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Evaluation of tunnel interaction in Kenny Hill Formation using Finite Element Modelling

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Abstract: The number of town population growth is the reason for the expansion of transportation and infra-structures in metropolitan cities. Due to that urban tunnelling has turned out to be common in most area. Considering the environmental impacts, going underground become a feasible choice for the development of transportation. But, when dealing with urban tunnelling, one always meet with complex mechanism due to soil interaction between ground and tunnels. Tunnelling problem must be considered as a three-dimensional problem. However, we can simulate the three-dimensional plane problem into a two-dimensional plane problem by considering certain assumption which governs the missing dimension. This paper is to show the simplified method for ground settlement prediction of tunnelling excavation using the PLAXIS 2D software. The two simplified methods are lining contraction and stress reduction method. The comparison between these two methods is described in this paper in terms of contraction ratio and unloading factor which can be used for tunnelling problems. This study was done in the Kuala Lumpur Kenny Hill Formation basically based on geotechnical data of Klang Valley Mass Rapid Transit (KVMRT) system. Hardening soil model is choosen as the constitutive model for this analysis because of its ability to represent the actual soil behaviour compared to Mohr Coulomb Model. The effectiveness of simulation using these two methods was verified with the monitored ground movement data. A relationship between these two methods was formed as the outcome of the study.

Keywords: Lining contraction, stress reduction, Kenny Hill Formation, hardening soil model, tunnelling

INTRODUCTION

Development of roadways and highways are no longer adequate in recent time because of populace and cities growth. To solve this issue urban tunnelling concept come into practice in most area. In real case, tunnelling construction involves a three-dimensional concept. Due to time consumption of three-dimensional analyses, engineers prefer two-dimensional in practice. Moreover, three-dimensional analyses are not suitable to apply for a large tunnel project that involves several kilometers of excavations and various cross sections (Moller & Vermeer, 2006). The geology of Kuala Lumpur and Klang Valley is mainly Kuala Lumpur Limestone and Kenny Hill Formation. This study only concentrates on the Kenny Hill Formation. The Kenny Hill Formation is a metasedimentary rock which consist of phyllites, quartzite and other soil particles. One of the developments in Kuala Lumpur and the area surrounding it is the construction of the Klang Valley Mass Rapid Transit (KVMRT) system which started construction in 2012. The reason for the project was to improve public transportation facilities and reduce traffic congestion problem in the populated area. This project includes twin tunnel excavations, deep excavations and geotechnical works.

These days, Finite Element Method (FEM) comes to mind when one needs to deal with tunnel excavation problems. This method is a famous and useful device to simulate tunnel construction works. Many geotechnical software developers apply FEM in their computational tool to solve geotechnical problems. However, the use of FEM in settlement prediction is still not that much accurate because of many factors such as simplified geometry and boundary condition, mesh generation, initial input of ground data and the type of constitutive model chosen for the analysis (Likitlersuang *et al.*, 2014). To understand the behaviour of the soil, researchers developed soil constitutive model. A soil constitutive model is a mathematical relationship that represents the soil interaction and its behaviour. The simple and widely used soil constitutive model is the

Mohr-Coulomb Model which based on linear elastic and perfectly plastic concept. Nevertheless, the soil interaction is much more complex which cannot be demonstrated by the Mohr-Coulomb Model. This is because, at a different stage of loading condition, the soil will experience different behaviour (Ti *et al*., 2009). To solve this problem, use of Hardening Soil (HS) model in simulation and analysis comes into the application. HS model was framed based on the concept of plasticity theory and stress-dependent stiffness. The formulation and verification of the HS model were described in detail by Schanz *et al*. (1999).

This paper aims to show the simplified technique for surface settlement computation of tunnelling excavation based on the KVMRT project using the PLAXIS 2D software. This study will emphasize on the use of lining contraction and stress reduction method. This two-method used and back analysing of surface settlement due to tunnel excavation was done at the final stage of the study. The result of the two methods was compared and back analysing results verified with ground monitoring data to justify the method applied is valid. This study will benefit the underground excavation project in terms of understanding the effect of 2D modelling method and constitutive model for the prediction of twin tunnel induced surface settlement and its suitability to adopt for Finite Element analysis for better prediction of surface settlement in Kenny Hill Formation.

