda, 1998, (b) Yan et al., 2017, (c) Lee et al., 2020.

Table 1.Ground parameters for Melbourne Formations.

	γ (kN/m^3)	**E$_{rm}$ (MPa)**	**v**	**ϕ (°)**	**c (kPa)**	**σ$_t$ (kPa)**
MF4	22.5	100	0.3	30	37	0
MF3	23	200	0.25	34	60	1
MF2	24	800	0.2	43	115	7
MF1	25.5	2500	0.2	54	270	50

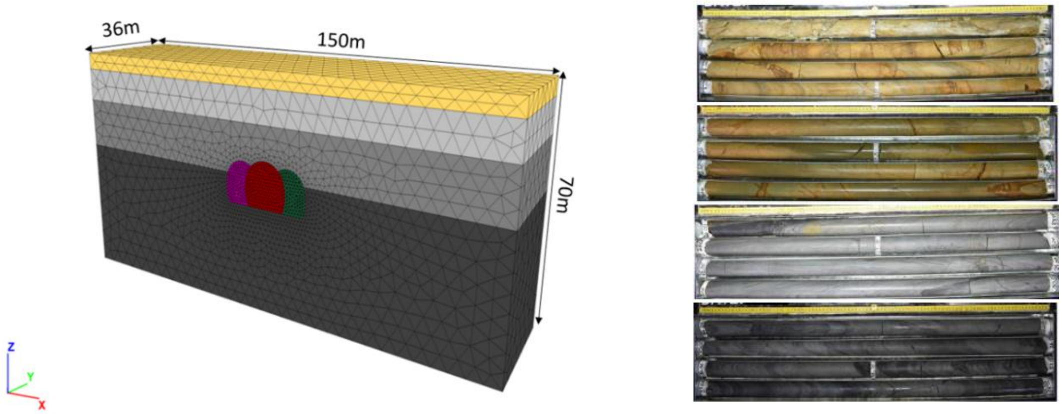
Table 2.In-situ horizontal stresses

	Major σ_h/σ_v	Minor $\sigma h/\sigma v$	Direction (to cavern axis)
MF4	0.6	0.6	45°
MF3	1.2	0.5	45°
MF2	1.5	0.75	45°
MF1	2.0	1.0	45°

Table 3.Ground support parameters

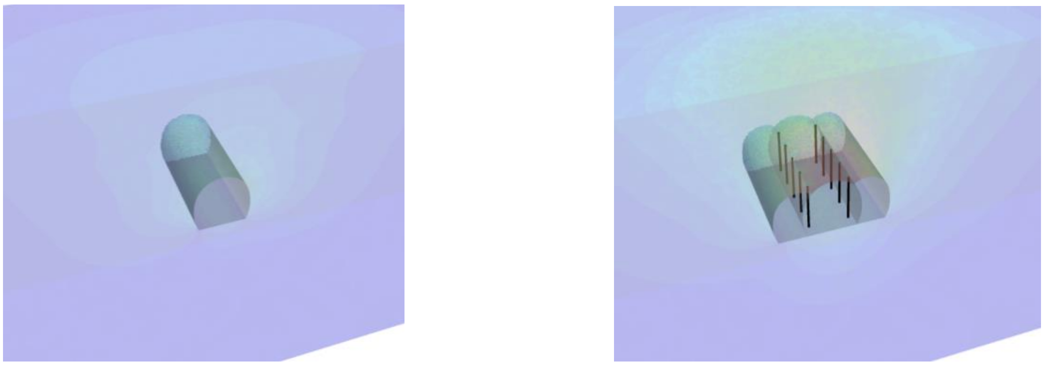
Supporting element	Properties
Shotcrete lining	γ = 25 kN/m^3, thickness = 30 cm, E = 3 GPa, v = 0.2
Concrete floor	γ = 25 kN/m3, thickness = 100 cm, E = 15 GPa, v = 0.2
Rock bolts	L = 4 m, E = 200GPa, Spacing: 1.5m x 1.5m
Steel column	H = 12.5 m, Cross-section: 1m x 2m, E = 200 GPa, v = 0.27

The 3D model of the studied area has a dimension of 150m x 36m x 70m. It has been divided in to four layers based on the geological models provided. Figure 3 shows the 3D model and the corresponded Melbourne Formations borehole core photos (MF4 at top and MF1 at bottom). The model has approximately 200,000 tetrahedral elements, with edge size varying from 1 m (at excavation zone) to 5 m (at boundary). The mesh size is set to 1 m to ensure best connection of lining (shell elements) and steel column (beam element). The modelling process has utilised a simplified excavation sequence for time saving purposes, as shown in Figure 4. Each excavation step is 1.5 meters, and the entire model is solved to equilibrium for each step.



