Numerical Modelling of the Stability of Metro Tunnel Stations

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ABSTRACT: Melbourne Metro Tunnel project is aimed at building 9km twin tunnels across CBD underground area, and the settlement prediction and control are essential to protect existing buildings on the ground from collapse. However, some factors like supporting systems and existing underground structures might be the issues causing serious settlement and collapse of the tunnels. Therefore, it is necessary to apply the two-dimensional and three-dimensional finite element methods (i.e. RocScinece2D and RocScience3D software) to simulate the excavation conditions and assess the influence of potential factors. The models are set for tri-arch State Library Station and twin tunnels under Melbourne Formations. It is found that the maximum settlement on State Library Station is approximately 6.4 mm. Several methods, a robust supporting system including rock bolt, segment lining and column, optimised excavation sequence, and avoiding building new structures near the station, can reduce the settlements both on tunnels and ground surface. Moreover, the alignment design of twin-tunnels is suggested to excavate relatively deeper when interacting with the existing Citylink tunnels. This paper generates settlement prediction and the assessment of factors on the tunnel project, which not only provides settlement prediction and recommendation of factors on settlement control for the tunnel project practically, but also demonstrates a comprehensive analysis of settlement prediction that considering potential factors.

1. INTRODUCTION

In the last decade, Melbourne public transport system has experienced unprecedented pressure because of the increased population and needs of growing cities. Melbourne Metro Tunnel, one of the largest transport infrastructure projects undertaken in Australia, is building 9km twin rail tunnels across Melbourne CBD area with five new underground metro stations by Tunnel Boring Machine (TBM) and road headers to facilitate the improvement of Melbourne rail network. Tunnel excavation will cause settlement and stress redistribution (Valizadeh, Sadaghiani & Ahmadi 2012), which is the key challenge that needs to be overcome. Otherwise, it will affect the stability of twin tunnels with stations and the safety of high-rise buildings and historical heritage places on the ground surface in CBD area. Many factors like complex geological compositions and existing underground structures can bring difficulties on settlement prediction and tunnel design before real construction. Therefore, numerical modelling of mechanized excavations will be applied by using the two-dimensional (2D) and three-dimensional(3D) finite element methods (RocScience2D and RocScience3D software) to identify the potential risks and analyse the stability of tunnels before construction phase. The factors that might affect the settlement will also be assessed as well.

Numerical modelling methods have been widely used for underground projects, such as settlement prediction and control (Ağbay & Topal 2020; de Farias et al. 2004, p. 283; Karakus & Fowell 2003; Khademian et al. 2017, p. 658; Li, Zhao & Zhou 2016; Nemati Hayati et al. 2013, p. 2170; Yertutanol, Akgün & Sopacı 2020); influence of long plain faults and stability of weathered rocks (Alex & Lawrence 2019); optimal analysis of support system (Kanik & Gurocak 2018; Morovatdar, Palassi & Ashtiani 2020; Prazeres, Thoeni & Beer 2012); influence of excavation sequence (Wu, Huang & Zhao 2018; Rehman et al. 2020, p. 381; Sharifzadeh et al. 2013, p. 178; Yoo 2009); interactions between excavation and other underground structures (Lee 2009); comparison of modelling results with monitoring results (Ağbay & Topal 2020; Li, Zhao & Zhou 2016; Wu, Huang & Zhao 2018; Fargnoli, Boldini & Amorosi 2013); and the combined 2D and 3D finite element methods in single case numerical analysis (Neuner et al. 2020, p. 10). Although some influencing factors on numerical modelling analysis have been assessed, some limitations still exist in the applicability of different geometry of tunnels, geological compositions, and methods of construction on particular projects.

The aims of this paper are introduced as follows: settlement prediction for Melbourne Metro Tunnel project along with particular geological conditions; assessment of factors on settlement effect, including the supporting system, existing underground structures, surface loading, and excavation sequences.

2. METHODS

Finite element method (FEM) is one of the most common methods in continuum modelling approach, which assumes rock mass as continuous material and analyses the mechanical performance on intact rock and rock properties. RS2 and RS3 applied in this research are two common finite element modellings. RS2 is simple to use but has limitations on long plan

faults for example, while RS3 is more applicable by simulating complicated situations but is time-consuming and expensive (Neuner et al. 2020, p. 1).
The applied basic failure criterion in RS2 and RS3 in this study is the Mohr-Coulomb criterion, which is the most common failure criterion in geotechnical engineering. The Mohr-Coulomb criteria define the situations when isotropic material will fail and describes a linear relationship between maximum and minimum principal stresses in failure. The Eq.1 shows the Mohr-Coulomb criteria for direct shear and Eq.2 shows that for triaxial test data (Coulomb 1776).
Eq. Mohr-Coulomb criteria for direct shear,

$$\tau' = c' + \sigma_n' \tan\,\phi' \tag{1}$$

Eq. Mohr-Coulomb criteria for triaxial test data,

$$\sigma_1' = \frac{2c'\cos\,\phi'}{1-\sin\,\phi} + \frac{1+\sin\,\phi'}{1-\sin\,\phi}\sigma_3' \tag{2}$$

where τ' is the shear strength, c' is the cohesion, σ_n' is the normal stress, σ_1' is the maximum principal stress, σ_3' is the minimum principal stress and ϕ is the material angle of friction.
Furthermore, the surface settlement will be theoretically predicted by Gaussian distribution approach. Eq.3 by Peck (1969) is presented for the theoretical settlement (Gaussian) curve.
Eq. for the settlement curve,

$$S(x) = S_{max}\mathrm{e}^{(-x^2/2i_x{}^2)} \tag{3}$$

The settlement curve in Eq.3 is demonstrated in Figure 1. The relevant parameters in Eq.3 and Figure 1 are: diameter of the tunnel (D), depth of to-axis tunnel (H), overburden (C), surface settlement profile (S_x), maximum vertical settlement (S_{max}), horizontal offset distance from tunnel centreline (x), and trough width parameter (i_x).