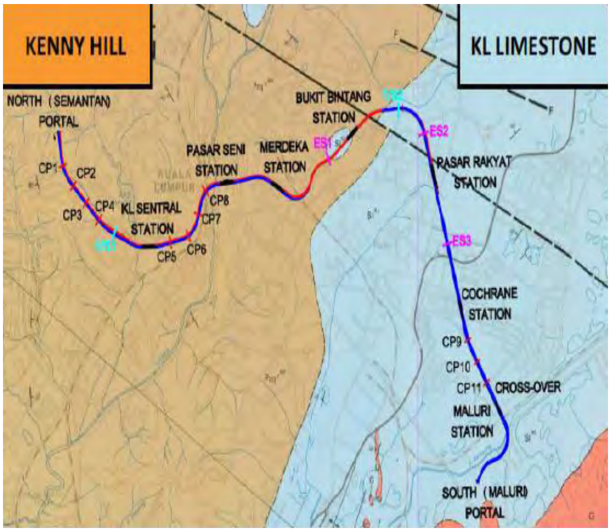

Figure 1: Two different geological formations along alignment of KVMRT Line One (Wallis & Kenyon, 2014).

STUDY AREA

Greater Kuala Lumpur or also known as Klang Valley is an urban area formed by Kuala Lumpur and its attached cities and towns with high rate of population. KVMRT is a transformation project of public transportation service in Kuala Lumpur which aims to upgrade the public transportation facilities. The twin tunnel alignment of KVMRT line, one which is named as the Sungai Buloh to Kajang (SBK Line) cut through two different geological formations specifically Kenny Hill Formation and Kuala Lumpur Limestone, as shown in Figure 1.

The geological and soil mechanical characterisation of Kenny Hill Formation and Kuala Lumpur Limestone are varied from one to another. As mention previously in this study, we only focus on the Kenny Hill Formation because the study of tunnel interaction in Kenny Hill Formation is still new. Kenny Hill Formation comprises of interbedded clastic sedimentary rocks such as siltstone, sandstone and shale.

The SBK line is about 51 km in length and consist of 31 stops which includes elevated and underground stations. About 9.5 km underground alignment with a tunnel diameter of 6.7 m of SBK line passes through the centre of Kuala Lumpur with a total of 7 stations, as shown in Figure 2.

METHODOLOGY

Basically, this study was divided into three major parts. The first part is subsurface characterization. Second is the empirical correlations of stiffness parameters and soil properties determination for the

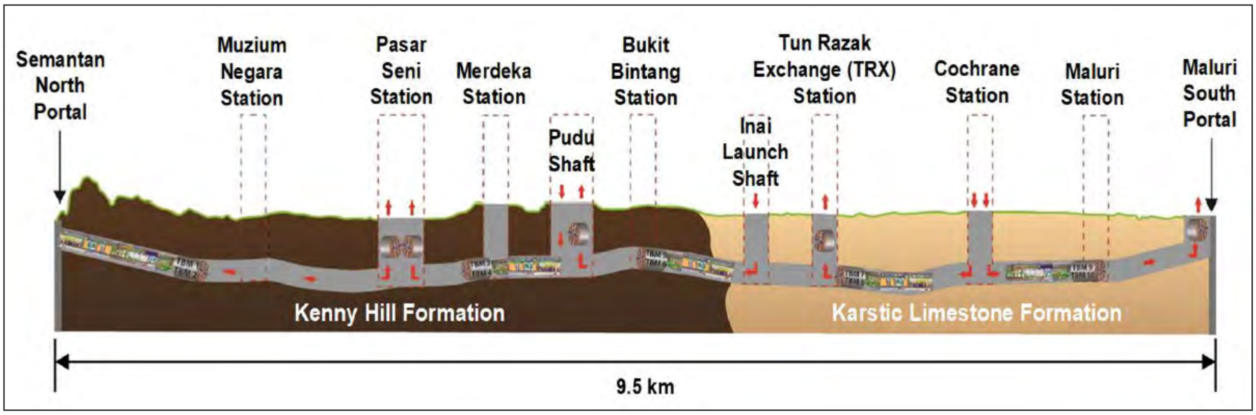

Figure 2: Scope of underground works (Wallis, 2015).