(a) (b)

Figure 3. (a) FLAC3D model overview and (b) corresponded formation borehole core photos.



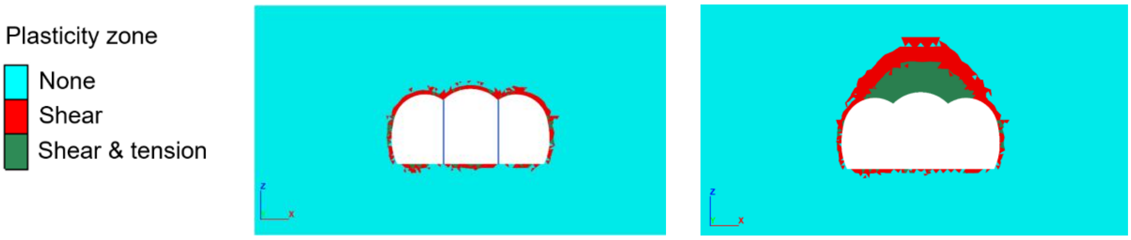
(a) (b)

Figure 4. Simplified excavation sequence: (a) excavation of central cavern; (b) activating steel columns, excavation of both side cavern

3. RESULTS

3.1 Parametric study on factors affecting column loads

Since the proposed design has utilised a very conservative support strength, with a longitudinal twin column distance (S) of 6 m, the rock mass plasticity zone around excavation is of minimum and the maximum rock mass deformation is only 18 mm. Therefore, in order to study the supporting mechanism of the tri-arch cavern, a parametric study with numerical modelling has been performed. Firstly, an extreme case of a tri-arch cavern without any steel columns are modelled and calculated, and the cross-sectional view of rock mass plasticity zone is presented in Figure 5. It is obvious that the rock mass above the central cavern will experience potential shear and tension failure, and eventually form a natural 'rock arch' at the boundary of the plasticity zone.



With columns

Without columns

Figure 5. Comparing of rock mass plasticity zone: with columns vs without columns

Also, the effect of longitudinal column spacing (S) are being studied (Figure 6). By changing the column spacing, the total number of columns will also change. From the results in Figure 6, it is noticed that when the column spacing is greater than 6 m, arching zone of plasticity is also shown at longitudinal section, similar to the arching zone for cross-sectional section without columns. Hence, the central crown area (from Figure 4) and the region in-between columns at longitudinal direction (from Figure 5) are identified as key reinforcement area. To evaluate this hypothesis, four different ground supporting plans has been developed, which include:

- 3G30Sc : Control group, no extra reinforcement but only 30 cm shotcrete lining, E = 3 GPa
- 15G60Bm: 2m wide lining reinforcement (60 cm thick, E = 15 GPa) right above each role of column.
- 15G60Cr: Entire central crown reinforcement (60 cm thick, E = 15 GPa)
- 30G120Cr: Extreme case, very strong entire central crown reinforcement (120 cm thick, 30 GPa)

The efficiency of these ground supporting plans is evaluated by following factor:
Efficiency = Column load / S
Where Column load is the total load on one single column, S the longitudinal spacing between columns. The illustration of the four supporting plans and results of their efficiencies are presented in Figure 7. For a high efficiency supporting plan, more load is taken by columns which will results in a higher value of Column load/S, and less load is taken by the rock mass itself thus ensures better ground stability; for a low efficiency supporting plan, less load is taken by columns which will results in a lower value of Column load/S, and more load will be taken by the rock mass itself which increase chances of rock mass failure (increased area of plasticity zone in modelling results). From results in Figure 7, it is noticeable that generally there is a great improvement of supporting efficiency when the central crown is reinforced. Also, 15G60Bm and 15G60Cr have almost identical results, which suggested the lining right above the columns are the most critical region. Furthermore, even though 30G120Cr has a huge increase in strength and thickness, the improvement of supporting efficiency is not very significant.