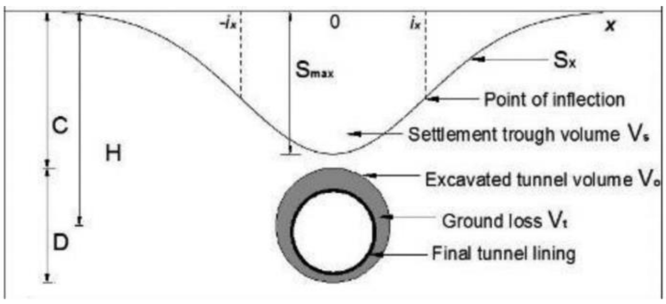

Figure 1. Settlement trough of a circular tunnel (Shiau et al. 2014, p. 348, Fig. 2).

In this paper, the on-site geological units from highly weathered to fresh/slightly weathered Melbourne Formation (MF) are analyzed based on the Mohr-Coulomb criterion to determine the failure condition during excavation, and the parameters that input into models are based on this failure criterion as well.
The finite element modelling program RocScience 2D will be applied to simulate the excavation of State Library Station along with different supporting system. The influence of existing underground basements, surface loading, and excavation sequences would be modelled and analysed as well. Meanwhile, RocScience 3D will be applied for the twin-tunnel model, assessing the twin-tunnel alignment design in the special case with existing underground Citylink tunnel. RS2 and RS3 are provided by RocScience Incorporated (2020).
Before modelling, there are some premises and assumptions should be made according to the features of numerical modelling program: Firstly, a mono-tonically decrease in internal outward radial pressure which is beard by the tunnel boundary would be properly offset by TBM while excavation to keep the excavation surface stable (Cantieni & Anagnostou 2011). Secondly, the material of supporting structures is assumed to have isotropic high quality, and the modelled rock mass is assumed as intact that having isotropic rock properties, according to the setting of RS2 and RS3.

2.1 *Data description*

2.1.1 Melbourne Formation Geological Parameters

The geological information of Melbourne Formation (MF) on site is investigated by Golder (2016). For the State Library Station precinct, the location in long section-interpreted geological profile is shown in the red box in Figure 2, and the geological condition and elastic mechanical properties are shown in Figure 2,3,4 and Table 1 (a), (b). Because the geological composition varies in different places, three sections with typical geological compositions at chainage CH99+290, CH99+440, CH99+460 are particularly chosen and modelled in RS2.

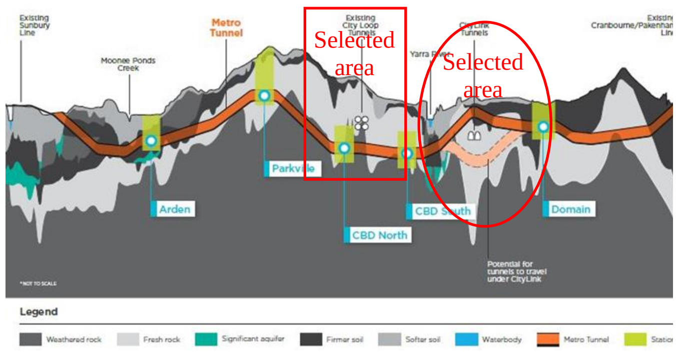

Figure 2. Long section-interpreted geological profile (modified from Golder 2016).

Figure 3. Plan view of the State Library Station (modified from Golder 2016).

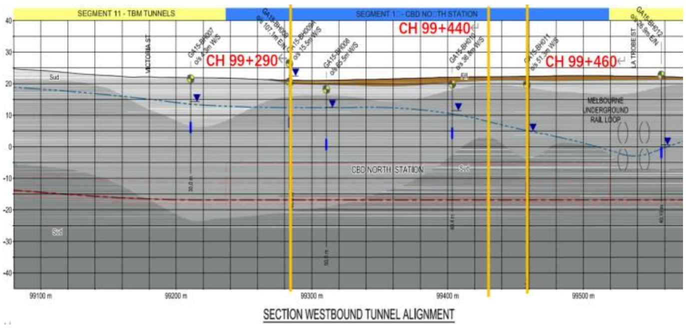

Figure 4. Section westbound tunnel alignment at State Library Station (modified from Golder 2016).

Table 1 (a). Preliminary geotechnical parameters for mined caverns (Golder 2016).

Geological Unit	Unit Acronym	Description	Unit Weight γ	Effective Cohesion c'
			kN/m^3	kPa
FILL	Fill	Man-made fill	19	0
MF4	Sud	EW	22	50
MF3	Sud	HW	23	150
MF2	Sud	MW	24	400
MF1	Sud	SW/FR	26	650

Table 1 (b). Preliminary geotechnical parameters for mined caverns (Golder 2016).

Geological Unit	Friction Angle φ’	Secant Modulus E	Poisson's Ratio v
	degree	kpa	-
FILL	30	10	0.3
MF4	30	80	0.3
MF3	38	300	0.25
MF2	45	500	0.2
MF1	48	2000	0.2

For the precinct that near the Citylink tunnels, the geological condition can be shown in Figure 2 above and circled in red. It is noticed that the two excavation options, excavating twin-tunnels above or below the Citylink, design twin-tunnels in geological unit MF1 and MF4, respectively. Therefore, for the interaction analysis between twin-tunnel and Citylink in RS3 model, the geological information is set as the same as that shown in Table 1 (a), (b) above. Furthermore, the analysed cross-section for this model will be chosen at the place where Citylink is crossing through, with the chainage 101+400m.

2.1.2 State Library Station Dimensions

The State Library Station is designed as a tri-arch cavern and combines multi-tunnels to provide large needed underground space. The station is 45m deep below the ground surface, which is measured from the axis of station to the ground surface, and it is noticeable that all the depth information in this paper are measured from the axis of the structure. The station model is drawn using AutoCAD and then input into RS2 as the basic model. Figure 5 shows the metro tunnel station design drawing.