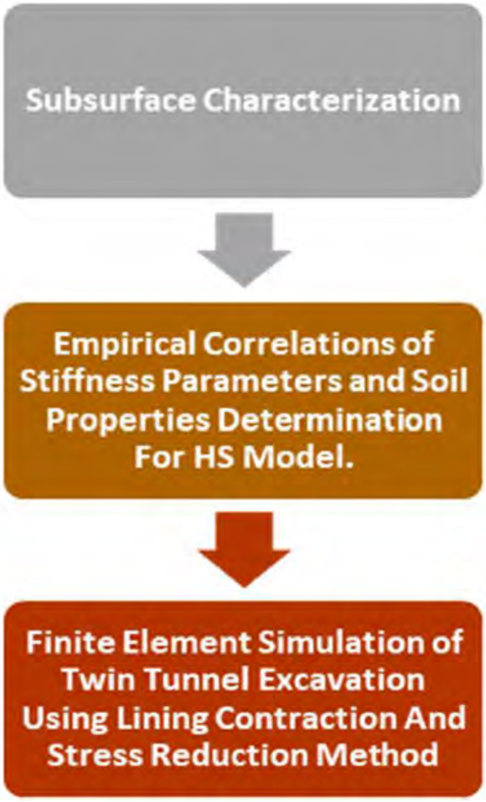

Figure 3: Methodology of study.

HS model. Lastly, the third part which is the Finite Element simulation of twin tunnel excavation using lining contraction and stress reduction method. Figure 3 shows the overall workflow of the study. Each part of the study is very important.

Subsurface characterization

All the information such as soil sampling data, in-situ testing data, bore log data and laboratory testing data are gathered to create subsurface modelling and characterization. The sum of bore log data is large for this project. The Standard Penetration Test (SPT-N) values and the soil lithology are studied in detail and categorized into few zones based on its subsurface information. This study only focusses on the one zone which contains a large percentage of fine-grained soil with a low percentage of coarse-grained and rock sample. With the help of RockWorks16 3D, the ground model is created using spatial interpolation method. Next, the tunnel filtered model is obtained from the 3D ground model. Information such as SPT-N value and soil type within the tunnel segment was obtained. Based on the output, two greenfield tunnel sections selected. The section also selected based on the availability of information such as existing monitoring data and soil test result. The selected chainage for this study is NB1590 and NB1960 as shown in Figure 4. Based on the soil profile, further analysis was

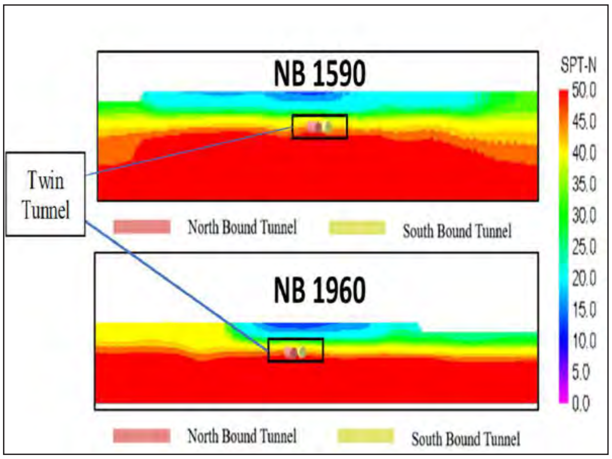

Figure 4: Cross section of selected tunnel.

done. The soil profile was simplified, so it can be easily inputted in the PLAXIS 2D software.