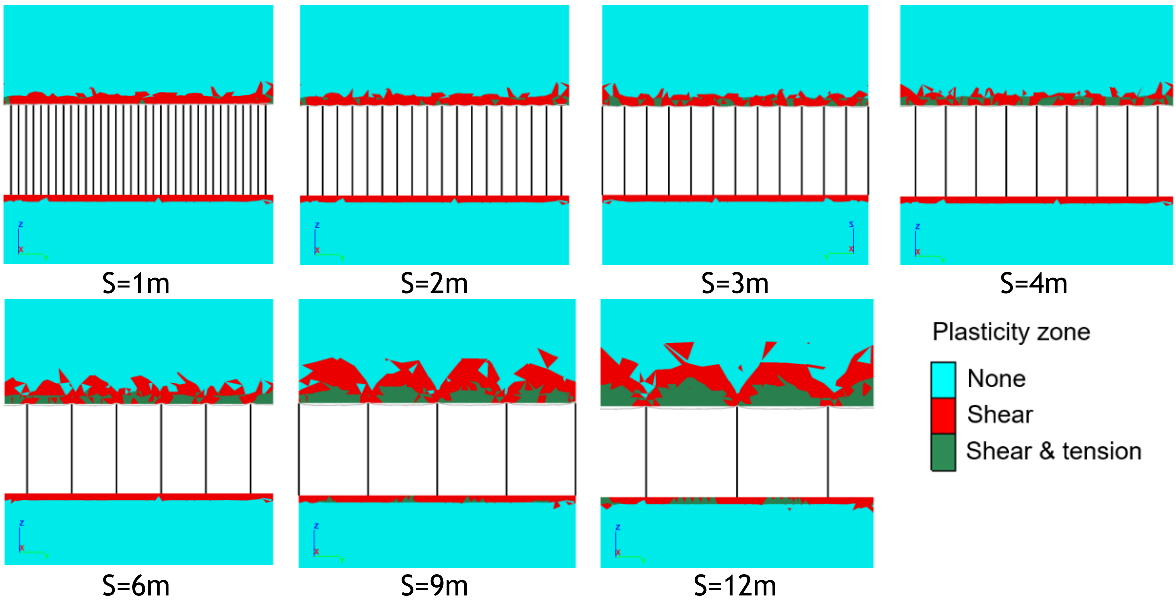


Figure 6. Effects of column spacing on rock mass plasticity zones, results taken from longitudinal section along the columns.