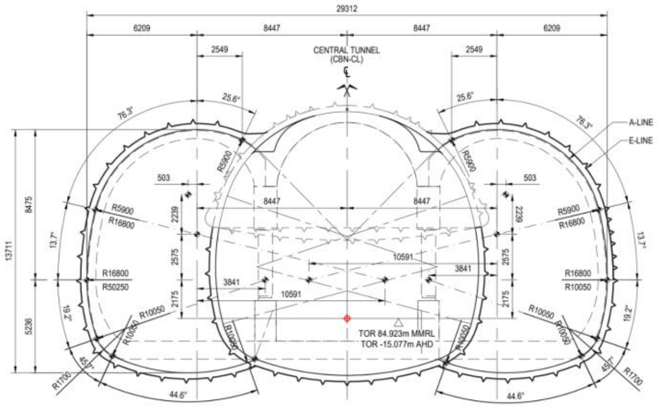

Figure 5. Design drawing of the State Library Station (unit: mm) (Zhang 2019, Fig. 1).

2.1.3 Loading on the ground Surface

The loading on the ground surface is set to be uniformly 25 kN/m^2, assumed the loading is from the reinforced concrete buildings on the ground surface.

2.1.4 Groundwater Setting

Groundwater level is investigated by using monitoring bores (Environment Effects Statement 2019a, p. 18-6) and is set differently in models according to the different typical geological sections chosen above. The groundwater depths in typical sections are listed in Table 2. Furthermore, a fully drained model is set conservatively under the consideration of the influence of long faults and weathered rocks.

Table 2. Groundwater depth in three typical sections (Golder 2016).

Section chainage	Groundwater depth
m	m
CH 99+290	9.5
CH 99+440	15
CH 99+460	17

2.1.5 Supporting Structure Mechanical Properties

The supporting structures, rock bolts, shotcrete/ segment lining, and piles/column, would be installed during the metro tunnel station excavation. Particularly, the rock bolt is steel bolt applied with constant pretensioning force in the install stage, the permanent lining is cast in place reinforced concrete, and the pile is chosen as the soldier pile. The mechanical properties of those supporting materials that applied to the model are shown in Table 3 (a), (b), while the spacing of the rock would vary in different models to determine the optimal value. In Table 3 (a), T=Thickness, L=Length, D=Diameter, A×B=Cross section area.

Table 3 (a). Parameters of supporting structures (Zhang 2019).

Structure	Dimension	Unit weight γ	Elastic modulus E	Possion's ratio v
	m	kN/m^3	GPa	-
Lining of adit	T=0.45	22	15	0.25
Rock bolts	L=4; D=0.05	78.5	210	0.3
Columns in platform	A×B=0.5 ×1	25	30	0.25

Table 3 (b). Ultimate bond stress of rock bolt in different geological conditions (Zhang 2019).

Geotechnical Unit	Ultimate Bond Stress
	kPa
MF4	1500
MF3	700
MF2	500
MF1	300

2.1.6 Twin-Tunnel and Citylink Dimensions

The interaction between twin-tunnel and existing Citylink tunnel will be analysed based on RS3 in the section with chainage 101+400m. According to the design, the twin tunnel will be 9km long with diameter 7-7.5m (Environment Effects Statement 2019b, p. 17) and have the assumed 16.9m distance between twin tunnels, which keeps the same distance between tunnels in State Library Station. For the two excavated options, the twin-tunnel that would go above the Citylink is 11m deep below the ground surface, while the other options to go below the Citylink is 38m deep, according to the design shown in Figure 2. Meanwhile, the existing Citylink is simplified as one tunnel that is three-lane two-way with 16.9m TBM excavation diameter in 21m deep (Vicroads 2007).

2.2 Model description

RS2 and RS3 are professional programs for finite element analysis and are used in geotechnical structure applications. The expected models in this research are described as follows.

2.2.1 Models for Supporting System

In the RS2 modelling program, the excavation of the State Library Station will be simulated along with different supporting systems in one of the typical sections with chainage CH99+460, as it is the section that has the most common geological composition. The planned supporting systems are listed in Table 4 below. The aims of these models are analyzing the supporting effects on the station and generating an optimal supporting system.

Table 4. Possible supporting structure plans.

No.	Support structure plan
1	Bolt (L=4m, distance=1m) & Column
2	Column & Linear
3	Bolt (L=4m, distance=1m) & Linear
4	Bolt (L=4m, distance=2m) & Linear & Column
5	Bolt (L=4m, distance=1m) & Linear & Column

2.2.2 Models for Settlement Analysis

The settlement analysis in RS2 is the most important part of this paper, demonstrating the settlement data on the ground surface and on the top of the tunnel surface. Models in three different typical sections at chainages CH99+290, CH99+440, CH99+460 will be made together with the optimal supporting system that generates before. The aim of these models is to predict and analyze the settlement of this State Library station during the whole construction stage. In addition, a special case with no loading added on the ground surface will be modelled in RS2 as well.

2.2.3 Models for Other Basement Structures

Special cases of existing and future basement structures with different locations will be modelled in RS2 to analyze the influence on the excavated State Library Station with the optimal supporting system. The size of basement is set normally to be 30m width and 10m depth.

2.2.4 Models for Excavation Sequence

Excavation sequence is another factor that might influence the settlement and stress on the station. Figure 6 shows the normal excavation sequence, excavating central tunnel firstly and then excavating side-tunnels stage by stage. This normal excavation sequence will also be applied for all the models in RS2 above. By contrast, another excavation sequence is planned to excavate side-tunnels firstly and then excavate the central tunnel.