Empirical correlations of stiffness parameters and soil parameters determination for HS model

The HS model involves more parameters compared to the Mohr-Coulomb Model. The three-main stiffness parameter that involves in the HS model is triaxial secant stiffness (E_{50}), oedometer stiffness (E_{oed}) and unloading-reloading stiffness (E_{ur}). For this study, the stiffness parameters for HS model in Kenny Hill Formation were determined based on the empirical correlation suggested by Law *et al.* (2014) and Tan *et al.* (2001). This correlation is based on SPT-N values, so the effective triaxial secant stiffness (E^{ref}_{50}) and effective oedometer stiffness (E^{ref}_{oed}) can be empirically correlated. Next, the effective unloading-reloading stiffness which is (E^{ref}_{ur}) is three times of the triaxial secant stiffness value. In the normal case, the effective oedometer stiffness (E^{ref}_{oed}) will be the same as effective triaxial secant stiffness (E^{ref}_{50}). The effective friction angle and cohesion which are the strength parameters were taken from triaxial test results. The empirical correlations were verified with numerical back analysis by using the two different sets of soil parameters that obtained from the empirical relationship. Table 1 shows the HS model parameters obtained from empirical correlation. Correlation based on 1.5 SPT-N as proposed by Law *et al.* (2014) was adopted for further analysis since it can agree well with the monitored settlement.

Finite element simulation of twin tunnel excavation using lining contraction and stress reduction method

Tunnel excavation method can be simulated in a two-dimensional plane. However, to convert the three-dimensional plane into a two-dimensional plane we need to consider certain aspects. We must assume the missing

Table 1: Soil parameters obtained from empirical correlation.

SPT-N	φ′	c′	γ_b	E^{ref}_{50}	E^{ref}_{oed}	E^{ref}_{ur}	v_{ur}	K_0^{NC}	p^{ref}	*m*
Correlation 1.5N (Law et al., 2014)										
5	31.75	8.75	18	7500	7500	22500	0.2	0.47	100	0.5
20	30.9167	4.83	18.5	30000	30000	90000	0.2	0.49	100	0.5
40	30.25	5	19	60000	60000	180000	0.2	0.50	100	0.5
50	29.8333	7.17	20	75000	75000	225000	0.2	0.50	100	0.5
Correlation 2.5N (Tan et al., 2001)										
5	31.75	8.75	18	12500	12500	37500	0.2	0.47	100	0.5
20	30.9167	4.83	18.5	50000	50000	150000	0.2	0.49	100	0.5
40	30.25	5	19	100000	100000	300000	0.2	0.50	100	0.5
50	29.8333	7.17	20	125000	125000	375000	0.2	0.50	100	0.5

dimension with other aspects. The lining contraction involves two phases. First is the deactivation of soil cluster in the tunnel. Then, the second phase is the step-wise application of tunnel contraction ratio. This method uses the contraction ratio to determine the best fit settlement curve with monitoring data. Next, the stress reduction method which uses an unloading factor (β) to consider the three-dimensional effect into the two-dimensional plane. For the stress reduction method includes three calculation phases. In the first phase, the initial support pressure (p_o) acts on the tunnel. This support pressure reduces to p_β, where p_β is the relationship of βp_o in the second calculation phase to help the surrounding soil to deform. The β value will be between 0 to 1. In the last phase, the soil cluster inside the tunnel is deactivated, the same time the tunnel lining is activated. For further details about lining contraction and stress reduction method can be referred to Likitlersuang *et al*. (2014). As mention, the procedure of lining contraction and stress reduction was done in the PLAXIS 2D software with the selected soil profile as shown in Figure 5.

Based on the soil profile and procedure both lining contraction and stress reduction method analyzed in PLAXIS 2D software to obtain a suitable range of contraction ratio and unloading factor for Kenny Hill Formation. The sequence of the simulation depends on the construction of twin tunnel. For this section, the North Bound (NB) excavated first and then only the South Bound (SB) continued for excavation. So, the simulation begins at NB and ends at the SB. Figure 6 shows an example of output from the lining contraction method for chainage NB 1590 in PLAXIS 2D software.