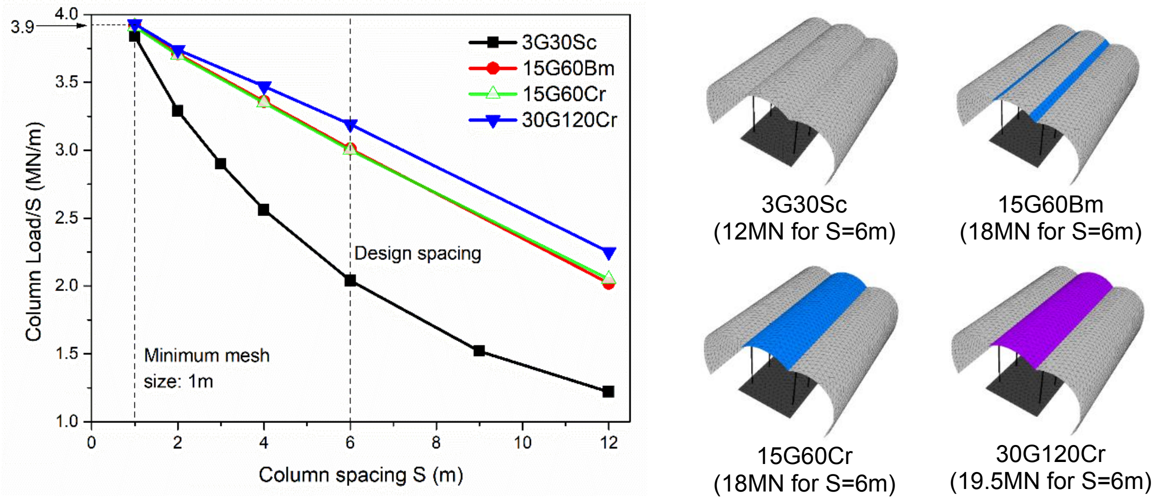
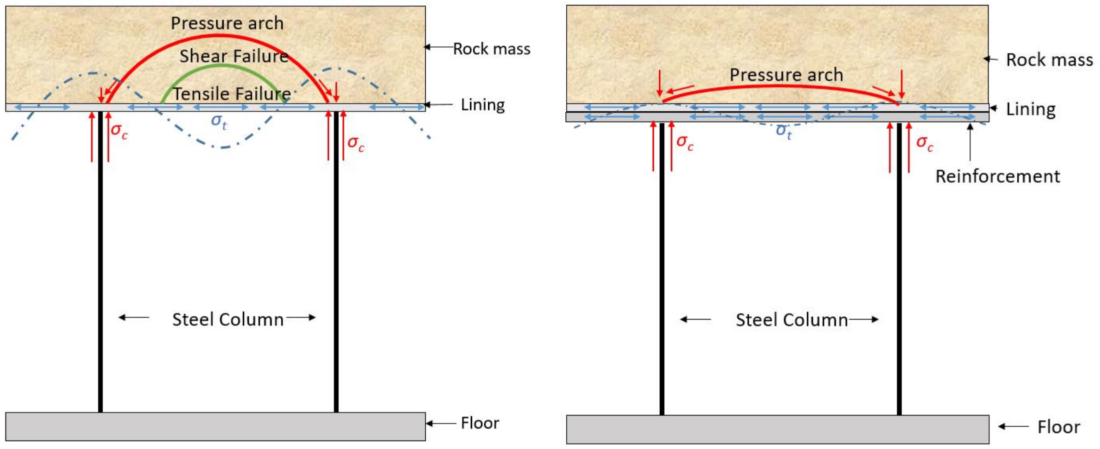


Figure 7. Illustrations of supporting plans and their modelling results for supporting efficiency.

3.2 Load transferring mechanism for tri-arch cavern

Based on results presented and discussed in Section 2.2, a load transferring mechanism is developed for tri-arch cavern, which is presented in Figure 8. It is concluded that the most significant load transferring mechanism taken place at the part of lining right above columns. The reinforcement of that part of lining will provide extra tensile restrain to the rock mass, thus limiting the deformation of rock mass and lining, resulting in higher load in the strong steel columns, and increasing the overall supporting efficiency.



(a) Central crown not reinforced (b) Central crown reinforced

Figure 8. Illustration of load transferring mechanism between lining above columns and steel columns

By the time of submission of this paper, the primary support construction and monitoring of State Library Station has been completed. The actual steel column consists of six parallel steel elements and strain gauges are used to monitor the load on each single element. There is an extra "downstand beam" used as reinforcement between columns in longitudinal direction. From monitoring results, the load on each single element varies from 1.7 MN to 3.3 MN, which means for one column (six elements) the load varies from 10.2MN to 19.8MN. The modelled results are 12MN (3G30sc), 18MN (15G60Bm and 15G60Cr) and 19.5 MN (30G120Cr), which are highly comparable with the monitoring data. The presence of geological structure and uneven ground may have caused the uneven distribution of column loads.

4. CONCLUSION

In this paper, the supporting mechanism of tri-arch cavern is being evaluated using 3D numerical modelling approach. The modelling results are very comparable to monitoring results. The key findings of this paper include identifying the central cavern crown as the critical structure, proposing a load transferring mechanism between different structures and suggesting the major supporting mechanism to be providing tensile restrain to surrounding rock mass. The findings from this paper provide supplements to the supporting mechanism of such caverns/tunnels, which can used as design theoretical basis for future projects.

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