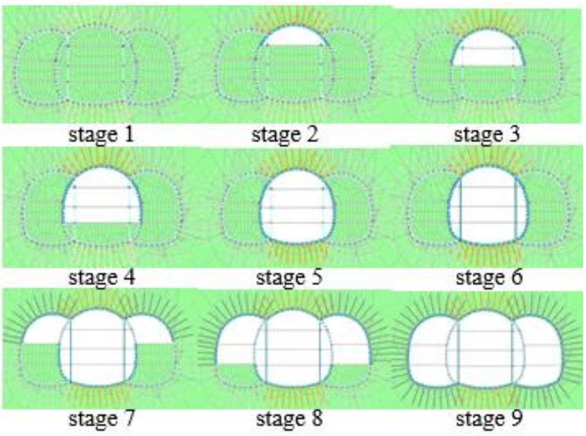

Figure 6. Normal simulation sequence.

2.2.5 Models for Excavation Options around Citylink

The twin-tunnel alignment design is limited by the existence of Citylink, therefore, RS3 will be used to model the situation involving cross-sectional and longitudinal effects. 25 kN/m^3 surface loading will be set to simulate the loading effect brought by reinforced concrete on the ground. The aim of this model is analyzing the interactions between twin-tunnels and Citylink in different excavation options of having twin-tunnels going above or below the Citylink tunnels. Moreover, the models of twin-tunnels excavated together or separately will also be analyzed, in order to find the influences of excavation sequences on tunnels and Citylink. Figure 7 shows a basic model with the excavation plan of letting twin-tunnels excavate below the Citylink.

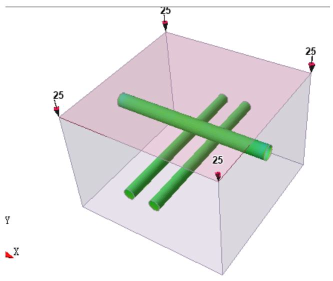

Figure 7. A basic RS3 model simulating the twin-tunnel excavated below the Citylink.

2.3 Data analysis

In RS2 and RS3 models, in order to analyze the settlement and stress on specific places, several typical query points will be added on the places: ground surface; top points of tunnels; supporting structures; connections of tri-arches. The observed data will be summarized in tables and the settlement curve will be graphed.

3 RESULTS

3.1 Supporting System

According to the different supporting systems listed in Table 4 above, the maximum settlement on State Library Station, axial force and bending moment on supporting structures are generated and shown in Table 5 (a), (b), and Table 6, in typical section with chainage CH99+460. Noticeably, the negative value of axial force demonstrates a tension force. Figure 8 (a), (b) reveal the diagram of axial force and bending moment on the station and support structures, based on the application of supporting system No.5 in section CH99+460. The maximum settlement and loading effects are observed in excavation stage 9, therefore, the data collected from supporting system models is in stage 9.

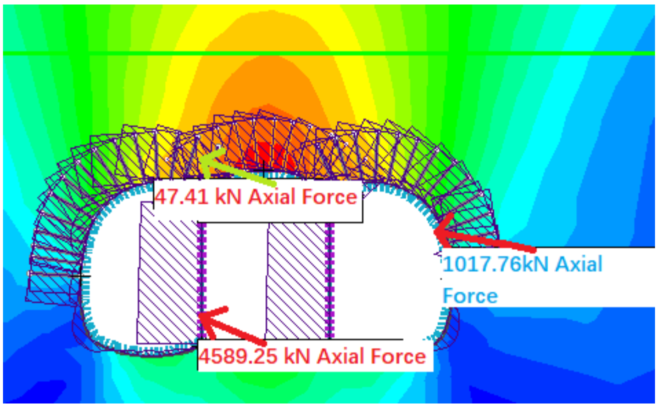

Figure 8 (a). Diagrams of axial force of State Library Station with supporting system No.5 in CH99+460.

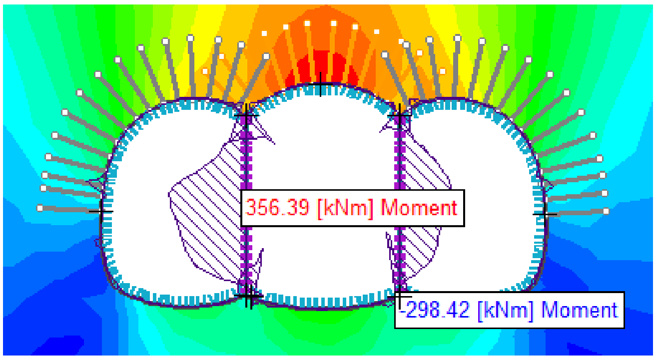

Figure 8 (b). Diagrams of bending moment of State Library Station with supporting system No.5 in CH99+460.

Table 5 (a). Maximum or minimum axial force for supporting systems in CH99+460.

Supporting system No.	Axial force		
	Rock Bolt	Linear	Column
	kN	kN	kN
1	59.32	/	4008.3
2	/	-1047.79	4599.98
3	62.09	1879.42	/
4	53.42	-1046.41	4603.96
5	47.41	-1017.76	4589.25

Table 5 (b). Maximum or minimum bending moment for supporting systems in CH99+460.

Supporting system No.	Bending moment		
	Rock Bolt	Linear	Column
	kNm	kNm	kNm
1	/	/	2.6E-12
2	/	41.98	63.50
3	/	84.04	/
4	/	41.35	63.21
5	/	47.21	356.39

Table 6. Total settlement for supporting system in CH99+460.

Supporting system No.	Maximum settlement	
	on the ground surface	on the top of tunnel
	mm	mm
1	3.8	6.3
2	3.3	5.5
3	5.7	9.3
4	3.3	5.4
5	3.2	5.3

From Table 5 (a), (b), and Table 6, the influences of supporting structures on themselves and the State Library Station are analyzed. Column, as a vertical support structure, provides a significant support effect on station and bears the maximum axial force and bending moment. By contrast, if the column is removed, the settlements both on the ground surface and tunnel stations will increase seriously. Rock bolt and shotcrete can provide support effects and bear axial force or bending moment. However, their support effects on settlement control are relatively smaller. After comparison, the supporting system No.5 (L=4m, distance=1m Bolt & Linear & Column) is optimal with minimum settlement and has relatively smaller loads that supporting system should carry.