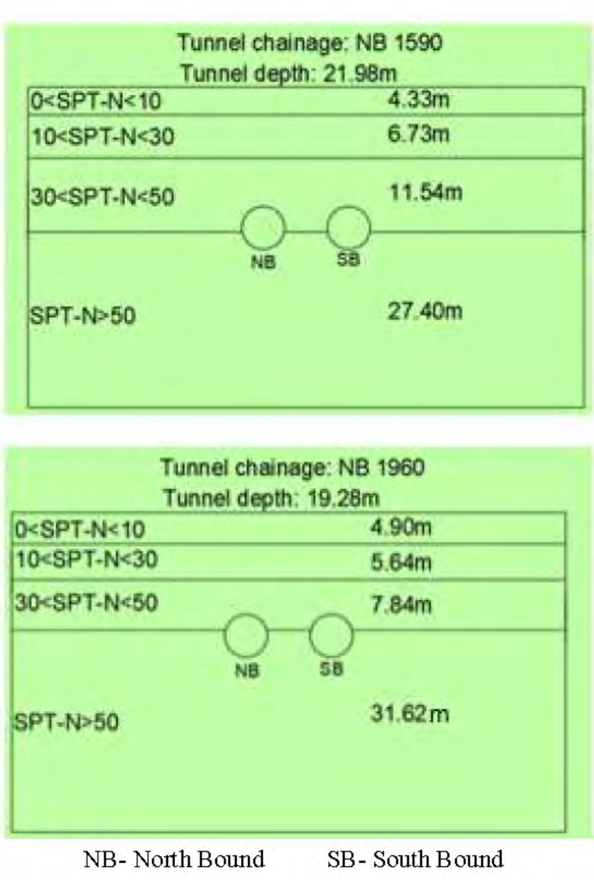

Figure 5: Soil profile of analysed sections.

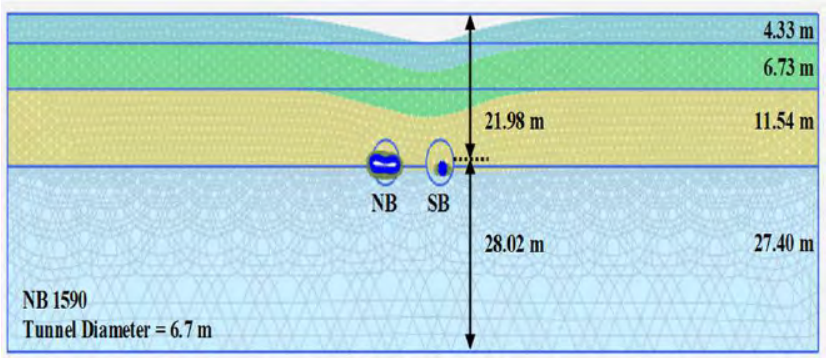

Figure 6: Finite Element Model (An example from NB 1590).

RESULTS AND DISCUSSION

The two sections of SBK Line were modelled using lining contraction and stress reduction method. The results of the simulation for the two sections are shown in Figures 7 and 8.

The simulated settlement curves for the two sections using both methods can fit back to the monitoring settlement with less difference and almost similar trend. Some of the monitoring settlement data of chainage NB 1590 was observed with a surface heave, this may be due to errors in the monitoring instrument. Table 2 summarized the maximum settlements from simulation and ground monitoring data. Table 3 shows the contraction ratio from lining contraction method and unloading factor from stress reduction method.

Stress reduction method fit back the curve better than lining contraction method. The difference of maximum settlement obtained from stress reduction to the monitoring data is less compare to the maximum settlement from lining contraction. From the contraction ratio results can say that higher the contraction ratio, higher the maximum settlement. For the stress reduction method higher the unloading factor, β the smaller the settlement. Can say that the relationship between contraction ratio and unloading factor is vice versa as shown in Figure 9. A good correlation was obtained between contraction ratio and unloading factor with R^2 of 0.9948.

CONCLUSION

This study emphasised the two-dimensional simulation of tunnel excavation. Lining contraction and stress reduction method was used to study the settlements. Two greenfield sections selected for the analysis. The contraction ratio of the two-section ranged from 0.25 to 0.50 and the unloading factor ranged from 0.30 to 0.68. The values are logical because it correlates well. This method can be used to solve tunnel problems especially ground settlements.