3.2 Settlement Analysis

Inputting related parameters and computing the models in three typical sections with chainages CH99+290, CH99+440, CH99+460, the modelled results are generated. The settlements on the ground surface and on the station should be analyzed most importantly, because those will affect the safety of existing buildings on the ground surface and the stability of State Library Station. Figure 9 shows the development of settlement during nine construction stages in the section CH99+460, and the graph named "legend" is the constant contour legend of settlement.

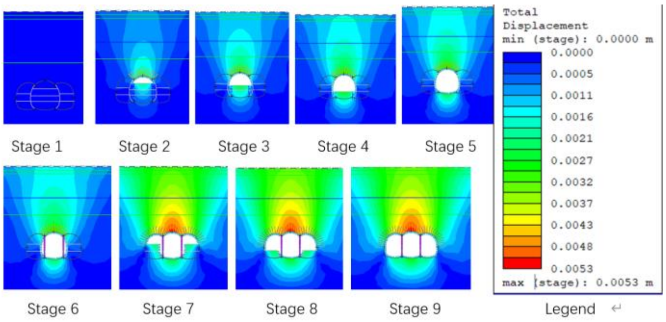

Figure 9. Total displacement during 9 stages in section CH99+460.

From Figure 9, it can be observed that the largest settlements are located at the critical points: for the station, the critical point is the top point of the central tunnel station; for the ground surface, the critical point is above the centerline of the central tunnel. Moreover, the largest settlements happen at the excavation stage 9. Figure 10 illustrates the settlement effects on the ground surface in three typical sections, and it also proves the location of the critical point on the ground surface. The distance in Figure 10 is longitudinally measured from the center point of the central tunnel, and the settlement curves have the same feature as the theoretical Gaussian Distribution curve introduced before.

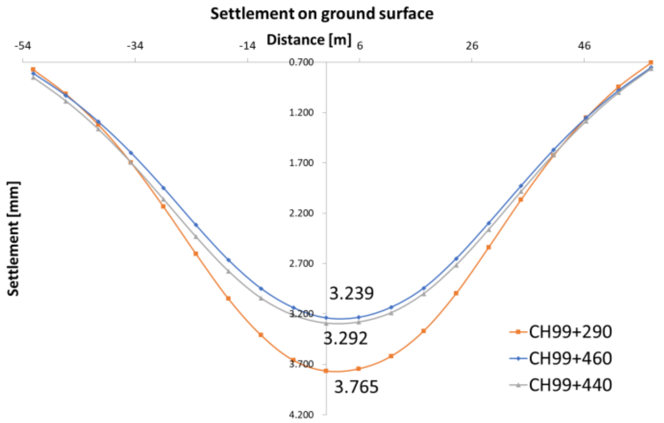

Figure 10. Settlement curves on the ground surface in models with three different sections.

Figure 11 (a), (b) show that the maximum stress critical point in section CH99+460 is located at the bottom of the central tunnel station in stage 9.

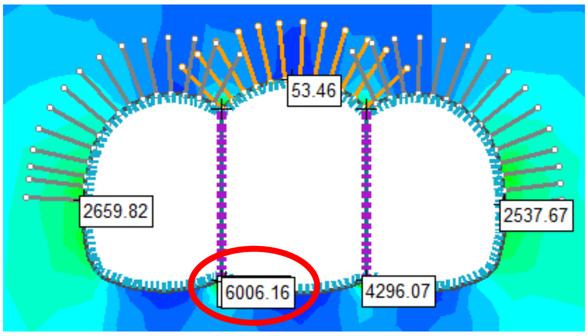

Figure 11 (a). Location of maximum sigma 1 at stage 9, section CH99+460.

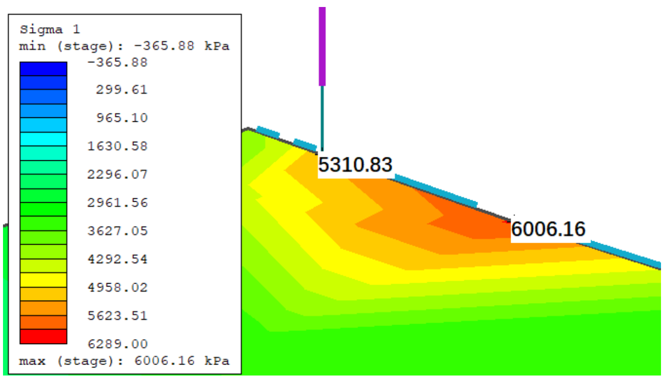

Figure 11 (b). Detailed diagram of maximum sigma 1 at stage 9, section CH99+460.

The same phenomena of critical points are shown in the other two typical sections with chainage CH99+290 and CH99+440. Summarize the maximum settlements in three typical sections, Table 7 below demonstrates the maximum settlement data along with the maximum stress (σ_1) at the critical points in stage 9.

Table 7. Maximum settlement and sigma 1 on critical points in typical sections with chainage CH99+290, CH99+440 and CH99+460.

Section chainage	Maximum settlement		Maximum sigma 1
	on the ground surface	on the top of tunnel	
m	mm	mm	kPa
CH99+290	3.8	6.4	5936.44
CH99+440	3.3	5.3	5153.17
CH99+460	3.2	5.3	6006.16

In terms of the results in Table 7, since the excavation simulation is generated in three typical sections, the results can almost represent the situations of the whole State Library Station. Meanwhile, even though the three sections have different geological compositions, the maximum stress and settlement for all the three sections under the same stage have similar values. The maximum settlement on the ground surface due to excavation is 3.8mm, the maximum settlement on the station is 6.4mm, and the maximum stress on the station is 6006.16kPa.
In addition, a special case that no loading is added on the ground surface is also modelled in section with chainage CH99+460, and is shown in Figure 12 (a), (b). The maximum settlement on the station is 5.3mm, while that on the ground surface is 3.2mm and the maximum stress is 5622.07kPa. It reflects that the surface loading is not a significant factor influencing the settlement of the construction structure.

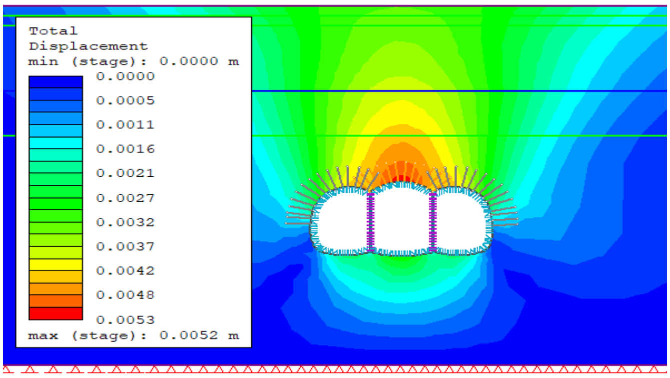

Figure 12 (a). Settlement of State Library Station model with no loading on the ground surface at chainage CH99+460.

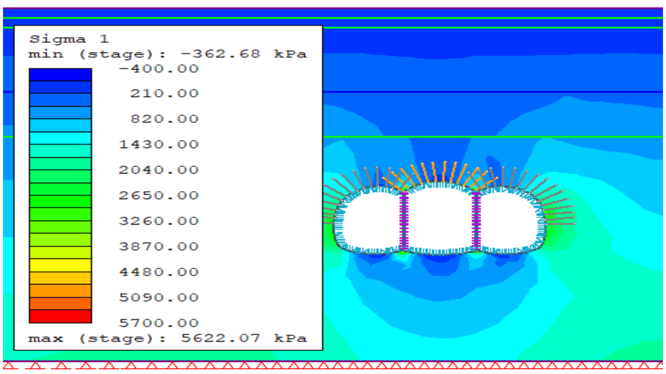

Figure 12 (b). Stress of State Library Station model with no loading on the ground surface at chainage CH99+460.

3.3 Other Basement Structures

Two special cases of different locations of the basement are modelled firstly. The models for the existing basement at different locations are shown in Figure 13. The models in special cases are based on the geological condition with chainage CH99+460 at stage 9, since it is the typical section and the max loading effects appear at stage 9. The loading area is set particularly within the excavated basement area.

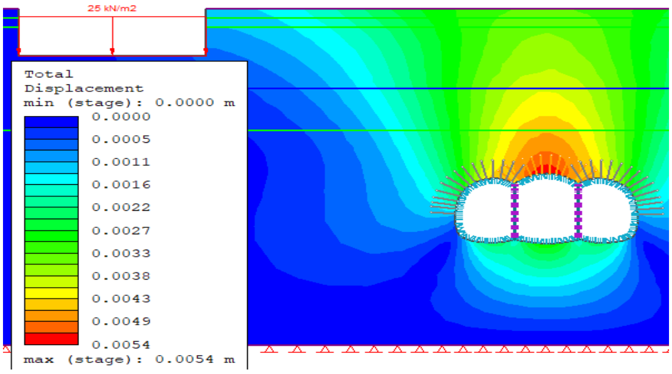

Figure 13 (a). Settlement of State Library Station with existing basement 40m away from station.

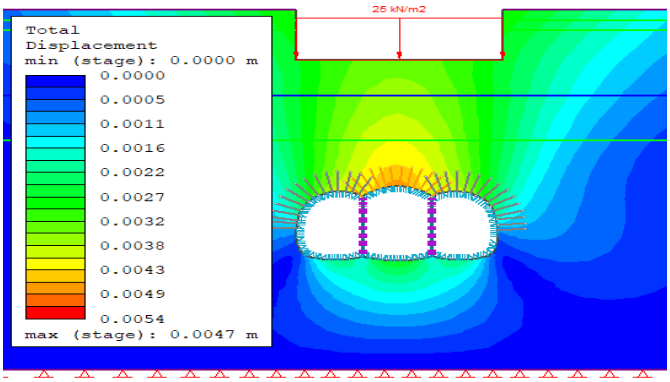

Figure 13 (b). Settlement of State Library Station with existing basement above the centre of the station.

Moreover, the other two special cases of basement excavated in the future are also modelled. The modelling results of all the four special cases are listed in Table 8 as follows.

Table 8. Maximum settlement under different basement conditions.

Basement Condition	Maximum settlement	
	on the ground surface	on the top of tunnel
	mm	mm
Existing basement is 40m away from station	3.3	5.4
Future basement is 40m away from station	3.3	5.4
Existing basement is above the central of the station	3.4	4.7
Future basement is above the central of the station	4.2	4.4

From Table 8, the closer the basement is to the station, the larger the settlement that will be caused by excavation. Moreover, it is noticeable that the excavation of the basement above the station in the future will cause a more obvious settlement effect on the ground surface, while the settlement is smaller when the metro station is excavated after the construction of basement.

3.4 Excavation Sequence

Based on the two options of different excavation sequences set in model description above, the models are generated in geological condition at chainage CH99+460. The results of maximum settlement on the ground surface and on the station are shown in Figure 14 (a), (b), under different excavation sequence and stages.