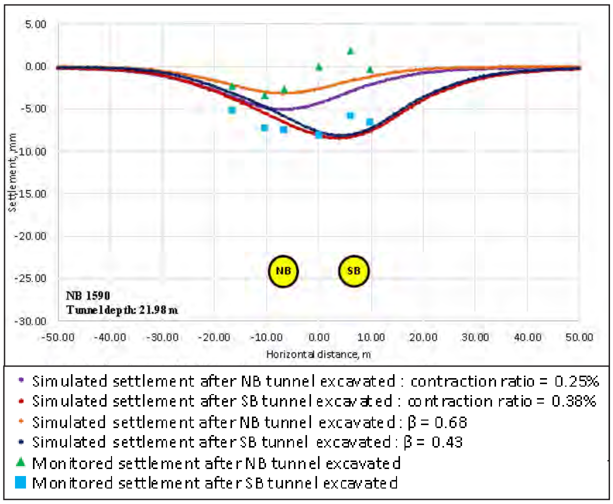

Figure 7: Results from the lining contraction and stress reduction method of chainage NB 1590.

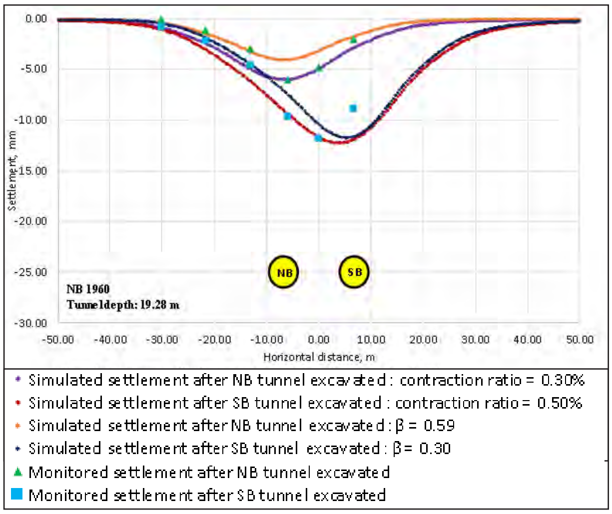

Figure 8: Results from the lining contraction and stress reduction method of chainage NB 1960.

Table 2: Maximum settlements from simulation and monitoring.

Tunnel Chainage	*Tunnel*	*Maximum settlement from lining contraction, mm*	*Maximum settlement from stress reduction, mm*	*Monitored maximum settlement, mm*
NB 1590	NB	5.042	3.21	2.63
	SB	8.445	8.16	8.13
NB 1960	NB	6.002	4.11	6.03
	SB	12.253	11.79	11.83

Table 3: Results of contraction ratio and unloading factor.

Tunnel Chainage	*Tunnel*	*Contraction ratio, %*	*Unloading Factor, β*
NB 1590	NB	0.25	0.68
	SB	0.38	0.43
NB 1960	NB	0.30	0.59
	SB	0.50	0.30

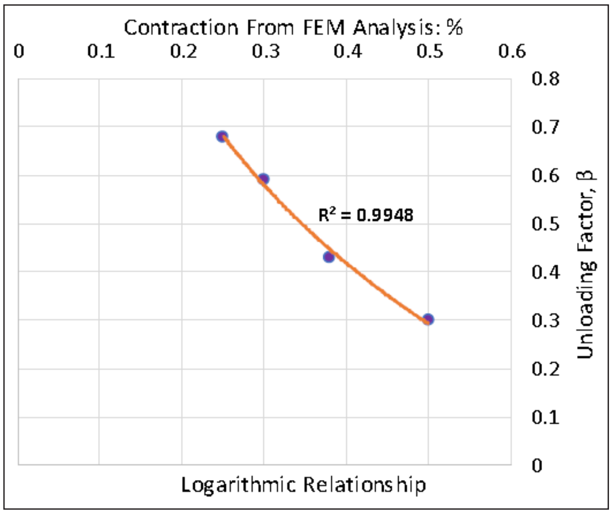

Figure 9: Relationships of contraction ratio and unloading factor.

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