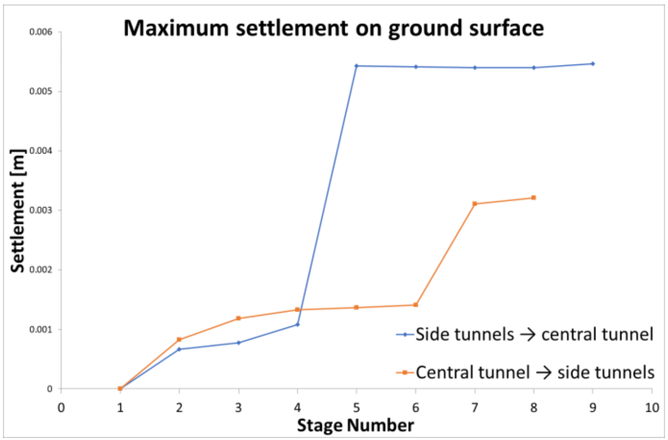

Figure 14 (a). Maximum settlement on the ground surface during different excavation sequences.

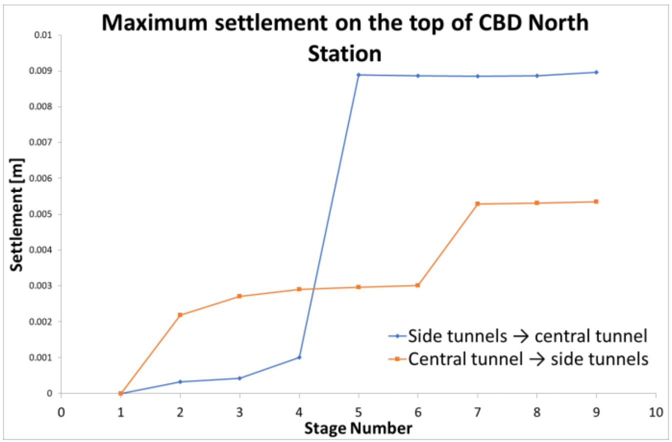

Figure 14 (b). Maximum settlement on the station during different excavation sequences.

From Figure 14 (a), (b), it is obvious that the excavation sequence is a significant factor in influencing the settlement of the excavated structure. The new excavation sequence—excavate side tunnels firstly and then central tunnel causes much larger settlements both on the station and on the ground surface.

3.5 Models for Excavation Options around Citylink

RS3 modelling program is applied to simulate the excavation conditions in three-dimensions with the existence of Citylink. Firstly, the two options of tunnel alignment design are analysed by models and the results are shown in Figure 15 (a), (b). Those models are set with simultaneously excavated twin-tunnels and 25kN/m^2 surface loading.

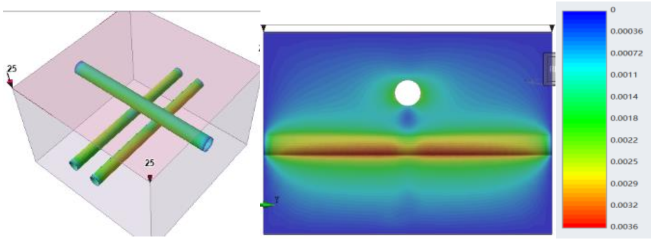

Figure 15 (a). Maximum settlement for 3D view (left), for twin-tunnel side view (middle) and contour legend (right) when twin-tunnel excavated below Citylink. The maximum settlement 3.6mm is on twin tunnels.

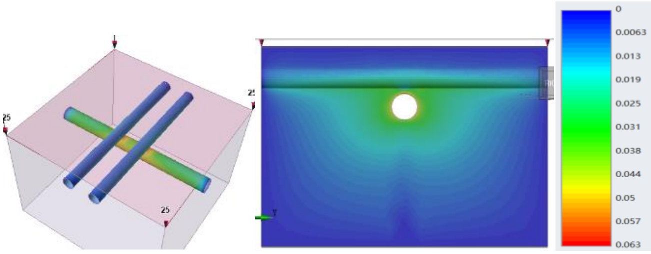

Figure 15 (b). Maximum settlement for 3D view (left), for twin-tunnel side view (right) and contour legend (right) when twin-tunnel excavated above Citylink. The maximum settlement 63mm is on Citylink, and the maximum settlement on twin-tunnel is 29mm.

From Figure 15 (a), (b), it can be noticed that the twin-tunnel excavated above the Citylink causes Citylink beard an obviously larger settlement of 63mm, which brings a high risk to the safety of the existing Citylink tunnel. By contrast, if twin-tunnels are excavated below the Citylink, it will suffer a much smaller maximum settlement of 3.6mm and is located on tunnels, which is safer.

Figure 16 (a), (b) indicate the models with the conditions that excavating twin-tunnels separately with 25kN/m^2 surface loading.

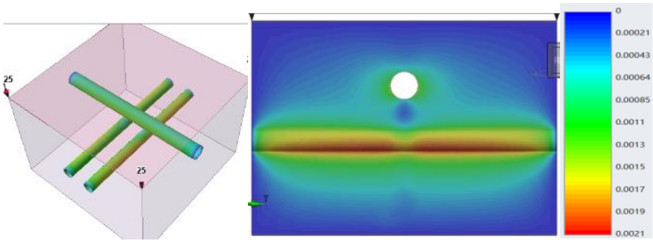

Figure 16 (a). Maximum settlement for 3D view (left), for twin-tunnel side view (right) and contour legend (right) when twin-tunnel excavated separately below Citylink. The maximum settlement 2.1 mm is on twin-tunnels.

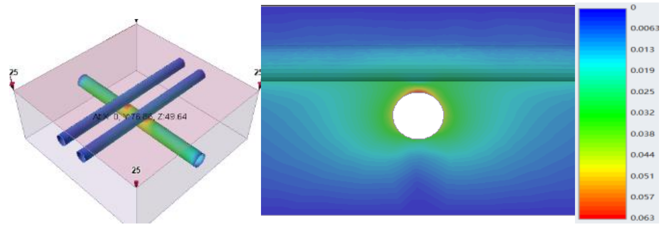

Figure 16 (b). Maximum settlement for 3D view (left), for twin-tunnel side view (right) and contour legend (right) when twin-tunnel excavated separately above Citylink. The maximum settlement 63 mm is on twin-tunnels, and the maximum settlement on twin-tunnel is 29mm.

The results in Figure 16 (a), (b) also indicate the smaller settlement when twin-tunnels are located below the Citylink. Moreover, it is noticeable that a smaller maximum settlement of 2.1mm on twin tunnels can be achieved when excavating twin tunnels separately. Therefore, for the twin-tunnel alignment design, it is suggested to excavate twin-tunnel below the Citylink with 38m deep and excavate tunnels separately, which can result in smaller settlement effects both on twin-tunnels and the existing Citylink tunnel.

4 CONCLUSIONS

In this paper, the excavation settlement of twin tunnels and the State Library Station in the Melbourne Metro project is assessed by using RS2 and RS3 numerical modelling programs. The research aims are covered: settlement prediction of excavations on State Library Station, ground surface, and other underground structures are computed; and the influence of factors of supporting system, surface loading, excavation sequence, and the existence of other structures are analysed. The key conclusions are summarized as follows.

- The curve of the settlement that on the ground surface is in Gaussian distribution, and the relevant point with maximum settlement on the ground surface is located above the centreline of the station, with a maximum of 3.7mm in all three typical sections. The maximum settlement on State Library Station happens on the top point of central tunnel to be a maximum of 6.4mm in all three typical sections.
- For supporting system, column acts as the most important supporting structure which heavily bears most of the axial force and bending moment. The supporting system that consists of rock bolt, segment linear and column can minimise the settlement that both on station and ground surface.
- For other basement structures, the basement excavated after the State Library Station in the future will cause more serious settlement particularly when it is near the metro tunnel station. Therefore, in this case, more support structures should be applied to minimize the settlement effect. Moreover, the short distance between excavated station and other basement structures is another factor causing a large settlement.
- What's more, the excavation sequence can significantly increase the settlement caused on the station and ground surface if side tunnels are excavated firstly before the excavation of the central tunnel.
- The twin-tunnel vertical alignment design will significantly affect the settlement of the existing Citylink tunnel, especially when twin tunnels are excavated above the Citylink tunnel. The construction plan, separately excavating twin tunnels below Citylink, can minimize the settlements both on twin-tunnels and Citylink tunnel to be maximum 2.1mm on twin-tunnels.

This paper provides an analysis of not only settlement prediction but also the assessment of some factors on settlement for Melbourne Metro tunnel project. It provides a case study by using the numerical modelling method on twin-tunnel settlement control and stability analysis and indicates a comprehensive analysis of different factors on settlement prediction.

However, some other factors like long plan faults and excavation machines still need to be assessed in the future, since they can influence the groundwater permeability and other properties and thus the settlement.

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Management Statement

The final year project with the topic—Numerical Modelling of the Stability of Metro Tunnel Stations lasted for a year in 2020, and it is an honor to reach the end of the project and generate results in this academic research. It is worthy to make a self-reflection management statement, in order to summarize the advantages of research progress management and the disadvantages that need to be improved in future researches.

The one-year project went well on time management, research progress direction control, and quality assurance overall, and the deeper research that has been done in this project was another excellent part. In terms of time management, a timetable that listed all the important milestones and the planned research progress details were generated and used to navigate the research direction and progress over the whole project period. Moreover, the submission of the weekly summary was another useful tool to check the research progress, compare the research real outcomes with the research plans, and adjust the future research timetable accordingly. With the help of the weekly summary, there were rare deviations from the plan, as they were corrected in time. Weekly summary also had an effect on objectively supervising the research progress, keeping progress going well. Especially, the good structure of the weekly summary also essentially supported this academic research. It contained the outcomes in the past week, questions that need to be addressed with the supervisor, the next step that would be done in the next week, and an overview of the whole project progress. Those advanced behaviors in this academic research are worthy to be kept in future research and improve research efficiency and quality.

Even though the overall academic research went well during this project period, there were some mistakes happened and should be avoided in future research. When making the timetable with key milestones, the lack of clear and reasonable expectations on research time consuming caused some small delays that happened during the real research progress. A lesson was learned from it: a buffer time or a backup plan should be made in case of unexpected events happen; a reasonable timetable should be advised by the supervisor or other experienced researchers.

In terms of the adaptation of the research, a deeper research on RocScience 3D models has been done, considering the research needs, the available research resource, and the extra research time due to the well-managed research schedule. It reflected the importance of research progress management, research direction, and quality control. With those helps, a clear view of the research was obtained, and the further research gap and needs were easily identified and addressed in the condition with available extra research time. In addition, some of the detailed research plans have been changed as well. The original plan was to generate two-dimensional models by simulating the State Library Station excavation with different supporting structures plans. However, after doing some deeper literature review, it was found that there were a lot of other factors that would affect the stability of the State Library Station and cause serious settlement. Therefore, some adjustments were made to the research plans: furtherly modeling the excavations under different conditions of varied existing basement distances, surface loadings, and excavation sequences, in order to assess the settlement and stability of the structure comprehensively. It reflected the importance of fully understanding current research status at home and abroad and the essentials of fully understanding the failure mechanisms and the possible influencing factors.

There are a lot of key points that learned in this project that would be helpful in future professional life. The most important one is the improved ability to structure a project. Key milestones are the framework that is set along with time schedule to ensure the deliverables of the project can be finished in time with high quality. Some useful tools like a weekly summary can be used to track and objectively supervise the project progress, in the meantime, some adjustments can also be made once the delay or deviation is noticed. Furthermore, efficient interactions with supervisor is vital in the whole project period. A good information structure during interactions can quickly point out the key outcomes and the existing problems, providing a clear view of the research to the supervisor and resulting in a more efficient interaction on solving problems and directing research outcomes.